Functions and Interfaces in Particle Therapy System Simulation Framework

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[3] High Energy Accelerator Research Organization (KEK)

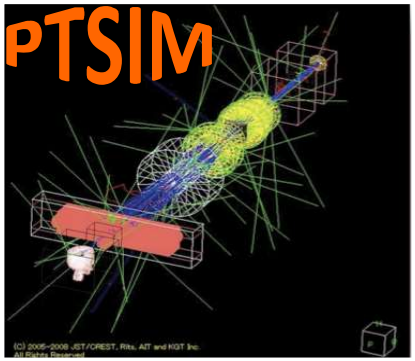
Outline

I. PTSIM Overview

II. PTSIM functions and interfaces

III. Future extensions for MPEXS-h

IV. Summary



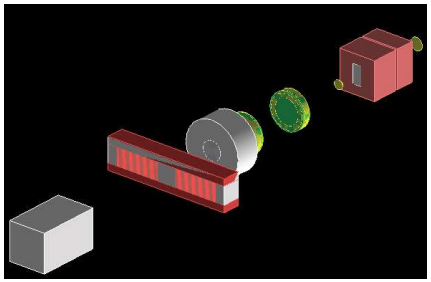
PTSIM Overview

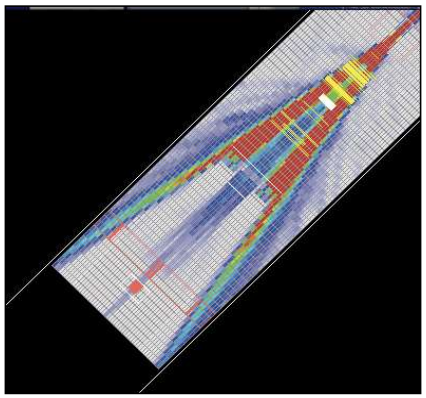
PTSIM (Particle Therapy system SIMulation framework)

- "Development of simulation framework for advanced radiotherapy", funded from 2003 to 2010.
- Japan Science Technology Agency, Core Research for Evolutional Science Technology, (Prof. T. Sasaki KEK)

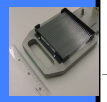
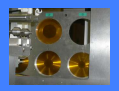
Features

- A specialized simulation software for particle therapies
- Monte Carlo simulation software framework
  - Geant4 based application program
  - Providing many modules and user Interface (UI) commands
  - Many irradiation systems have been implemented on the framework
- Users can easily perform simulations on PTSIM :
  - Modeling various irradiation systems
  - Importing patient CT images
  - Dose calculation based on particle tracks

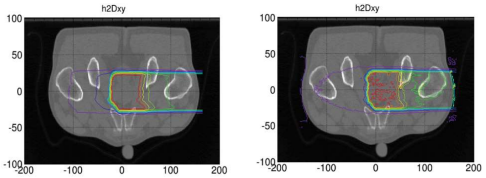




Example implementation of irradiation systems

Facility	Accelerator	Beam Energy	Lateral Spreading System	Range Modulator
HIBMC Gantry	Synchrotron	P 150,190,230	Wobbler magnets and scatter  	Ridge filter 
NCC Gantry	Cyclotron	P 150,190,235	Scatter and double scatter 	Ridge filter 
UCSF	Cyclotron	P 67.5	N/A 	Propeller blades 
HIMAC	Synchrotron	C 400 MeV/u	Wobbler magnets and scatter	Ridge filter
HIBMC	Synchrotron	C 320 MeV/u	Wobbler magnets and scatter	Ridge filter
GSI	Synchrotron	C 400 MeV/u	Beam scanning / Fine Ridge filter 	
NPT	Synchrotron	Protons	Beam scanning	
FPHPTC	Synchrotron	Protons	Wobbler magnets and scatter, Ridge Filter	
NCC-East	Cyclotron	Protons	Passive mode / Scanning mode	
NCC-Korea	Cyclotron	Protons	Passive mode / Scanning mode	
CGMH	Cyclotron	Protons	Passive mode /Scanning mode	

PTSIM Users and Collaborators

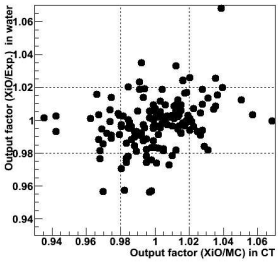


RBE in MKM

Hyogo Ion Beam Medical Center
Proton / Carbon-ion

Gunma Univ.
Heavy Ion Medical Center

Hokkaido Univ.
Proton Beam Therapy Center

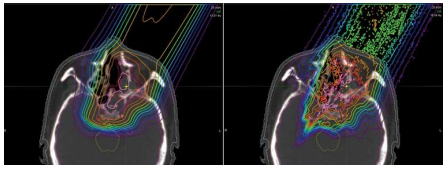


Validation of output factor

FUKUI Prefectural Hospital
Proton Therapy Center

PTSIM

Chang Gung Univ./ Chang Gung Memorial Hospital
Proton Therapy Center



Verification of TPS in Spot scanning

Nagoya City West Medical Center
Proton Therapy Center

KOBE Proton Therapy Center

KEK Inter-University Research Institute Corporation High Energy Accelerator Research Organization

Tokyo Women's Medical Univ.

PTSIM tutorial Activities

- **Geant4 Japanese Tutorial & Workshop for Medicine in Japan**
  - 2019 Geant4 Japanese Tutorial for Medicine in Tsukuba
  - 2018 Geant4 Japanese Tutorial & Workshop for Medicine in Hokkaido
  - 2017 Geant4 Japanese Tutorial for Medicine in Kobe
  - 2016 Geant4 Japanese Tutorial in Sendai
  - 2015 PTSIM Tutorial/Geant4 Medical Application in NIT-ToyamaC
  - 2015 Geant4 Japanese Tutorial for Medicine in National Cancer Center
  - 2014 PTSIM Tutorial in Nagoya (Nagoya-U and NPTC)
  - 2011 Geant4 Training Course (PTSIM-HandsOn) in Tsukuba
  - 2010 Geant4/PTSIM School in NIT-ToyamaC.
- **PTSIM tutorial in overseas**
  - 2018 PTSIM Tutorial in Taiwan (Chang Gung U., Tzu Chi C. of Technol.)
  - 2013 PTSIM Tutorial in Taiwan (Chang Gung U.)
  - (Several small meetings with NCC Korea, Asan medical center.)

