A GEANT4 based Simulation for Proton Therapy

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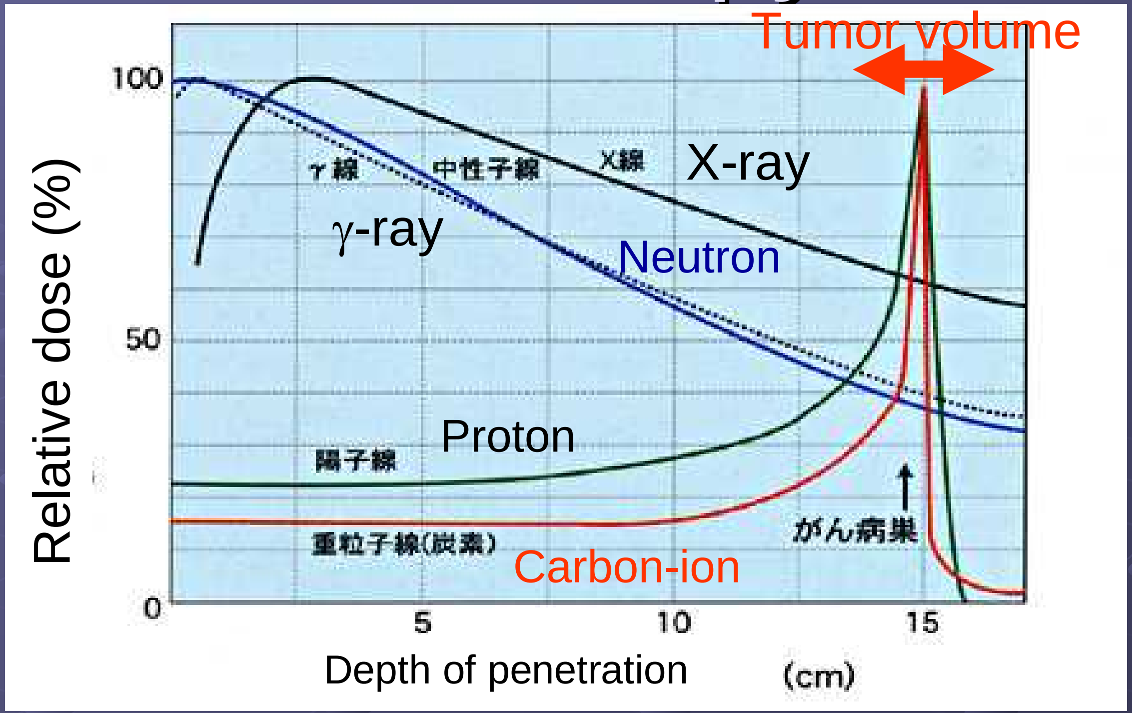
Outline

- 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



	X-ray	Proton	Carbon
RBE	1	1	2.5
OER	3	3	1.8
Physics	EM only	EM+Had	EM+Had
Costs Facility (System)	($4M)	$60M ($30M)	$270M ($150M)
Dose localization	IMRT	good	excellent

