A GEANT4 based Simulation for Proton Therapy

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Outline

- **Introduction**
  - Hadron (Proton) Therapy

- **Simulation Framework**
  - User requirements, setups, UI commands

- **Physics Validation**
  - Dose distribution in water

- **Summary**
Introduction to hadron therapy

Hadron therapy
- Bragg peak characteristics is suitable for the radio-therapeutic treatment of tumors.
- This can reduce dose at healthy tissues while maximize the effect at deeper tumor region

Beam Irradiation System
- Similar components are adopted at facilities.

=> Simulation Framework can be commonly used.
- Not only
  - protons
  - carbons
- But also
  - X-ray radiation therapy

<table>
<thead>
<tr>
<th></th>
<th>X-ray</th>
<th>Proton</th>
<th>Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>RBE</td>
<td>1</td>
<td>1</td>
<td>2.5</td>
</tr>
<tr>
<td>OER</td>
<td>3</td>
<td>3</td>
<td>1.8</td>
</tr>
<tr>
<td>Physics</td>
<td>EM only</td>
<td>EM+Had</td>
<td>EM+Had</td>
</tr>
<tr>
<td>Costs Facility</td>
<td>($4M)</td>
<td>$60M</td>
<td>$270M</td>
</tr>
<tr>
<td>(System)</td>
<td></td>
<td>($30M)</td>
<td>($150M)</td>
</tr>
<tr>
<td>Dose localization</td>
<td>IMRT</td>
<td>good</td>
<td>excellent</td>
</tr>
</tbody>
</table>
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 to 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
Hadron Therapy Facility in Japan

Fukui Prefecture Hospital
Hyogo Ion Beam Medical Center
Southern Tohoku Research Institute for Neuroscience
Wakasa wan energy research center
Shizuoka Cancer Center
National Cancer Center
Gunma University
National Institute of Radiological Sciences
Proton Medical Research Center University of Tsukuba
GEANT4 based simulation framework

Motivation

- Use cases
  - Designing beam delivery system
  - Validating or Proposing a treatment planning
- Basic approaches
  - Experimental measurements (Trustable but hard to do everything)
  - Analytical calculations (Model limitation for simplicity)
- MC Simulation Tools
  - Complex geometrical effect
  - Material variety
  - Different Physics processes for comparison

Strategy

- Different facilities should be described in a simulator
  - Provides customizable beam modules
  - Commonly used for carbon-ion as well as proton.
- Minimize coding effort for beginners of C++ and Geant4.
  - User Interface command
  - Python interface (Koichi Murakami, KEK, and Hajime Yoshida, Naruto Edu. Univ.)
- Physics Validation
  - Proton physics specially focused on medical physics domain.
  - Heavy Ion physics (Presented at CHEP06 by S. Kamaoka)
Directory structure of PTS simulator

PTS simulator consists of modules and data files. Data files are prepared for particular irradiation systems with common format.
Setup of a irradiation system
- A irradiation system is build by specifying a set of beam modules and a primary generator.
- Derived class from G4MVParticleTherapySystem registers default components of a irradiation system to a particle therapy system.
- These beam modules are installed on the beam line as a geometry from the registered module list.

```
/G4M/Module/install <module name>
/G4M/Module/uninstall <module name>
/G4M/Module/select <module name>
/G4M/Module/translate <x> <y> <z> <unit>
/G4M/Module/rotate <rx> <ry> <rz> <unit>
```

```
/G4M/System <setup name>
/G4M/ChangeSystem <setup name>
```

```
G4MVGeometryBuilder
```

```
G4VUserPrimaryGeneratorAction
```

```
MyPrimaryGeneratorAction
```

```
My/PrimaryGenerator/select <beam type>
```

```
G4VPrimaryGenerator
```

```
G4MBeamGun
G4MFocusGun
G4MScanGun
```

```
G4MVParticleTherapySystem
HIBMCGantrySetup
NCCGantrySetup
UCSFSsetup
G4MBeamModule
G4MWobblerMagnet
G4MMLCX
G4MBolus
```
Example of irradiation systems

BeamModules

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

/HIBMC
/G4M/System HIBMC Gantry

/NCC
/G4M/ChangeSystem NCC Gantry

/UCSF
/G4M/ChangeSystem UCSF Setup
Customization-Beam module -
G4MMaterialFileConstruction
- Both user defined and/or Nist elements/materials are created by using UI command /G4M/Material/create <material name>.
- The data file of the material property should be prepared.
- The data file describes the material property, such as state, density, mean excitation energy, and fraction of components.

G4MVCatalogue (BeamModule)
- The catalogue object is assigned to the BeamModule.
- A catalogue class describes the procedure for accessing the module parameters.
- The UI command /G4M/Module/typeid <type name> read new parameters. Then, those parameters are set to the BeamModule.

```
BeamModule
  SetAllParameters
  Catalogue
    Prepare()
    Apply()
  FileCatalogue

Example of material data

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>G10</td>
<td>1</td>
<td>#solid state</td>
</tr>
<tr>
<td>1.70</td>
<td>#density</td>
<td></td>
</tr>
<tr>
<td>-1</td>
<td>#E_excit auto calculation</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>#Number of components</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>SiO2</td>
<td>0.773</td>
</tr>
<tr>
<td>M</td>
<td>Epoxy</td>
<td>0.147</td>
</tr>
<tr>
<td>M</td>
<td>Chlorine</td>
<td>0.080</td>
</tr>
</tbody>
</table>
```

Example of ridge data

```
0038
designed for SOBP 3 cm with proton 190 MeV, scatterer 025
2122
190_025
30.0, 0.0, 13.75
Aluminium
24
120.0
5.0
1
7
1.12755 0
1.467896 2.347418
1.752794 4.694836
1.965832 7.042253
2.171185 9.389671
2.325188 11.73709
2.5 14.08451
```
Customization-Primary Beam-