PTSIM wiki page
- Source code distribution and documents -

KEK Wiki site

- **http://wiki.kek.jp/display/g4med/PTsim**

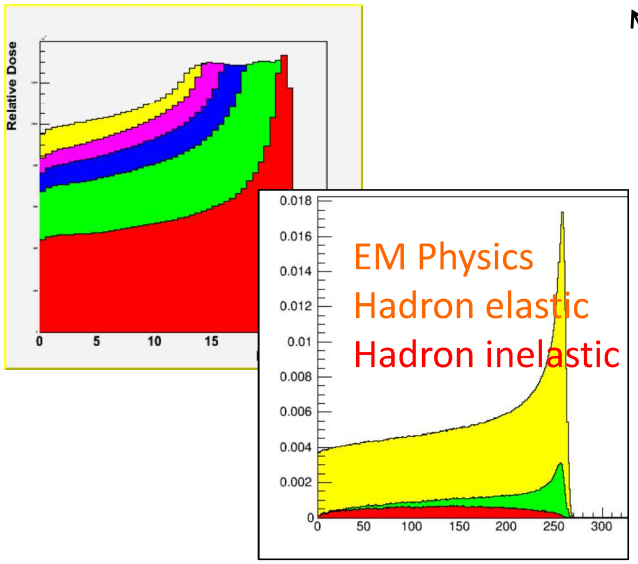
Rolls of PTSIM as a Monte Carlo simulation

Treatment port
Measurement

TPS
PBA

Verification
Validation

Patient (CT data)



QA

System optimization

Verification

Virtual measurement

Dose distribution

Dose components

Theory
Model

Assumption

Monte Carlo
Realistic simulation

Biology

New system
developments

PTSIM interfaces and functions

1. Beam Delivery System
   - Beam Devices
   - CT geometry
   - Primary Beam Generator
2. Scoring
3. Example applications

Beam delivery system

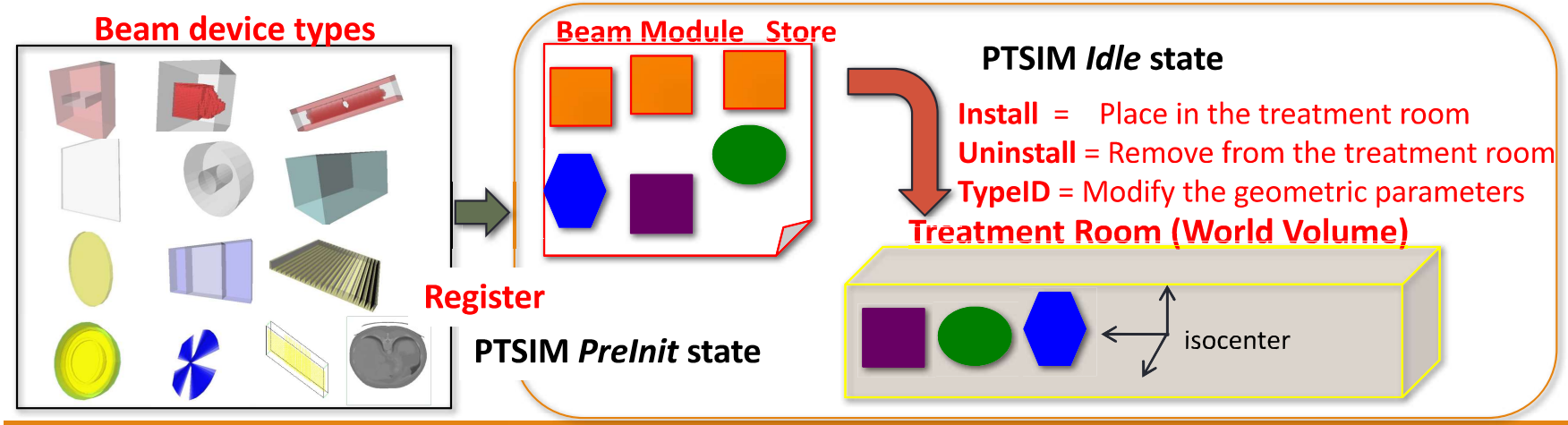
Beam port consists from beam devices

- Beam Module （Beam device）
  - Specialized by: **Device type** and Geometrical parameters
  - Beam modules are registered into PTSIM (*PreInit* state).
  - The beam modules are installed or uninstall in the treatment room (*Idle* state).

Beam Module Registration

install / uninstall Beam Module

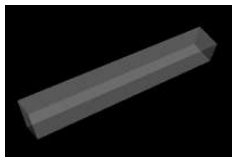
Change parameters of Beam Module



These placements of beam modules support parallel world geometry for:
(1) Scoring
(2) Layered geometry