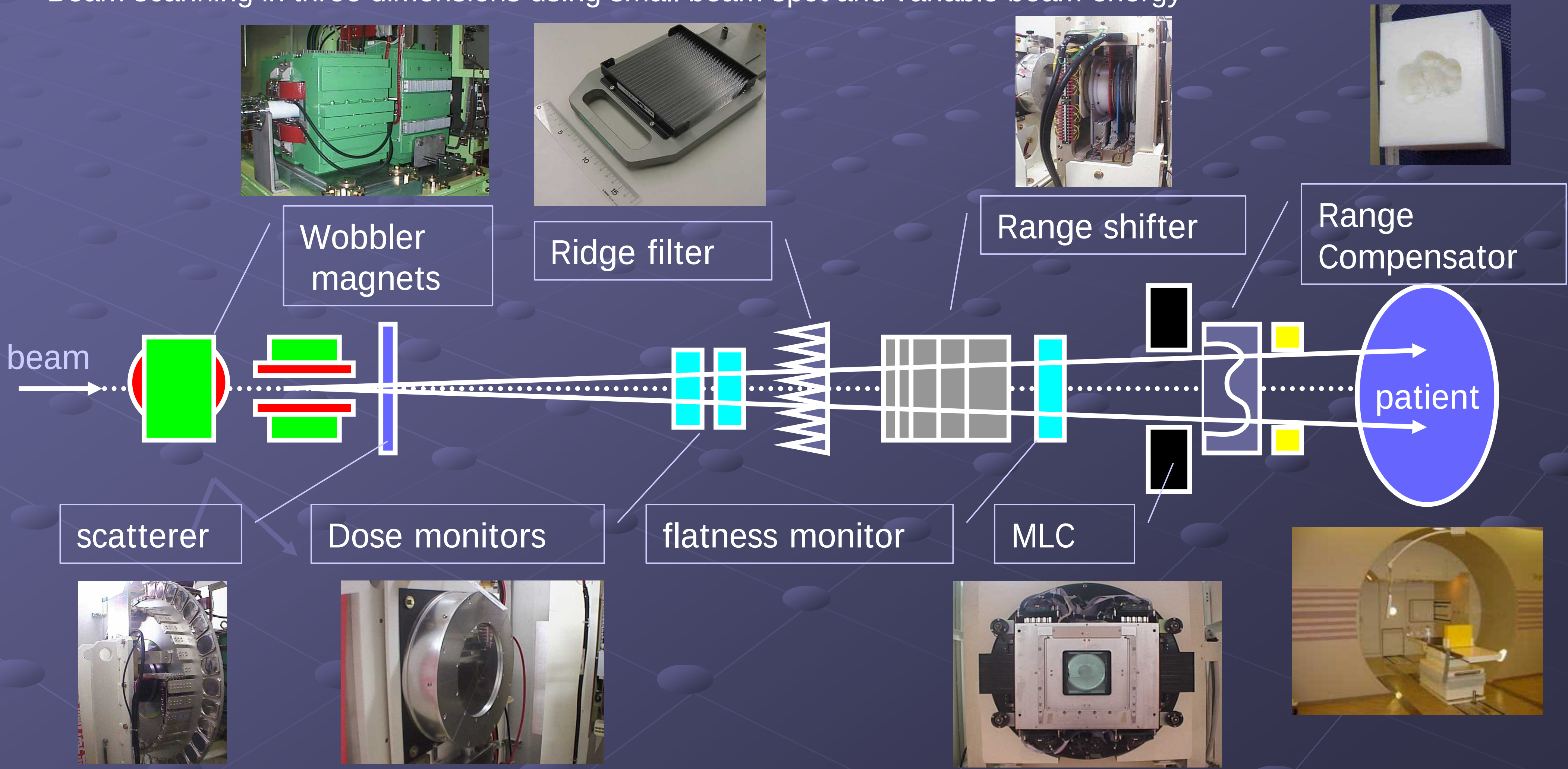
Basic design of Beam irradiation system

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

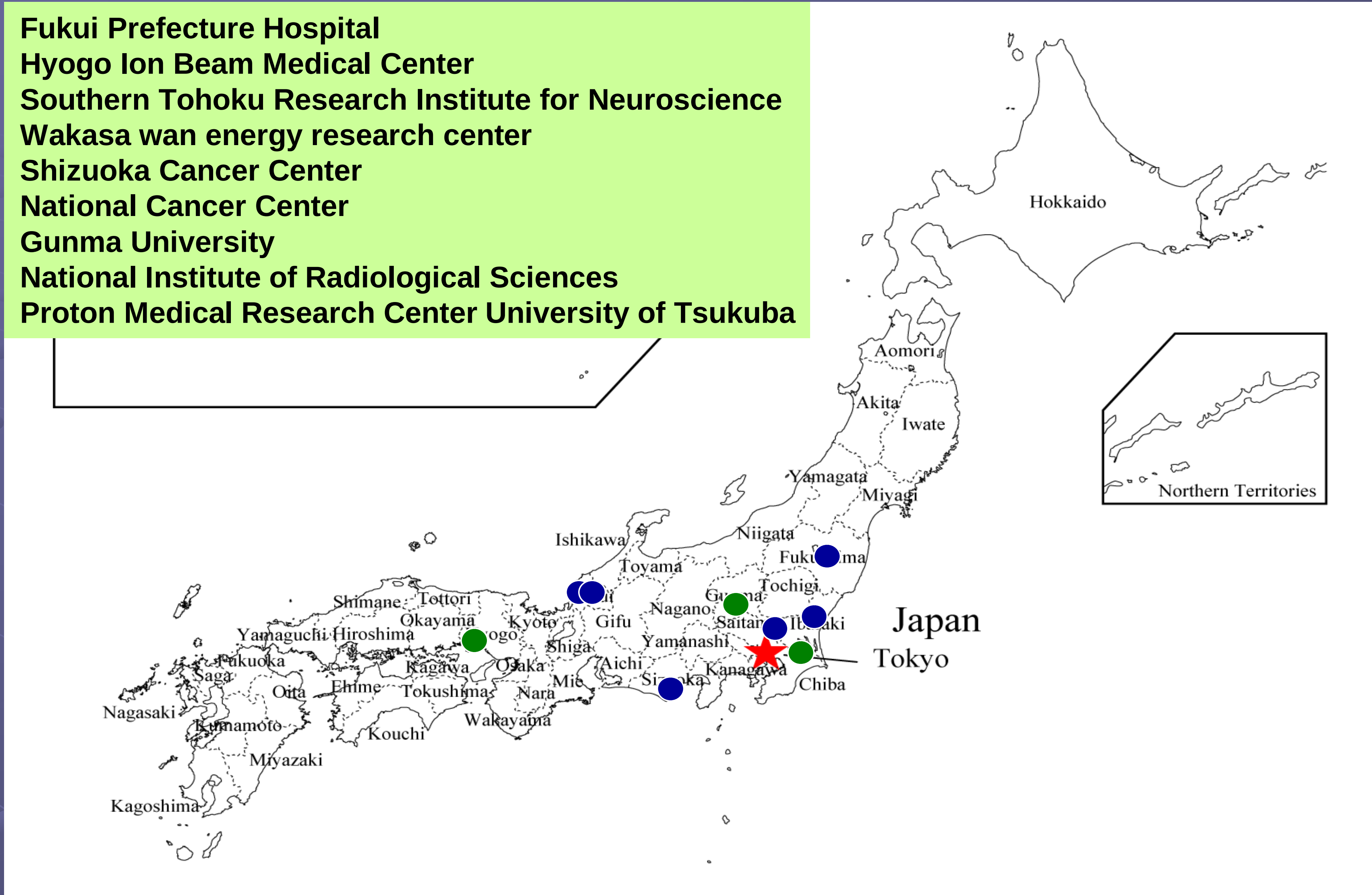
Other technology:

