Geant4 Medical Applications and Ion Physics

Toshiyuki Toshito (KEK/JST)
Medical application

- Radiology
  - Diagnosis
    - PET
    - Gamma camera
  - Treatment for cancer
    - Radiotherapy

for example, GATE
Radiotherapy

• How to focus the dose?
  – IMRT : intensity modulated radiation therapy
    • X-ray
  – Brachytherapy
    • Encapsulated radio isotope (\(\beta\)-ray, \(\gamma\)-ray)
  – Particle therapy
    • Proton, Ion
Cancer

- Cancer is the most common cause of death since 1981 in Japan. 31% in 2004
- About 40% of patients have a surgical operation. (National cancer center 2004)
  - Less than 10% of patients have a radiotherapy.
- New treatment techniques which improve treatment results and quality of life are desired.
  - radiotherapy, chemotherapy
Particle therapy


Amaldi and Kraft

BEVALAC (Berklay-US) 1975 - 1992 Ne, Si ~400
NIRS (Chiba-Japan) 1994 - $^{12}$C more than 3000
GSI (German) 1997 - $^{12}$C
HIBMC (Hyogo-Japan) 2002 - $^{12}$C

 proton vs. Carbon

Figure 4. Comparison of carbon beam with X-ray. The conformity to the target volume is improved with ion (IMPT—left panel) and with carbon beam (right panel).

a few 100MeV/n $^{12}$C beam
Particle therapy facilities in Japan

- The Energy Research Center Wakasa Bay (Tsuruga: 200 MeV)
- Hyogo Ion Beam Medical Center (HIBMC) (Hyogo: 320 MeV/n)
- Shizuoka Cancer Center (Mishima: 230 MeV)
- NIRS (Chiba: 400 MeV/n)
- U. of Tsukuba PMRC (Tsukuba: 250 MeV)
- NCC East Hospital (Kashiwa: 235 MeV)

Map showing locations of particle therapy facilities in Japan, with green markers indicating proton beams and red markers indicating ion beams.
HIMAC at NIRS (National Institute of Radiological Sciences)
HIBMC in Hyogo
Accelerator complex

Accelerator
Synchrotron
  proton(70-230MeV)
  Carbon-ions(70-320MeV/n)

Beam lines
  4 fixed-angle beam lines (proton & carbon)
  2 gantries for proton
The Project

• “The Development of Software Framework for Simulation in Radiotherapy”
  – funded by the Core Research for Evolutinal Science and Technology (CREST) program organized by Japan Science and Technology Agency (JST) from 2003 to 2008
• Joint project among medical physicists, astro-physicists and Geant4 developers in Japan
Member Institutes

- High Energy Accelerator Research Organization (KEK)
- Ritsumeikan University (RITS)
- Kobe University
- Naruto University of Education
- Toyama National College of Maritime Technology
- Japan Aerospace Exploration Agency (JAXA)

- National Institute of Radiological Science (NIRS)
- National Cancer Center, Kashiwa
- Gunma University Faculty of Medicine
- Hyogo Ion Beam Medical Center (HIBMC)
- Kitasato University
Goal of The Project

• Provide the software suit for simulation in radiotherapy, especially, particle therapy
  – Software framework and tools
    • Implementation of geometry of facilities
    • DICOM interface
    • Visualization
    • GRID
  – Tuned physics models

• Validation of simulation results
  – Collaboration with facilities
The system architecture

Knowledge DB

PTSim

DICOM interface

modeler

Geant4

GRID Deployment

Scoring/Tally Package

Physics List for Radiotherapy

framework for medical application

Dose Calculation Engines

JQMD

EGS4

others...
Use case and requirement sampling

- All of 6 facilities for particle therapy in Japan and one in Italy have been interviewed
  - NIRS
  - NCC-EAST
  - HIBMC
  - WERC
  - SCC
  - University of Tsukuba
  - INFN LNS at Catania, Italy

- Information on components in beam line and also treatment room have been gathered also
Software framework for facility implementation
Basic design of Beam irradiation system

Purpose:
- Widen the beam size to fit the tumor size with keeping lateral flatness of beam flux
- Adjust the depth of Bragg peak in a patient volume with the tumor position

Other technology:
- Double scattering, Spiral wobbling system for shortening the irradiation system
- Beam scanning in three dimensions using small beam spot and variable beam energy