Beam device types

G4MRoom



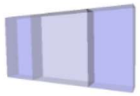
G4MDisk

G4MBox

G4MDiskStructure

G4MCollimator

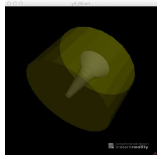
G4MBlockCollimator



G4MTubsMonitor

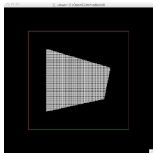
G4MWireMonitor

G4MPolyCones

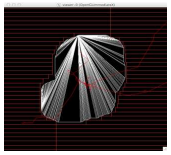


G4MSPolyCone

G4MPTCollimator

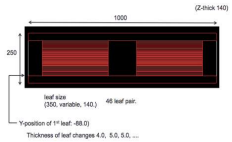


G4MPTCollimatorEx

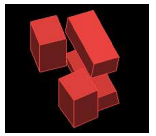


G4MMLCX

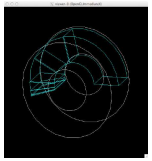
G4MMLCXV



G4MJaw

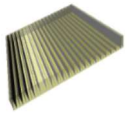


G4MRotatingRangeModulator

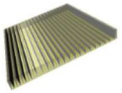


G4MPropellerBrades

G4MRidgeFilter

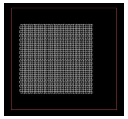


G4MRidgeWSctFilter



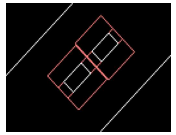
G4MBolus

G4MHoneyCombBolus

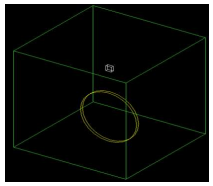


G4MWobblerMagnet

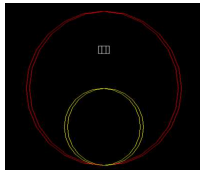
G4MScanningMagnet



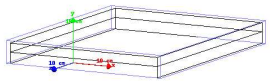
G4MBoxComposer



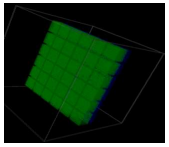
G4MDiskComposer



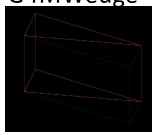
G4MCouch

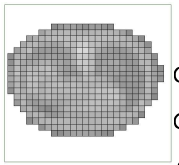


G4MBoxDetector



G4MWedge





G4MNestedDICOM

G4MNestedROIDICOM

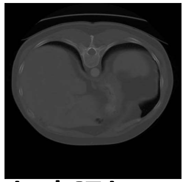
G4MWaterPhantom

G4MCylindricalPhantom

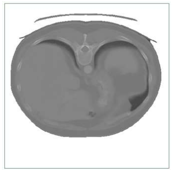
Patient geometry from CT images

DICOM CT images consist of pixel data

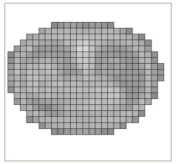
- **Filtering images and build the geometry with voxelization**



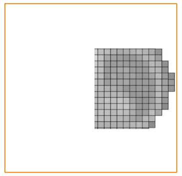
Original CT image



Outline extraction

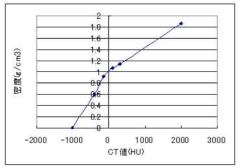


Reformation



Trimming

- **Material mapping**
  - Conversion table from HU to mass density
  - Mapping table for HU zone and the material
    - ✓U.Schneider et al.,Phys.Med.Biol.41(1996)
    - ✓U.Schneider et al., Phys.Med.Biol.45(2000)
    - ✓H.Paganetti et al., Phys.Med.Biol.53(2008)



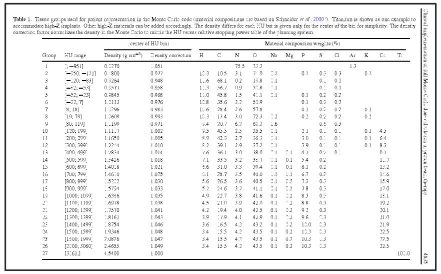


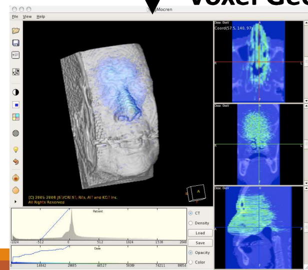
Table 1. Tissue groups used for patient representation in the Monte Carlo code (material compositions are based on Schneider *et al* (2000)). Titanium is shown as one example to accommodate high-Z implants. Other high-Z materials can be added accordingly. The density differs for each HU but is given only for the center of the bin for simplicity. The density correction factor normalizes the density in the Monte Carlo to mimic the HU versus relative stopping power table of the planning system.