- 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

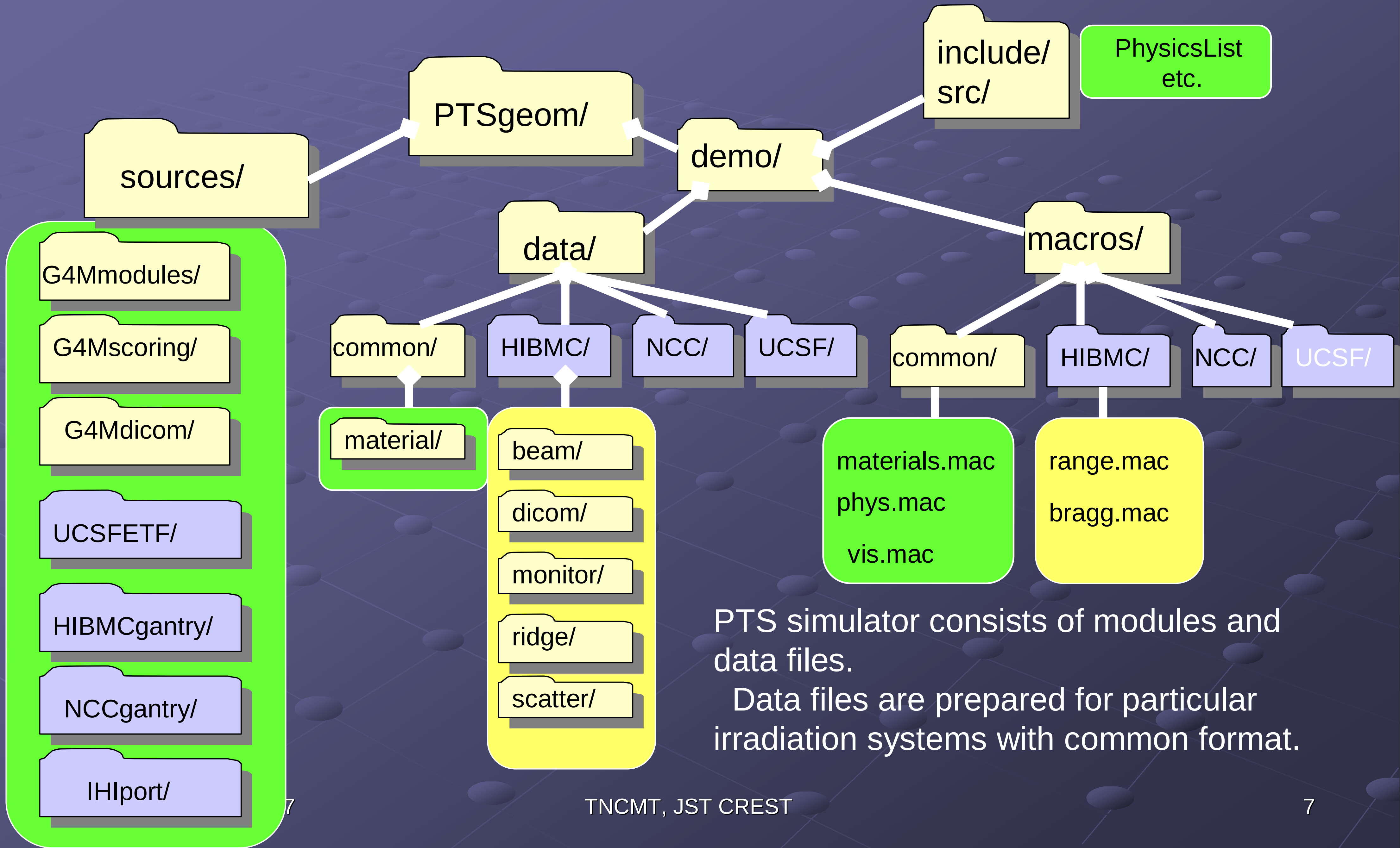
Fukui Prefecture Hospital
Hyogo Ion Beam Medical Center
Southern Tohoku Research Institute for Neuroscience
Wakasa wan energy research center
Shizuoka Cancer Center
National Cancer Center
Gunma University
National Institute of Radiological Sciences
Proton Medical Research Center University of Tsukuba