Primary generator
- G4MBeamGun
  - Created for HIBMC
  - Parallel beam with respect to z-axis
    - Beam spot size in x and y should be given by the standard deviation of Gaussian distribution
- G4MFocusGun
  - Created for NCC
  - Cone beam to have a different focusing point in x and y.
    - Two focusing position and the momentum fraction in x and y should be given.
- G4MScanGun
  - Created for GSI
  - Scanning beam toward final point
    - Generating position and the final position of x and y at the plane of isocenter should be given.
- G4GeneralParticleSource (GEANT4)
  - Used for IHlport at NIRS

Physics processes
- EM process: standard / low energy
- hadron process: elastic / inelastic
  - LHEP_PRECO
  - LHEP_BERT
  - LHEP_BIC
DICOM geometry

DICOM handler: (by A. Kimura)
- TOSHIBA, SIEMENS, and GE DICOM data had been tested.
- DICOM network is partly supported using DCMTK (OFFIS)
- Filters are available to convert original CT data for making a geometry.
  - Outline selection
  - Recombination of pixels
  - Density conversion from HU

Implementation of a DICOM geometry in PTSSim
- Material implementation
  - Water with corresponding density of CT
  - 9 representative tissue (Tentative)
- Geometry implementation
  - G4VParameterisation
  - G4VNestedParameterisation
- These conditions are also modified by UI commands.

Load DICOM data

Compensation of lack slices

Select window of interest

Outline extraction

Recombination of voxles

Material creation

Geometry construction

/Y4M/DICOM/select DICOM
/Y4M/DICOM/file:/data/HIBM/HIBM.dat
/Y4M/DICOM/mesh 15.mm
/Y4M/DICOM/sha 1000.
/Y4M/DICOM/ctcutoff -500.
/Y4M/DICOM/ct2density:/data/HIBM/HIBMCT2Density.dat
/Y4M/DICOM/paramtype H2O
/Y4M/DICOM/gantry 45. deg
/Y4M/Module/install DICOM
Dose verification

Results of the simulation were examined to measured data at HIBMC.

- The result had already been published in

- Physics processes for proton
  - Based on LHEP_PRECO_HP physics list
    - Standard EM package was replaced with Low energy package
      - G4hLowEnergyIonisation
        - below 10 MeV, SRIM2000 parameterization
    - Elastic process
    - Inelastic process
      - below 170 MeV, a pre-compound nuclear interaction model based on a pre-equilibrium decay model

- Verified items (Proton)
  - Range in water, aluminum, lead
  - Scattering by lead
  - Irradiation field size
  - Pristine Bragg peak with wobbling and scatter
  - Spread-out Bragg peak (SOBP) with wobbling and scatter
Dose verification at HIBMC

- Maximum relative difference in pristine Bragg peak is about 4%.
- The displacements of peak positions were observed.
  - For example, at 230 MeV, Mes. – Sim. = 1.6 mm
  - The precise beam parameters may improve this problem.
- In SOBP, this effect are smeared and not observed.
- In both pristine Bragg peak and SOBP, the shape of dose distributions are similar to the measurements.
Pristine Bragg peak without scatters
- The measurement of beam parameters are partly available but not finally fixed.
  - In treatment, the stability of the beam is confirmed every day with respect to clinical references.
  - Serious problem for particle physicists but not for medical physicists. They only believe measurements.
- Available measured data
  - Lateral distribution at the isocenter
  - Depth dose distribution
  - Focus point and its divergence of beam on the beam line
  - Energy fluctuation 0.815% (estimation from measurements)
- Simulation approach
  - Estimated using simulation
    - Beam energy at the injection point (upstream focusing point) was estimated with pencil beam to reproduce the peak position of pristine Bragg peak in the measurement.
    - Initial beam spot size of parallel beam (G4MBeamGun) was estimated to reproduce the measured lateral distribution at the isocenter.
  - Compared
    - Parallel beam (G4MBeamGun) versus Cone beam (G4MFocusGun) with measured depth-dose distribution.
Dose verification at NCC -2-

![Graph showing dose verification results for 150MeV beam.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Meas.</th>
<th>Parallel beam (diff)</th>
<th>Cone beam (diff.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak depth [mm]</td>
<td>135.0</td>
<td>135.0</td>
<td>135.0</td>
</tr>
<tr>
<td>Plateau/Peak ratio</td>
<td>0.290</td>
<td>0.267 (7.9%)</td>
<td>0.280 (3.3%)</td>
</tr>
<tr>
<td>FWHM [mm]</td>
<td>19.55</td>
<td>18.60 (4.9%)</td>
<td>19.29 (1.3%)</td>
</tr>
<tr>
<td>distal 90%-10% dose [mm]</td>
<td>5.07</td>
<td>5.02 (1.0%)</td>
<td>5.15 (1.6%)</td>
</tr>
</tbody>
</table>
Effect of the Nuclear Interaction to Dose (1)

By Takashi Akagi@HIBMC

beam
MLC
Water phantom

50mm depth

250mm depth

Dose given by Elastic/Inelastic protons

□ : Measurements
□ : G4 (histograms)

2007/09/03 CHEP2007
TNCMT, JST CREST
Effect of the Nuclear Interaction to Dose(2)

By Takashi Akagi@HIBM

beam
MLC
Water phantom

50mm depth

250mm depth

- : Measurements
- : TPS calculations
□ : G4 (histograms)
Summary

• The simulation framework for particle therapy has been developed.
  • The framework provides UI commands to compose irradiation systems.

• The physics validations are in progress.
  • The results of dose distribution in water reasonably reproduce the measurements.

• Physics validations using DICOM data will be a next stage.