Group	HU range	Density (g cm^{-3}) (center of HU bin)	Density correction	H	C	N	O	Na	Mg	P	S	Cl	Ar	K	Ca	Ti
1	[; −951]	0.0270	1.051			75.5	23.2						1.3			
2	[−950; −121]	0.4800	0.977	10.3	10.5	3.1	74.9	0.2		0.2	0.3	0.3		0.2		
3	[−120; −83]	0.9264	0.948	11.6	68.1	0.2	19.8	0.1			0.1	0.1				
4	[−82; −53]	0.9577	0.958	11.3	56.7	0.9	30.8	0.1			0.1	0.1				
5	[−52; −23]	0.9845	0.968	11.0	45.8	1.5	41.1	0.1		0.1	0.2	0.2				
6	[−22; 7]	1.0113	0.976	10.8	35.6	2.2	50.9			0.1	0.2	0.2				
7	[8; 18]	1.0296	0.983	10.6	28.4	2.6	57.8			0.1	0.2	0.2		0.1		
8	[19; 79]	1.0609	0.993	10.3	13.4	3.0	72.3	0.2		0.2	0.2	0.2		0.2		
9	[80; 119]	1.1199	0.971	9.4	20.7	6.2	62.2	0.6			0.6	0.3				
10	[120; 199]	1.1117	1.002	9.5	45.5	2.5	35.5	0.1		2.1	0.1	0.1		0.1	4.5	
11	[200; 299]	1.1650	1.005	8.9	42.3	2.7	36.3	0.1		3.0	0.1	0.1		0.1	6.4	
12	[300; 399]	1.2244	1.010	8.2	39.1	2.9	37.2	0.1		3.9	0.1	0.1		0.1	8.3	
13	[400; 499]	1.2834	1.014	7.6	36.1	3.0	38.0	0.1	0.1	4.7	0.2	0.1			10.1	
14	[500; 599]	1.3426	1.018	7.1	33.5	3.2	38.7	0.1	0.1	5.4	0.2				11.7	
15	[600; 699]	1.4018	1.021	6.6	31.0	3.3	39.4	0.1	0.1	6.1	0.2				13.2	
16	[700; 799]	1.4610	1.025	6.1	28.7	3.5	40.0	0.1	0.1	6.7	0.2				14.6	
17	[800; 899]	1.5202	1.030	5.6	26.5	3.6	40.5	0.1	0.2	7.3	0.3				15.9	
18	[900; 999]	1.5794	1.033	5.2	24.6	3.7	41.1	0.1	0.2	7.8	0.3				17.0	
19	[1000; 1099]	1.6386	1.035	4.9	22.7	3.8	41.6	0.1	0.2	8.3	0.3				18.1	
20	[1100; 1199]	1.6978	1.038	4.5	21.0	3.9	42.0	0.1	0.2	8.8	0.3				19.2	
21	[1200; 1299]	1.7570	1.041	4.2	19.4	4.0	42.5	0.1	0.2	9.2	0.3				20.1	
22	[1300; 1399]	1.8162	1.043	3.9	17.9	4.1	42.9	0.1	0.2	9.6	0.3				21.0	
23	[1400; 1499]	1.8754	1.046	3.6	16.5	4.2	43.2	0.1	0.2	10.0	0.3				21.9	
24	[1500; 1599]	1.9346	1.048	3.4	15.5	4.2	43.5	0.1	0.2	10.3	0.3				22.5	
25	[1600; 1999]	2.0826	1.042	3.4	15.5	4.2	43.5	0.1	0.2	10.3	0.3				22.5	
26	[2000; 3060]	2.4655	1.049	3.4	15.5	4.2	43.5	0.1	0.2	10.3	0.3				22.5	
27	[3061;]	4.5400	1.000													100.0

Clinical implementation of full Monte Carlo dose calculation in proton beam therapy 4835

Load DICOM data
↓
Compensation of lack slices
↓
Select window of interest
↓
Outline extraction
↓
Reformation of voxel size
↓
Trimming window of interest
↓

Voxel Geometry

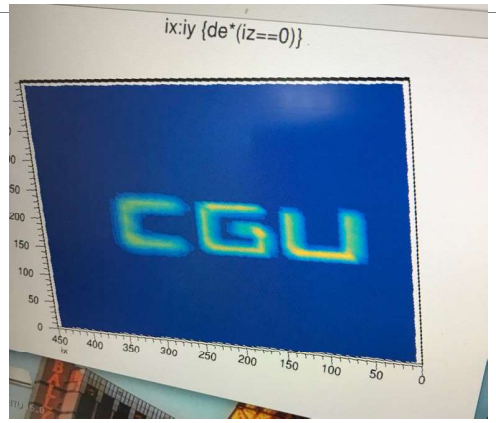


(FYI) Skelton code for DICOM-RT interface is also available.

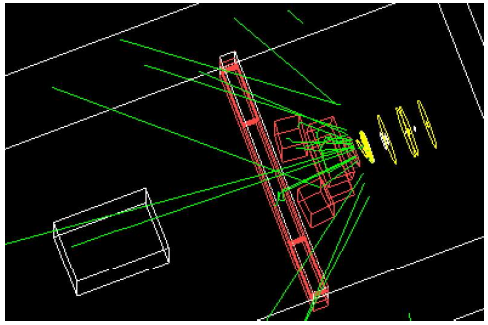
Check detail in today's Hands-on.

Primary Beam Generator

- Support:
  - G4ParticleGun
  - G4GeneralParticleSource
  - Focusing beam
  - Fan beam
  - Spot Scan Beam
  - Line Scan Beam
  - Phase-space data (IAEA, ASCII)



Line scan beam



Phase-space data

Scoring

Detector beam modules are automatically enabled as scoring volume.

- **WaterPhantom, DICOM, XXXDetector**
- The other modules can be also become scoring volumes by using UI commands.
- These scoring volumes score track information.

CERN ROOT Analysis tool is a default output format. (XML, CSV are available.)

- The quantities are recorded in TH3 and TTree (Ntuple) database.
- TH3 is currently used for deposited energy or dose distributions.

Name	Quantity
evno	Event ID
trkid	Track ID
pid	Particle ID (PDG)
de	Energy deposit
dose	Dose
stepL	Step length
ix, iy, iz	Voxel index number
imod,isec	Geometric index
w	Weight of track
proc	Physics process ID(*)
ke	Kinetic energy
x,y,z	x,y,z position

Name	Quantity
px, py, pz	Momentum
t	Time
xvtx, yvtx, zvtx	Initial track position (Production position)
parenttrkid	Parent track ID
parentpid	Parent particle ID(PDG)
triggerid	Trigger Bit
triggerx, triggery, triggerz	Position of trigger signal

Example commands for scoring (Ntuple)

```
/G4M/Module/install   WaterPhantom
...
/My/runaction/ntuple/create    WPA   WaterPhantom/HitsCollection
/My/runaction/ntuple/addColumn WPA evno I
/My/runaction/ntuple/addColumn WPA trkid I
/My/runaction/ntuple/addColumn WPA pid I
/My/runaction/ntuple/addColumn WPA de  F  keV
/My/runaction/ntuple/addColumn WPA dose  F  gray
/My/runaction/ntuple/addColumn WPA x  F mm
/My/runaction/ntuple/addColumn WPA y  F mm
/My/runaction/ntuple/addColumn WPA z  F mm
/My/runaction/ntuple/addColumn WPA xvtx  F mm
/My/runaction/ntuple/addColumn WPA yvtx  F mm
/My/runaction/ntuple/addColumn WPA zvtx  F mm
```

The Ntuple named **WPA** is assigned to the beam module, **WaterPhantom**.