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)*

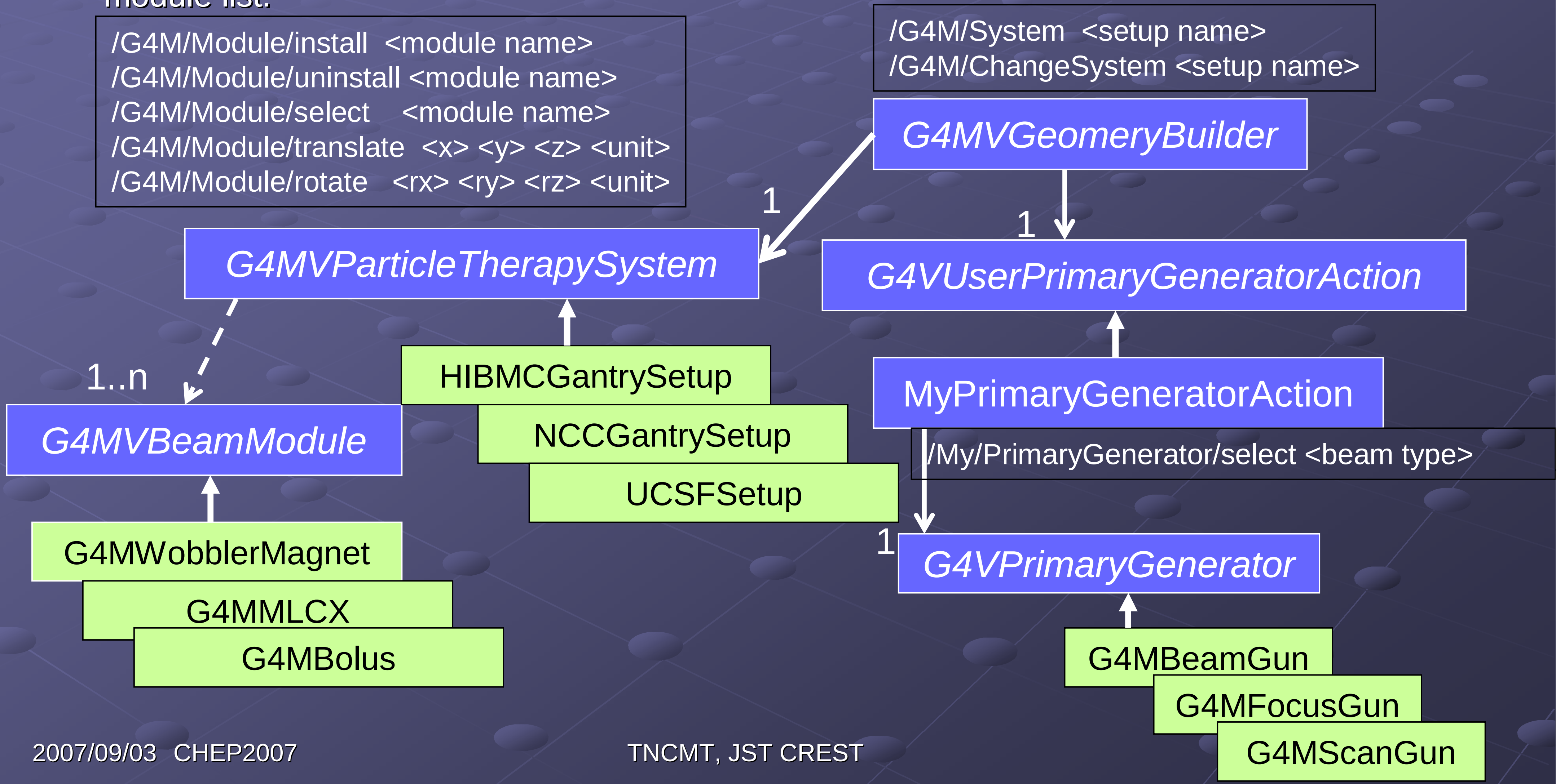
Directory structure of PTS simulator



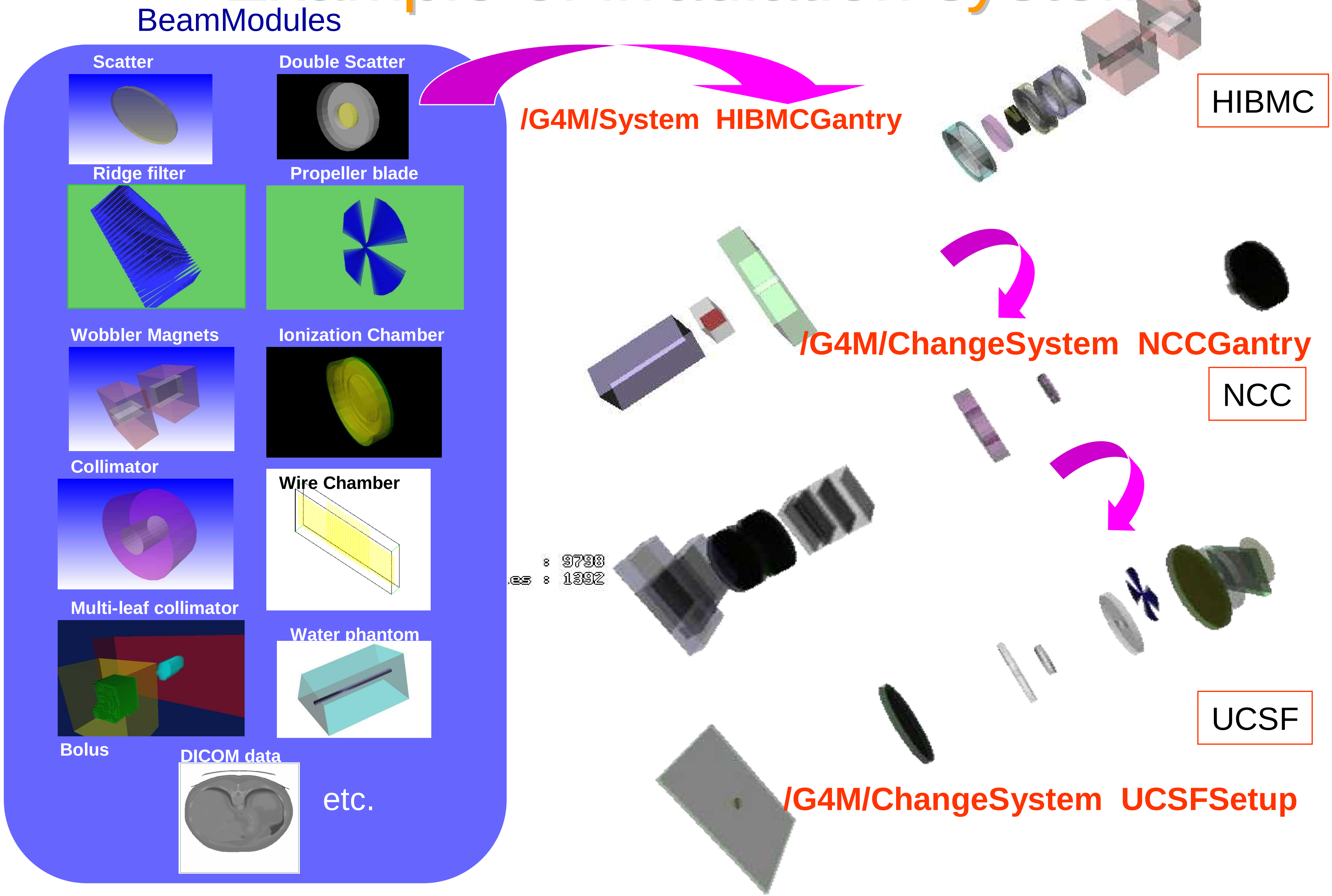
PTS simulator consists of modules and data files.
Data files are prepared for particular irradiation systems with common format.

Customization-Facility-

- 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.



Example of irradiation systems



Customization-Beam module-

G4MMaterialFileConstruction

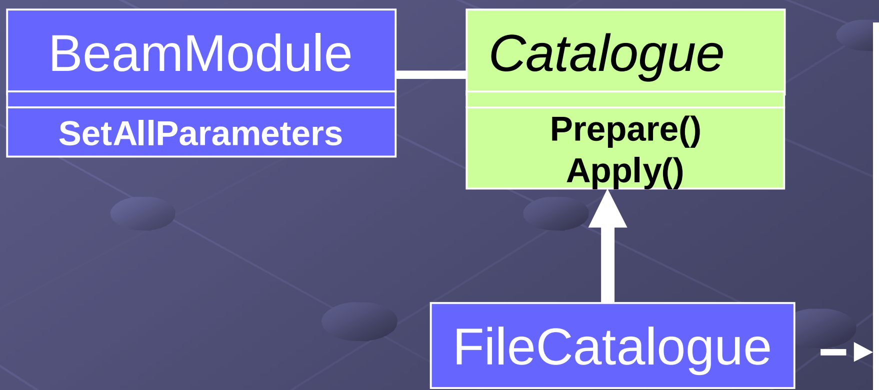
- Both user defined and/or Nist elements/materials are created by using UI command /G4M/Material/create <material name>.
- The data file of the material property should be prepared.
- The data file describes the material property, such as state, density, mean excitation energy, and fraction of components.

Example of material data

```
G10
G10    1          # solid state
1.70              # density
-1                # E_excit auto calculation
3                 # Number of components
M    SiO2      0.773
M    Epoxy     0.147
M    Chlorine  0.080
```

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.