T. Aso IEEE NSS 2007 N60-1
Directory structure of PTS simulator

- Applicable for multiple facilities
- Geometrical information of equipments can be given by text-file
- able to select physics models
- easy to use, does not require C++ programming
## Implemented irradiation systems using PTSsim

<table>
<thead>
<tr>
<th>Facility</th>
<th>Accelerator</th>
<th>Beam Energy (MeV)</th>
<th>Lateral Spreading System</th>
<th>Range Modulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIBMC Gantry</td>
<td>Synchrotron</td>
<td>Proton 150,190,230</td>
<td>Wobbler magnets and scatter</td>
<td>Ridge filter</td>
</tr>
<tr>
<td>NCC Gantry</td>
<td>Cyclotron</td>
<td>Proton 150,190,235</td>
<td>Scatter and double scatter</td>
<td>Ridge filter</td>
</tr>
<tr>
<td>UCSF</td>
<td>Cyclotron</td>
<td>Proton 67.5</td>
<td>N/A</td>
<td>Propeller blades</td>
</tr>
<tr>
<td>HIMAC</td>
<td>Synchrotron</td>
<td>Carbon 400 MeV/u</td>
<td>Wobbler magnets and scatter</td>
<td>Ridge filter</td>
</tr>
<tr>
<td>HIBMC Synchrotron</td>
<td>Carbon 320 MeV/u</td>
<td>Wobbler magnets and scatter</td>
<td>Ridge filter</td>
<td></td>
</tr>
<tr>
<td>GSI</td>
<td>Synchrotron</td>
<td>Carbon ~400 MeV/u</td>
<td>Beam scanning</td>
<td>Fine Ridge filter</td>
</tr>
</tbody>
</table>
Example of irradiation systems

- Scatter
- Double Scatter
- Ridge filter
- Propeller blade
- Ionization Chamber
- Wobbler Magnets
- Collimator
- Multi-leaf collimator
- Bolus
- Wire Chamber
- Water phantom
- DICOM data

/G4M/System HIBMCGantry
/G4M/ChangeSystem NCCGantry
/G4M/ChangeSystem UCSFSetup

T.Aso IEEE NSS 2007 N60
Others

• Primary generator
  – G4MBeamGun - HIBMC
    • Parallel beam with respect to z-axis
      – Spot size
    – G4MFocusGun - NCC
      • Cone beam with focusing points
        – focusing points and emittances of x and y direction
    – G4GeneralParticleSource (GEANT4) - IHIport at NIRS
DICOM handling, visualization and UI
DICOM (Digital Imaging and COmmunication in Medicine) interface

- DICOM handler had been developed independently
  - TOSHIBA, SIEMENS, and GE DICOM data had been tested.
  - Filter modules are plugged in for converting original CT data into a suitable format for making a geometry
    - Extraction of patient geometry
    - Reformation of voxels
    - Density conversion

- DICOM-RT (Radiation Therapy)
  - HIBMC-Mitsubishi is tested
**gMocren : DICOM visualizer**

3D (ray casting)  2D (MPR)

Opacity curve and color map editor

**Functionality Requirements :**

- To visualize
  - the modality image used by the simulation,
  - the calculated dose distribution and
  - the particle trajectories
  - in an agreeable speed
- Transfer function editor
- Multi-platform (Windows, Linux)

Calculated dose distribution

Particle trajectories

http://geant4.kek.jp/gMocren/

**Supported system :**
- Windows 2k/XP or PC Linux OS
- Pentium 4 or faster
- more than 1 GB (recommend)
- no special hardware is necessary

**gMocren and utility softwares are freely available.**

free hand or templates with WW&WL editing

Trajectory information in the simulation is available.

IEEE NSS/MIC (San Diego, Nov/2006)
Physics validation
Fragmentation reactions

- In the case of 400MeV/n (~30cm in water), only 30% of beams can reach the region of bragg-peak; about 70% of beams are lost by fragmentation.
- Fragments having lower Z than carbon contribute to tail and lateral dose.
- Fragmentation reaction largely modulate dose distribution.
- Knowledge of fragmentation reaction is important to calculate dose distribution.
Depth-dose distribution
($^{12}$C 290 MeV/n)

Pristine Bragg peak
wo/ Ridge filter

Relative dose

Depth in water (mm)

Normalized here

Spread-out Bragg peak
w/ Ridge filter

Relative dose

Depth in water (mm)

Depth-dose distribution
($^{12}$C 400 MeV/n)

Pristine Bragg peak
wo/ Ridge Filter

Relative dose

Depth in Water (mm)

Normalized Here

Spread-out Bragg peak
w/ Ridge Filter

Relative dose

Depth in Water (mm)

Simulation of penumbral measurement (1)

Beam

Half-closed MLC

Penumbra widening is well reproduced by simulation.