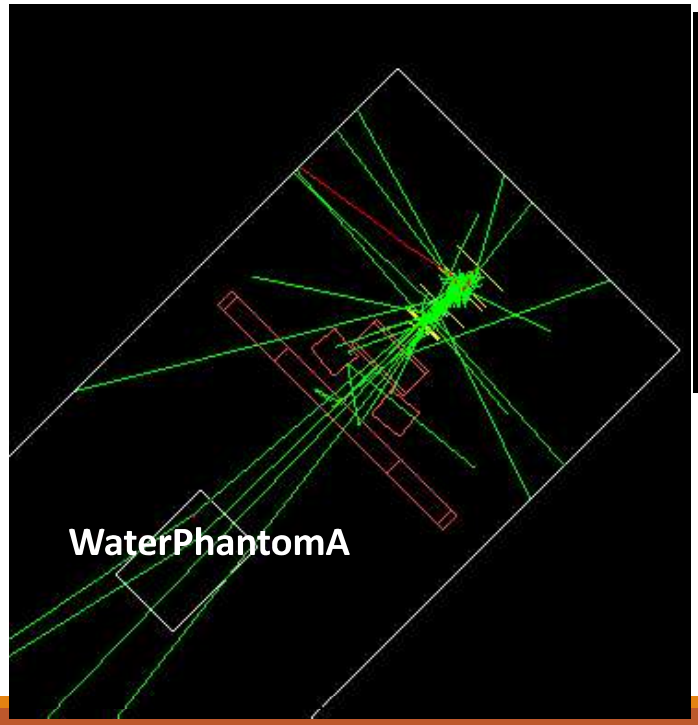
The quantities specified by its quantity-name are stored into the Ntuple, **WPA**.

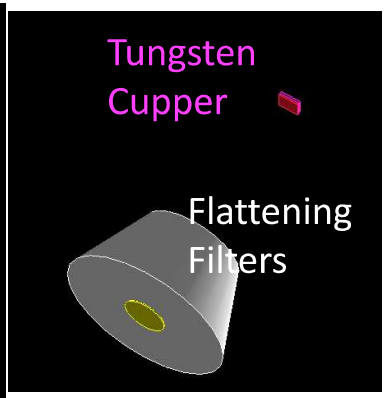
Here the third and fourth arguments are the variable type and units, respectively.

Example Applications

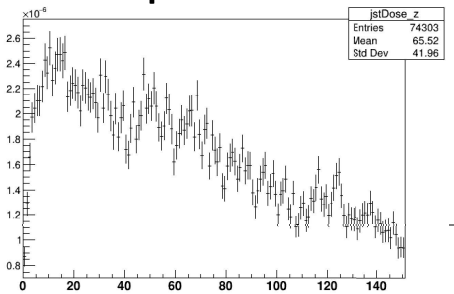
Medical linac

Photon conversion from electron beam by Tungsten



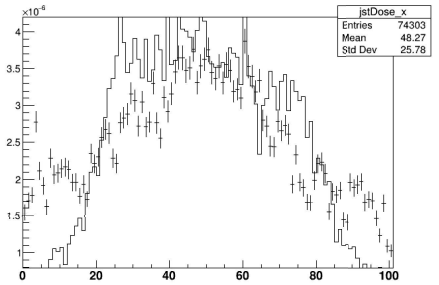


Depth Dose



WPA->Draw("z","dose")

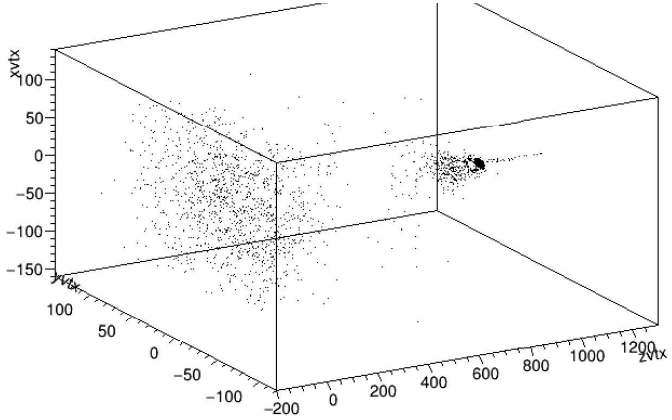
Lateral Dose



WPA->Draw("x","dose")

WPA->Draw("y","dose")

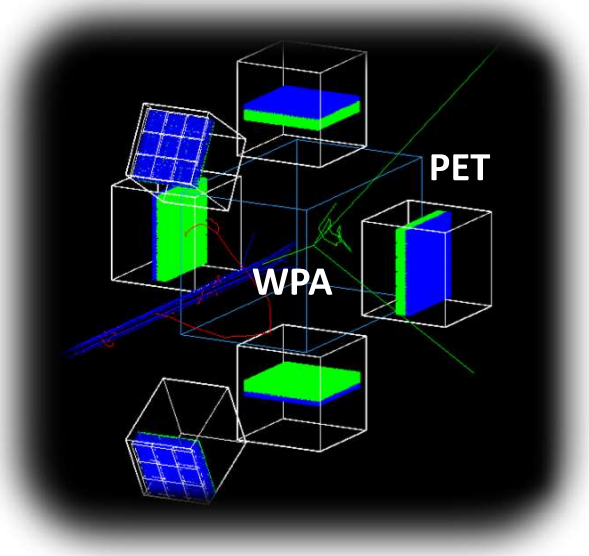
Photon production points



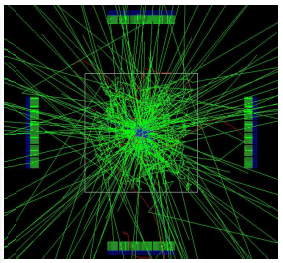
WPA->Draw("zvtx:yvtx:zvtx","pid==22")

Example Application

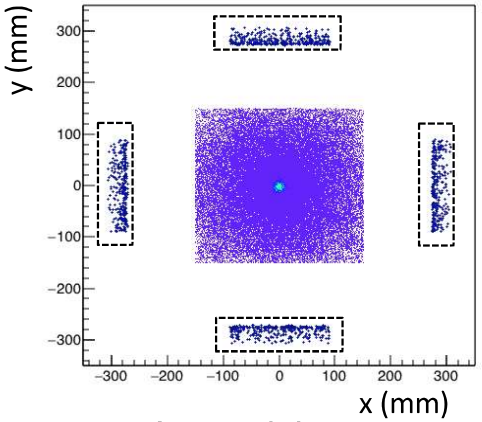
Prompt Gamma Imaging Devices



Copies of a PET beam module were placed with different copy numbers.