Example of ridge data

```
0038
desgined 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
```

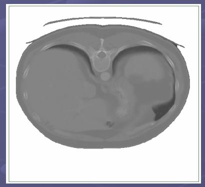
Customization-Primary Beam-

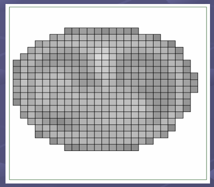
- Primary generator
  - G4MBeamGun
    - Created for HIBMC
    - Parallel beam with respect to z-axis
      - Beam spot size in x and y should be given by the standard deviation of Gaussian distribution
  - G4MFocusGun
    - Created for NCC
    - Cone beam to have a different focusing point in x and 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 IHIport at NIRS

- Physics processes
  - EM process : standard / low energy
  - hadronic process: elastic / inelastic
    - LHEP_PRECO
    - LHEP_BERT
    - LHEP_BIC

DICOM geometry

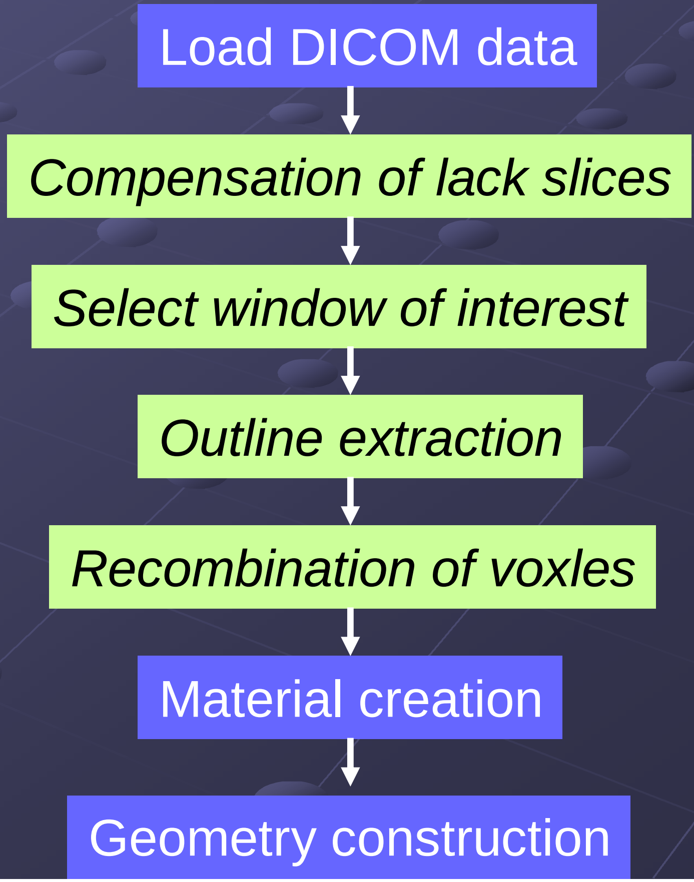
- DICOM handler: (by A.Kimura)
  - TOSHIBA, SIEMENS, and GE DICOM data had been tested.
  - DICOM network is partly supported using DCMTK (OFFIS)
  - Filters are available to convert original CT data for making a geometry.
    - Outline selection
    - Recombination of pixels
    - Density conversion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





- Implementation of a DICOM geometry in PTSsim
  - Material implementation
    - Water with corresponding density of CT
    - 9 representative tissue (Tentative)
  - Geometry implementation
    - G4VParameterisation
    - G4VNestedParamerisation
  - These conditions are also modified by UI commands.

```
/G4M/DICOM/select       DICOM
/G4M/DICOM/file         ./data/HIBMC/HIBMC.dat
/G4M/DICOM/mesh         15. mm
/G4M/DICOM/ctair        -1000.
/G4M/DICOM/ctcutoff     -500.
/G4M/DICOM/ct2density  ./data/HIBMC/HIBMCCT2Density.dat
/G4M/DICOM/paramtype  H_2O
/G4M/DICOM/gantry       45. deg
/G4M/Module/install     DICOM
```



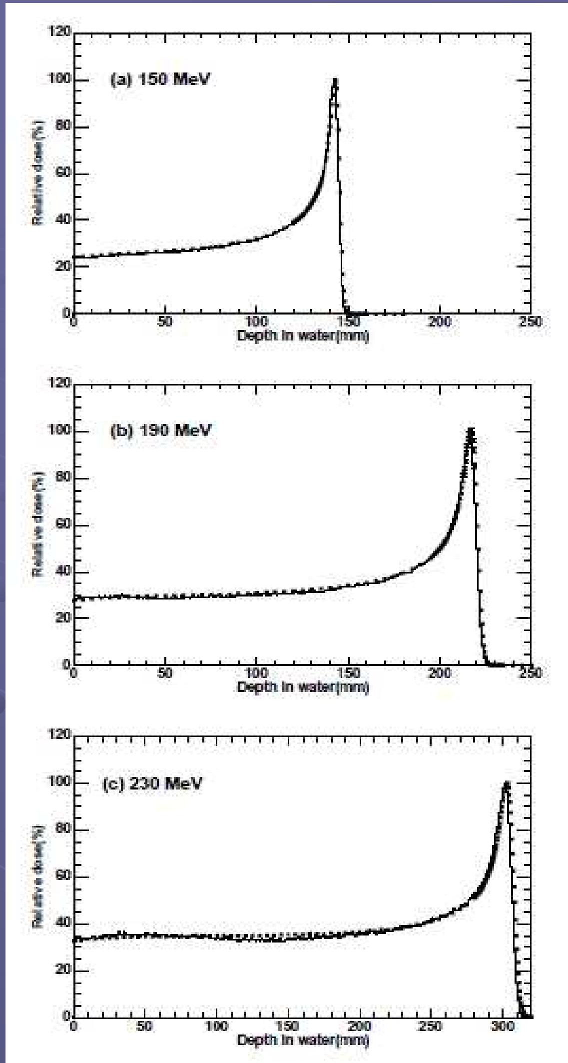
Dose verification

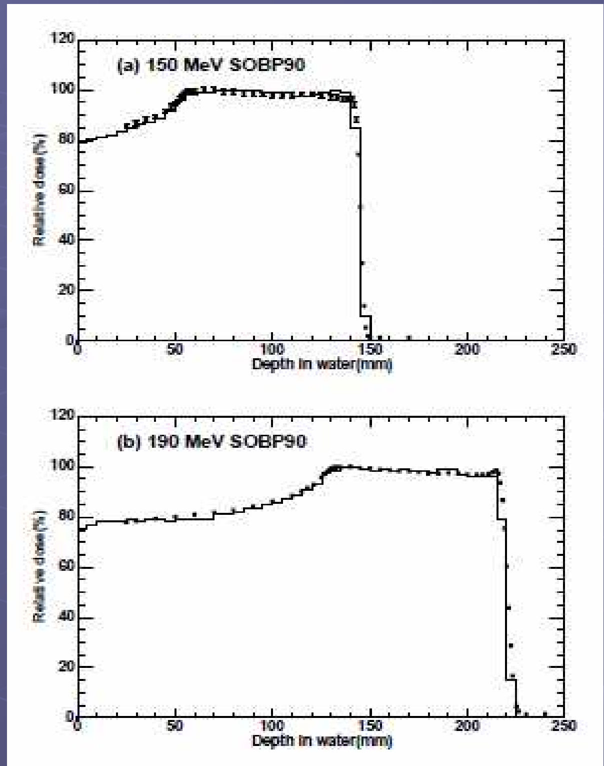
- Results of the simulation were examined to measured data at HIBMC.
  - The result had already been published in
    - IEEE TNS NS Vol.52, Issue 4, 896-901(2005)