IEEE NSS/MIC (San Diego, Nov/2006)
Depth-dose in water

320MeV/n $^{12}$C
Geant4 Binary cascade

Bragg peak

Tail dose

Dose by fragments

Entries: 3.1815e+08
Mean: 102
RMS: 58.83
Dose by fragments

320 MeV/n $^{12}$C

Geant4 Binary cascade

- Bragg peak
- C
- B
- Be
- Li
- He
- H

Relative dose

Depth (mm)
Models for fragmentations in Geant4

- Binary cascade (G4BinaryLightIonReaction)
- Wilson’s abrasion (G4WilsonAbrasionModel)
- JQMD (JQMD2G4InelasticModel)
  T. Koi et al., CHEP03 ECONF C0303241 THMT005 (2003)

Cross section: Shen formula (G4IonsShenCrossSection)

Version 4.9.0
Carbon-Water
total charge-changing cross sections

![Graph showing carbon-water total charge-changing cross sections with data points and lines for Wilson, JQMD, BC, Golovchenko, and Schall.]

Data (P152)
Wilson
JQMD
BC
Golovchenko
PRC66 014609 (2002)
Schall
NIM B 117 221 (1996)

T. Toshito IEEE NSS/MIC 2007
Carbon-Water partial charge-changing cross sections

- $C \rightarrow B$
- $C \rightarrow Be$
- $C \rightarrow Li$

Data

T.Toshito IEEE NSS/MIC 2007
Angular distributions of H and He fragments in Carbon-Water int.

200-400MeV/n

Important for lateral dose

T.Toshito IEEE NSS/MIC 2007
Carbon-Water

$^8\text{Be}$ and $^9\text{B}$ production cross sections

T. Toshito IEEE NSS/MIC 2007
Application at HIBMC
Beam profile

• Comparison of beam profile
  – Geant4.8.2.p01 and pencil beam algorithm used in therapy planning system at HIBMC
  – 150 MeV proton, 2 cm range shifter, 0.16 cm scatterer, bolus, ridge filter designed for 10 cm SOBP and collimator
Comparison of dose profiles in water

- Geant4.8.2.p01
- Pencil beam algorithm
- Measurements in water
Beam profiles in the patient

- G4 in the patient (left)
- Pencil beam algorithm (right)
Functionality under development
GRID: distributed computing over the Internet

Grid Web UI

Grid access via HTTP
✓ Job submission, management, monitoring
✓ Get and browse results

Virtual Organization
✓ Based on GSI
✓ Across the institutes

Resource Broker
✓ Inquiry resource information
✓ Job queuing and logging

Job Submission

Network Server

Task Queue

Match Maker

Information Supermarket

Site-A

Globus I/F

Site-B

Globus I/F

Site-C

Globus I/F

WMS

File Catalogue
✓ Independent of physical location of files
✓ Replication and transfer automatically

Resource Broker

Job Submission

IEEE NSS/MIC (Puerto Rico, Oct/2005)

GRID: distributed computing over the Internet

Site-A

Globus I/F

Site-B

Globus I/F

Site-C

Globus I/F

WMS

File Catalogue
✓ Independent of physical location of files
✓ Replication and transfer automatically

Virtual Organization
✓ Based on GSI
✓ Across the institutes

Resource Broker

Job Submission

IEEE NSS/MIC (Puerto Rico, Oct/2005)
1.198 MeV gammas entering 3.004 cm of water
40 events are displayed to “measure” the probability of the through gammas
Summary

• Geant4 is extensively applied to radiology because of its capability to handle all particles including ions, complex geometry and electromagnetic fields and flexibility.

• The software suit for simulating radiotherapy has been developed in the CREST project “The Development of Software Framework for Simulation in Radiotherapy”.