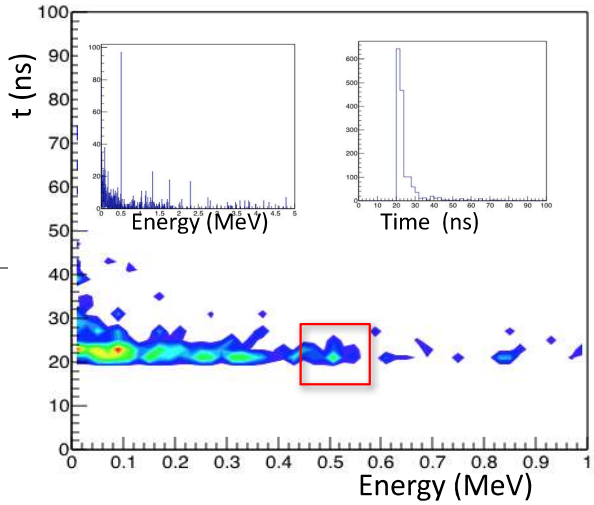
Particle trajectory



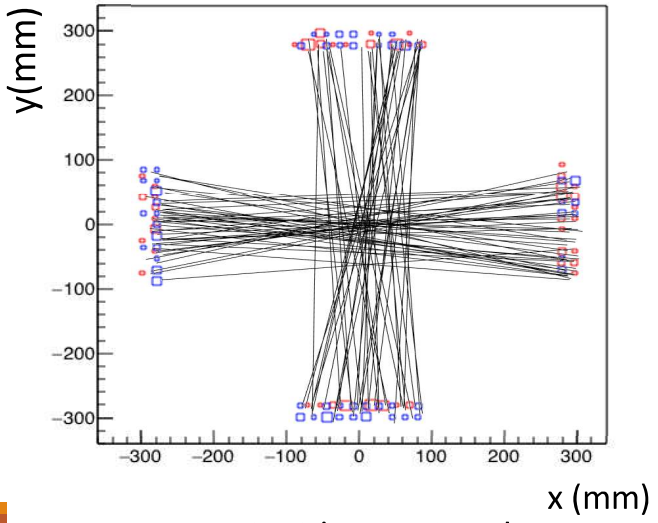
PET hits and dose in water

WPA->Draw("x:y","dose")

PET->Draw("x:y","edep")



PET->Draw("edep:t","","col")



Coincidence signal

PTSIM parallelization

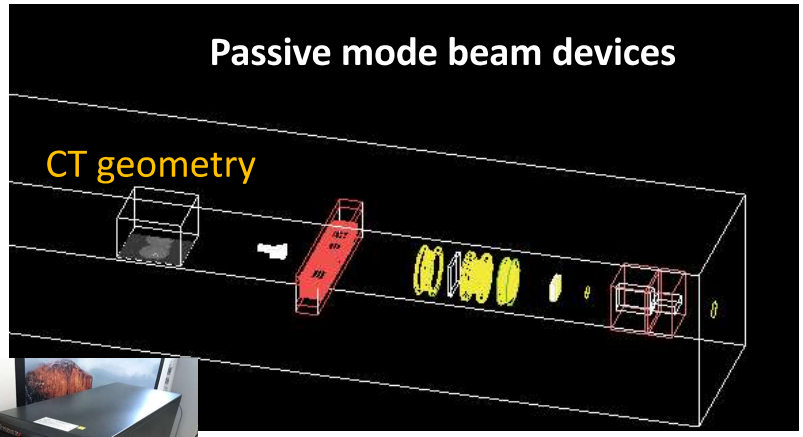
PTSIM supports:

- **Batch JOB system (GRID, LSF, PBS)**
- **MPI interface (G4MPI)**
- **Multi-thread mode (Geant4 ver. 10)**

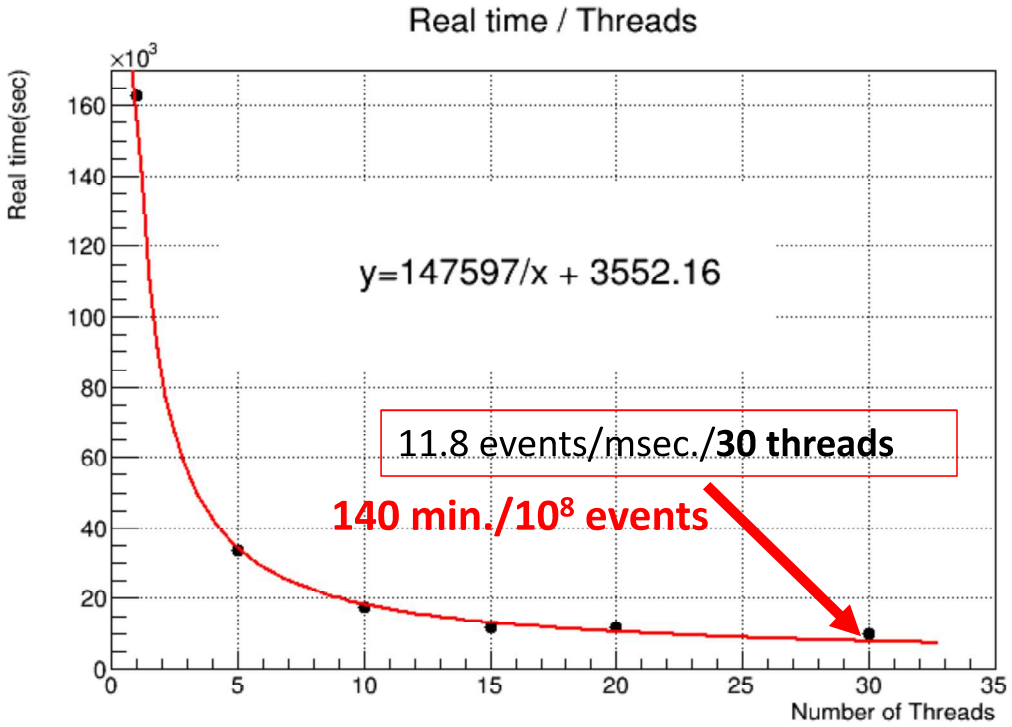
Example shell scripts and macro files for these environments are provided with PTSIM source code.