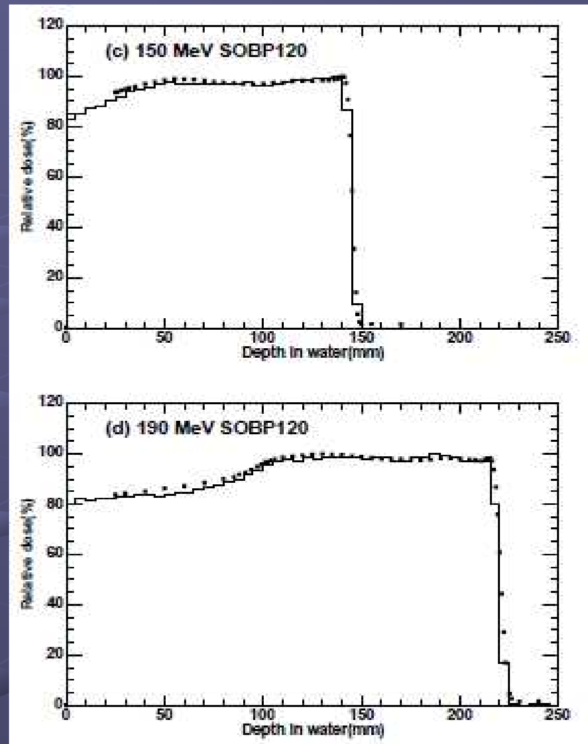
  - Physics processes for proton
    - Based on LHEP_PRECO_HP physics list
      - Standard EM package was replaced with Low energy package
        - G4hLowEnergyIonisation
          - below 10 MeV, SRIM2000 parameterization
        - Elastic process
        - Inelastic process
          - below 170 MeV, 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





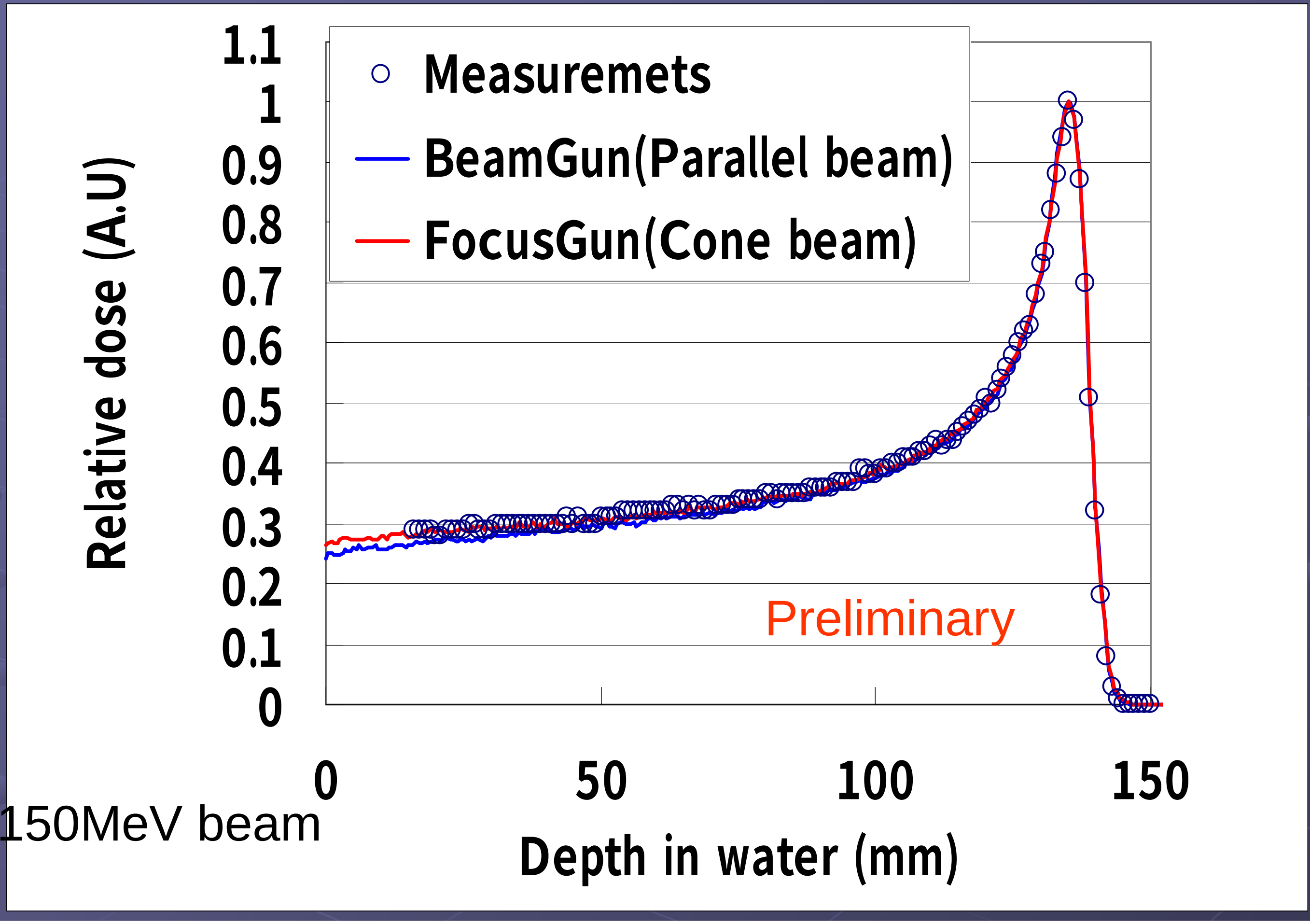


- Maximum relative difference in pristine Bragg peak is about 4%.
- The displacements of peak positions were observed.
  - For example, at 230MeV, Mes. – Sim. = 1.6mm
  - The precise beam parameters may improve this problem.
  - In SOBP, this effect are smeared and not observed.
- In both pristine Bragg peak and SOBP, the shape of dose distributions are similar to the measurements.

