Simulation Studies of a Therapeutic Proton Beam Delivery System

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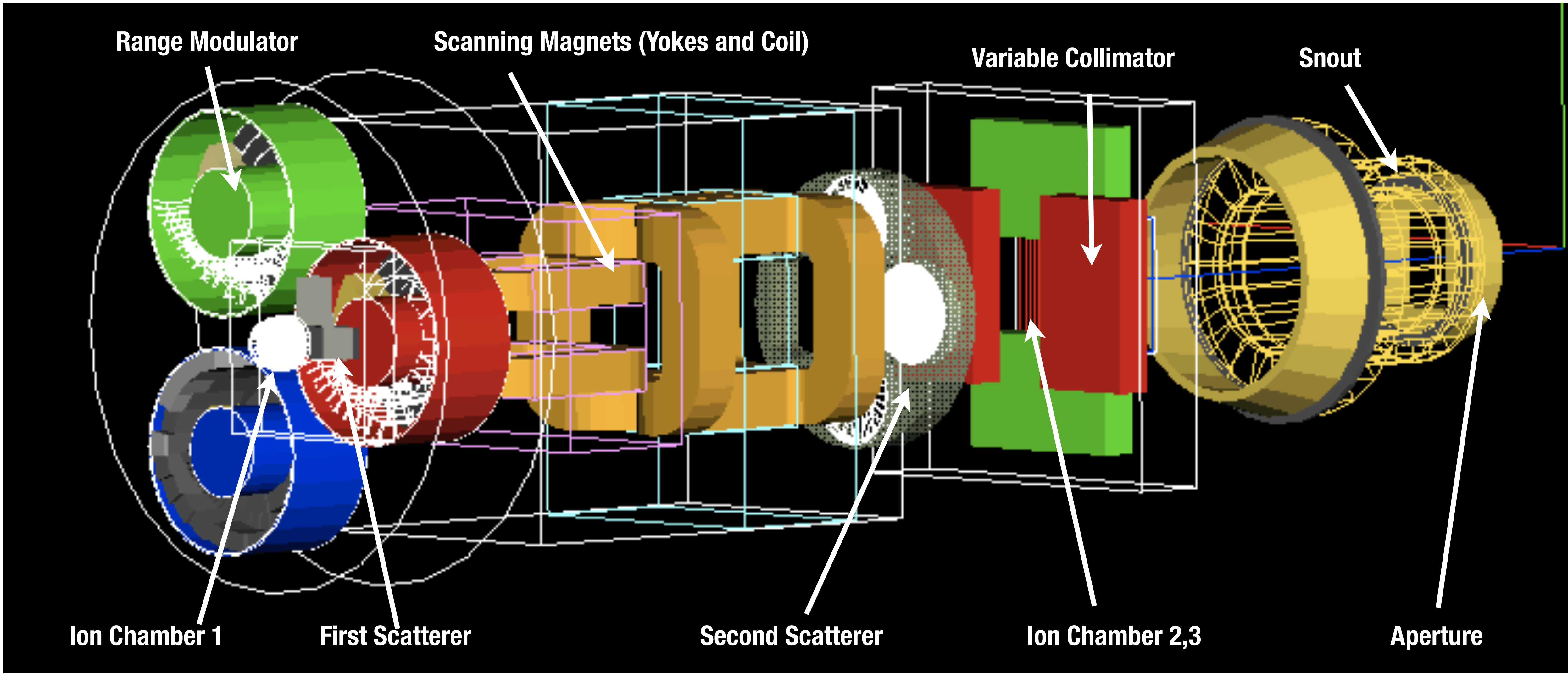
"Development of a Monte Carlo Simulation for the proton therapy in National Cancer Center, Korea"
- 13th Geant4 Workshop



IBA Proteus235 System

BeamTransportSystem
1. Energy distribution
2. Spot size
3. Momentum direction

Treatment Room
1. FBTR
2. GTR2
3. GTR2

Treatment Modes
1. Passive
2. Uniform Scanning (**US**)
3. Pencil Beam Scanning (**PBS**)