Scalability in multi-threaded mode

Examined with mimic parameters in proton therapy treatment condition.



OS CentOS 6.7
CPU intel(R) Xeon(R) E5-2667 v4
3.2GHz x 2CPU (8 cores/CPU)
Memory 64GB (8GB × 8)



Future extensions for MPEXS-h

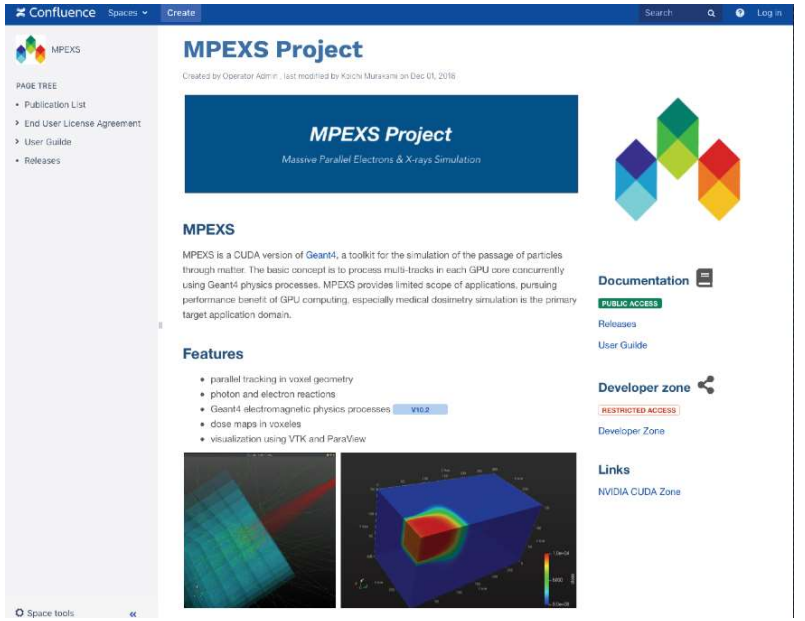
Although a multi-threaded PTSIM improves its computational efficiency, the dose calculation takes a few hours. It is an issue for clinical applications.

MPEXS project

Massive Parallel Electrons and X-rays Simulator, (It has been recently extended to include hadronic processes, **MPEXS-h**.)

- ✓ Developed on NVIDIA CUDA platform.
- ✓ Redesigned to be suitable for GPU with the experiences of Geant4.

https://wiki.kek.jp/display/mpexs/MPEXS+Project

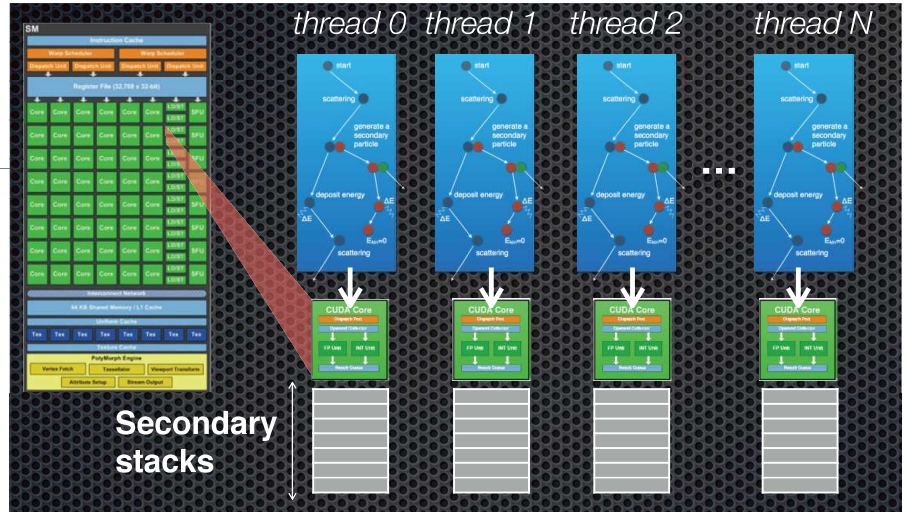


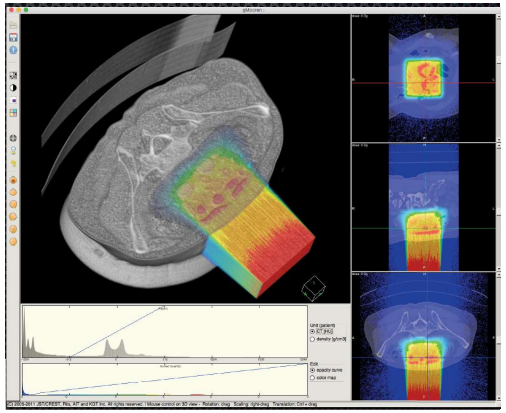
MPEXS and MPEXS-h

- **Features**
  - ✓ Simulating with **parallel tracking on GPU.**
  - ✓ Standard EM physics processes for gamma/e^+/e^-.
  - ✓ Proton/neutron/ion physics processes are additionally implemented in **MPEXS-h.**
    - Binary cascade, Precompound, Fermi Breakup, Evaporation, Photon Evaporation
  - ✓ Water equivalent material
  - ✓ Voxelized geometry

Practical application will be presented by Dr. T. Toshito on Wednesday.