Dose verification at NCC -1-

- 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.

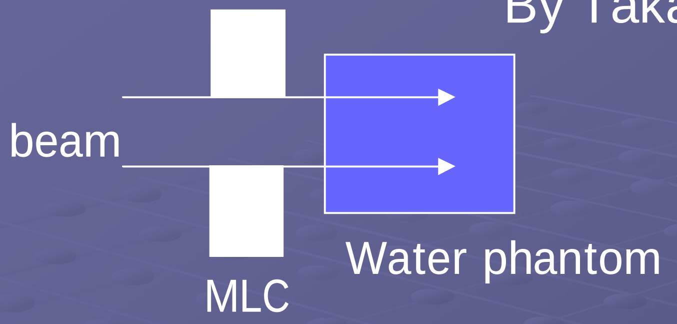
Dose verification at NCC -2-

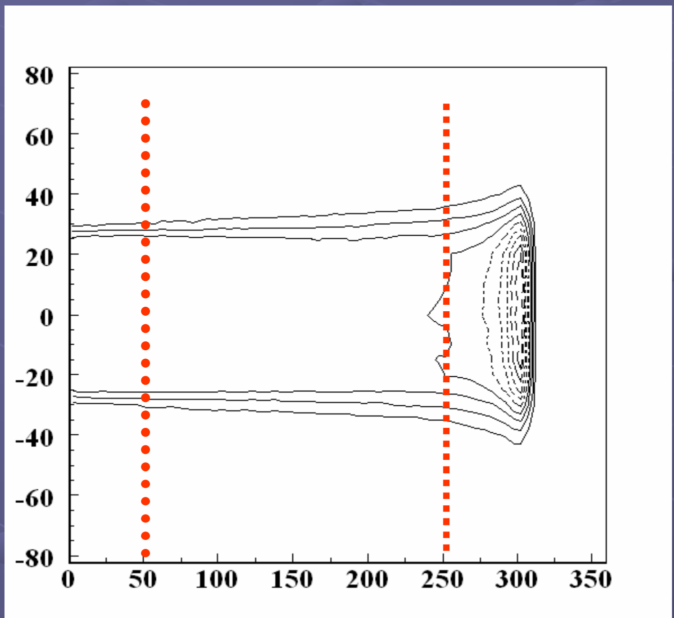


	Meas.	Parallel beam (diff)	Cone beam (diff.)
Peak depth [mm]	135.0	135.0	135.0
Plateau/Peak ratio	0.290	0.267 (7.9%)	0.280 (3.3%)
FWHM[mm]	19.55	18.60 (4.9%)	19.29 (1.3%)
distal 90%-10% dose[mm]	5.07	5.02 (1.0%)	5.15 (1.6%)

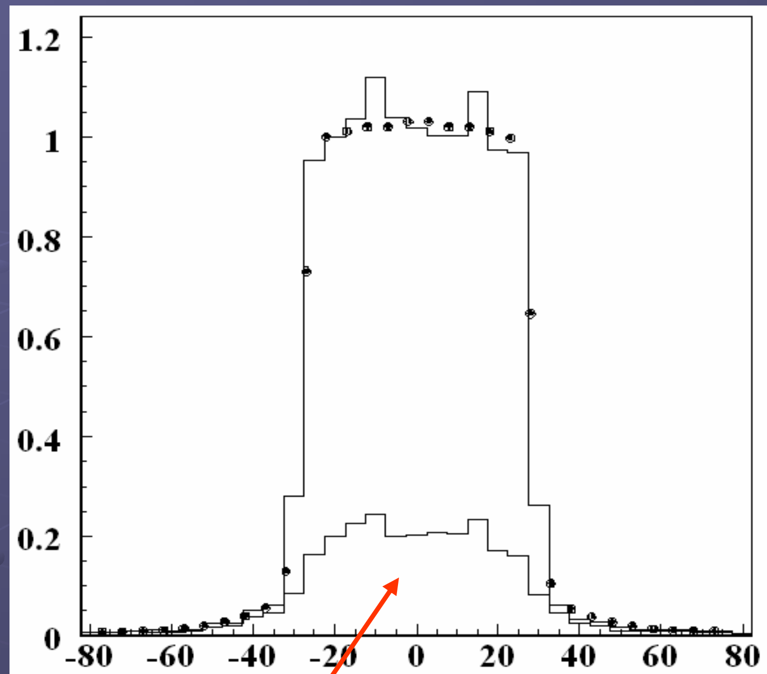
Effect of the Nuclear Interaction to Dose(1)

By Takashi Akagi@HIBMC





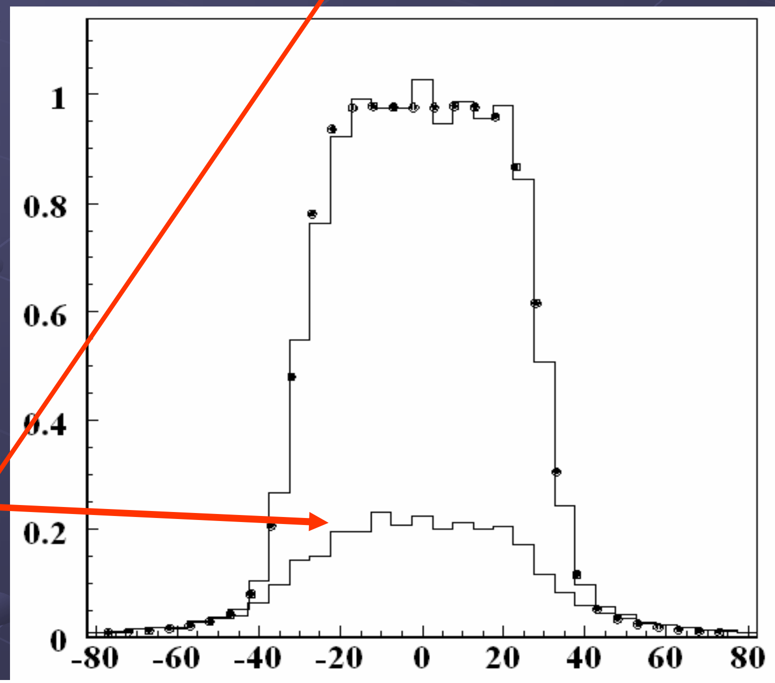
50mm depth



● : Measurements

□ : G4 (histograms)