Parallel Tracking on GPU





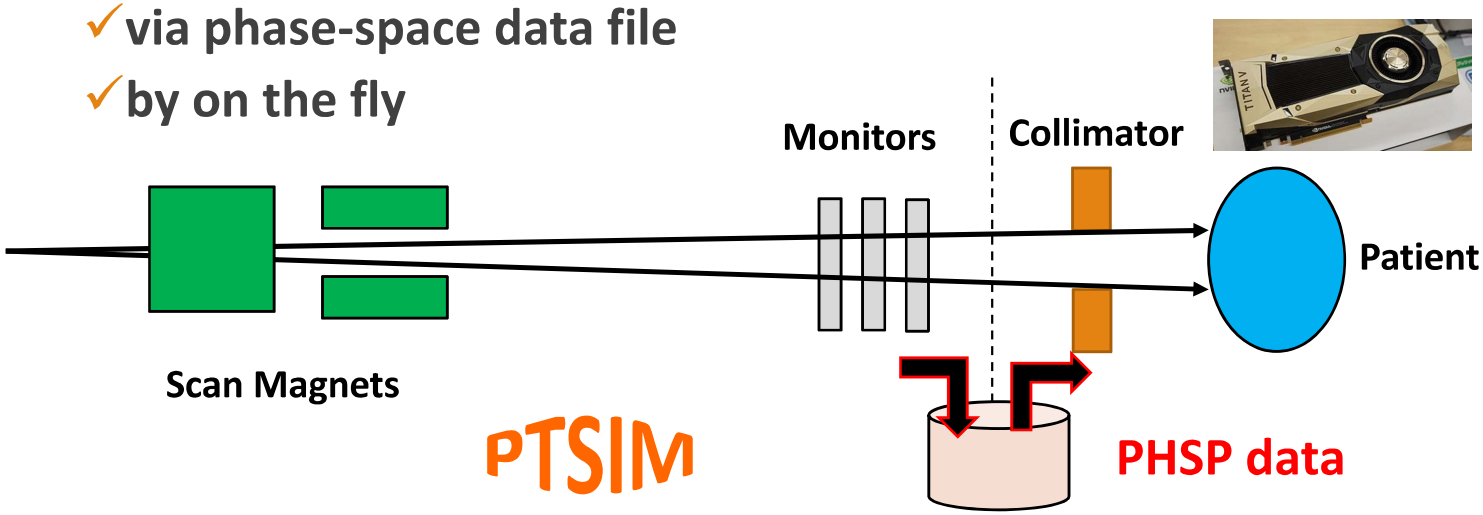
Demonstrating electron beam simulation with CT data

PTSIM interface for MPEXS-h

- Because particle therapy facilities which use PTSIM have validated PTSIM codes for their treatment ports, the PTSIM is still needed at least for simulating the beam delivery system. **Therefore, the data exchange interface is needed.**

➢The phase-space data is needed to exchange track information.

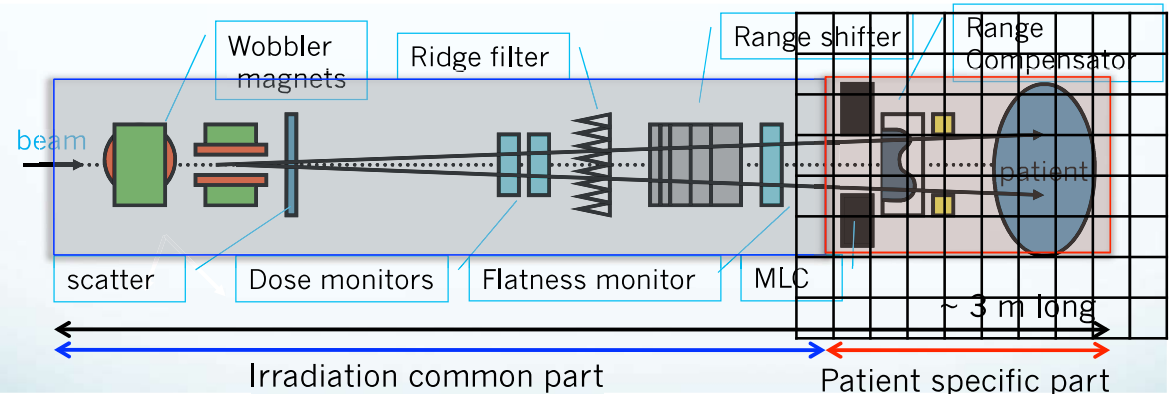
- ✓**via phase-space data file**
- ✓**by on the fly**



Prototype has been already available., but it will be better to follow IAEA phase-space format.

PTSIM interface for MPEXS-h

- We also need to develop functions for the migration from PTSIM to MPEXS-h.
  - ✓ Converting the beam delivery system to a voxelized geometry
  - ✓ Study may be needed to ensure the optimized voxel size in each devices
  - ✓ Providing PTSIM like user interface is desirable.



Summary

- **PTSIM has been adopted in several particle therapy facilities.**
- **It provides not only dose distribution but also track information for further analysis.**
- **Almost all the configuration can be handled with UI commands.**

- **MPEXS-h simulates with parallel tracking on GPU.**
- **We started to develop interfaces in PTSIM working with MPEXS-h.**
- **Also a migration of PTSIM to MPEXS-h requires PTSIM like user interfaces in MPEXS-h.**