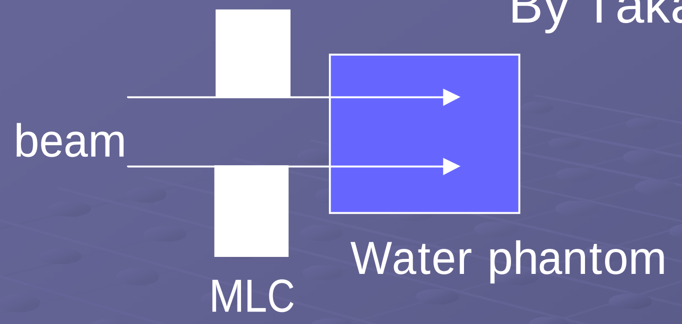
250mm depth

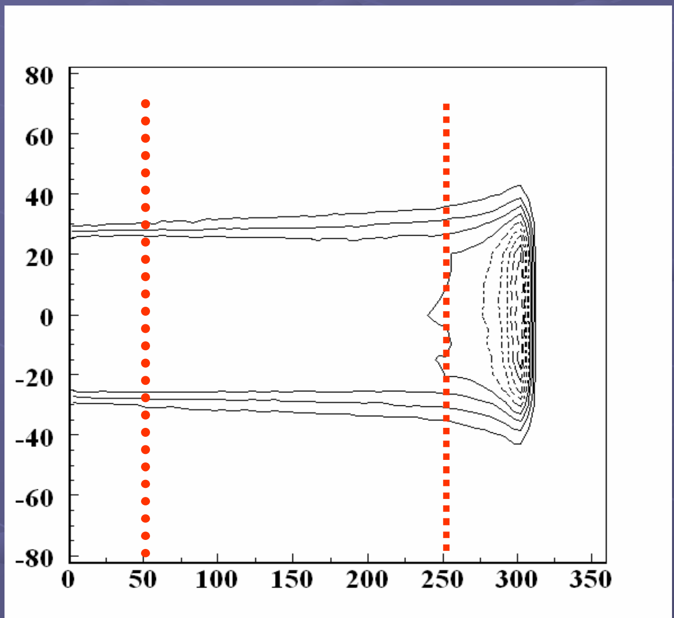


Dose given by Elastic/Inelastic protons

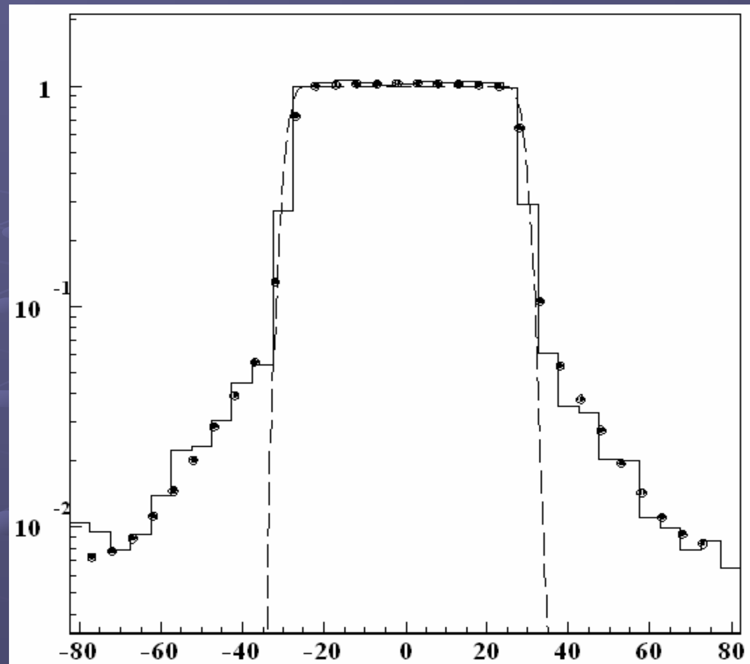
Effect of the Nuclear Interaction to Dose(2)

By Takashi Akagi@HIBMC

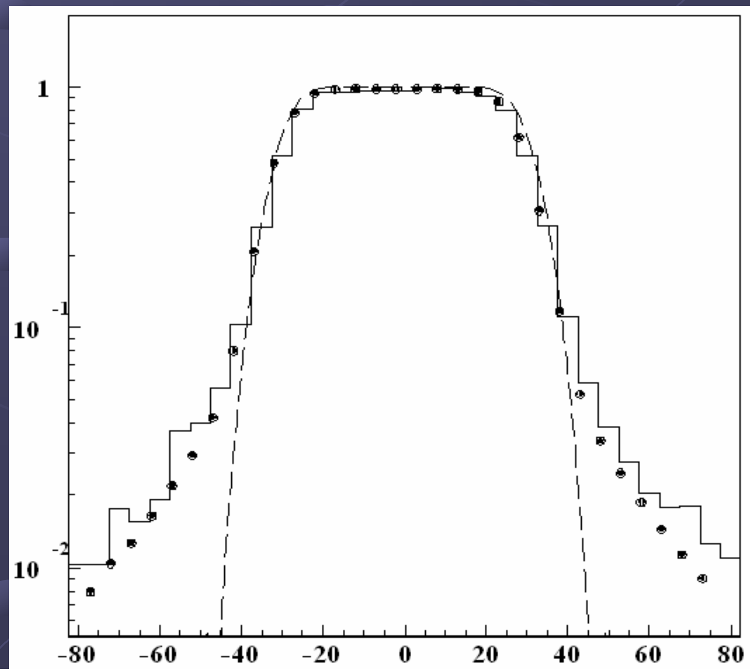




50mm depth



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.