General purpose packages

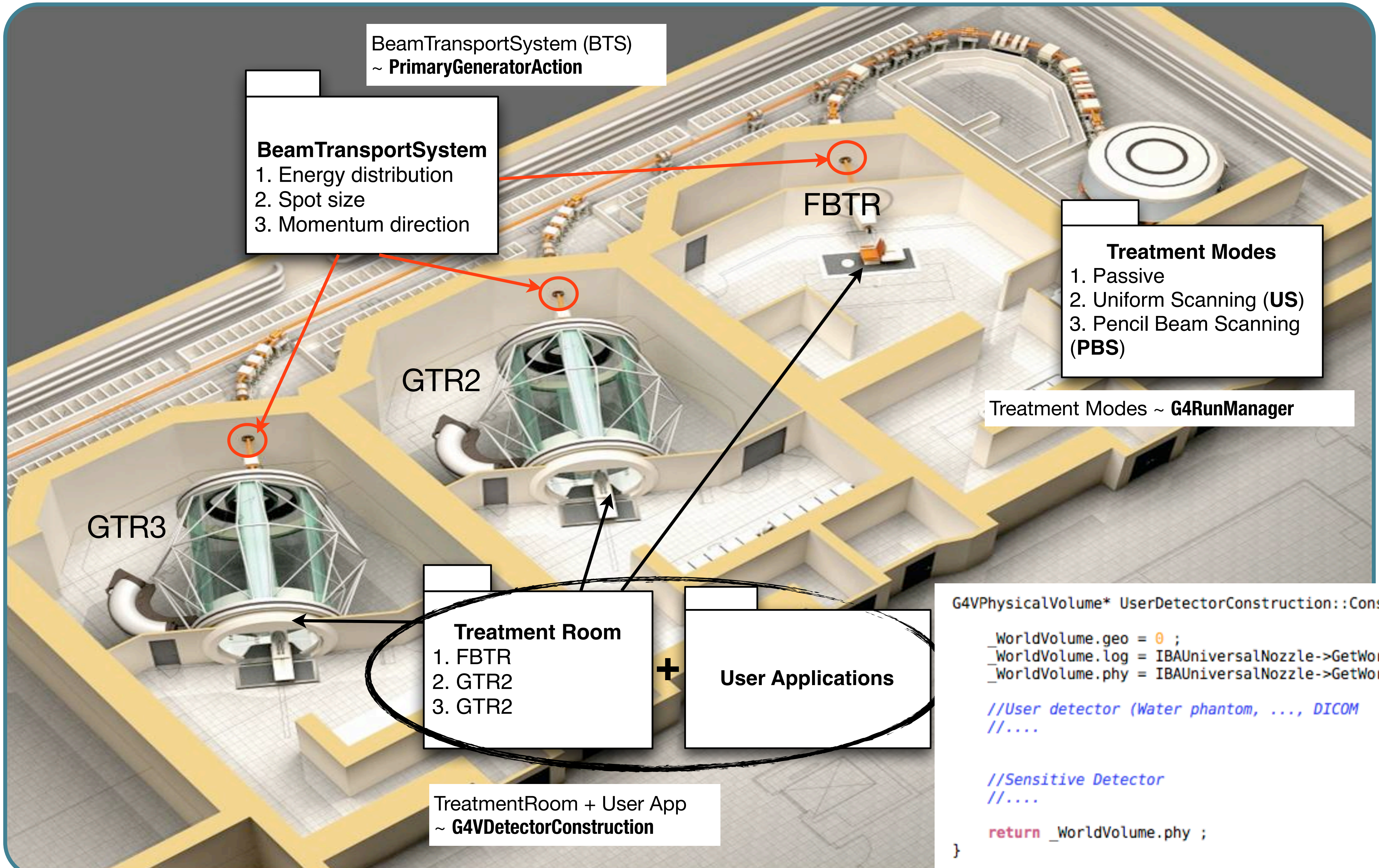
Physics List

LHEP_PRECO_HP
Low EM (ICRU49p)
...

I/O

root
gMocren

User Applications




```
G4VPhysicalVolume* UserDetectorConstruction::Construct(){

    _WorldVolume.geo = 0 ;
    _WorldVolume.log = IBAUniversalNozzle->GetWorldLogicalVolume();
    _WorldVolume.phy = IBAUniversalNozzle->GetWorldPhysicalVolume();

    //User detector (Water phantom, ..., DICOM
    //....


    //Sensitive Detector
    //....

    return _WorldVolume.phy ;
}
```

ex) $ ./proteusMC --tr={FBTR |GTR2 | GTR3} --mode={passive| us | pbs} --io={*.root | *.gdd} *.mac

Clinical parameters (input)	inputs	
Range in patient:	10	g/cm²
Range Modulation:	3	g/cm²
Field Radius:	11.0	cm
Dose:	100	MU
Dose rate:	2	Gy/min
ExpectedIrradTime (*):	300	sec
Range compensator length:	10.0	cm

Rp (Range in Patient), SOBP

RUN

CONVALGO (Conversion Algorithm)
provided by Manufacturer

Equipment	output	
a) Cyclo:		
Range @ nozzle entrance:	20.08	g/cm²
Beam current @ cyclo exit:	191	nA
b) ESS:		
Slits opening:	40	mm
B12:	1.343605	T
c) Nozzle:		
Option #:	12	-
FS thickness:	1.306	mm
FS thickness:	1.483	g/cm²
FS setting:	2	5
RM #:	5	-
RM track:	5	-
Stop position:	141	digit
BCM filename:	TR2_B4_1	-
SS #:	8	
SS position:	2	
VC x:	15.6	cm
VC y:	15.7	cm
presetCountIC2:	30000	cts
presetCountIC3:	29784	cts
Snout axial position:	10.0	cm
Phantom position:	41.5	cm

beam energy

```
/BTS/beam/particle proton
/BTS/beam/energy L cm 20.08
```

Range to M.C Energy conversion required!
i.e) E = R2Energy(20.08)
BTS ~ "Beam Transport System"

nozzle

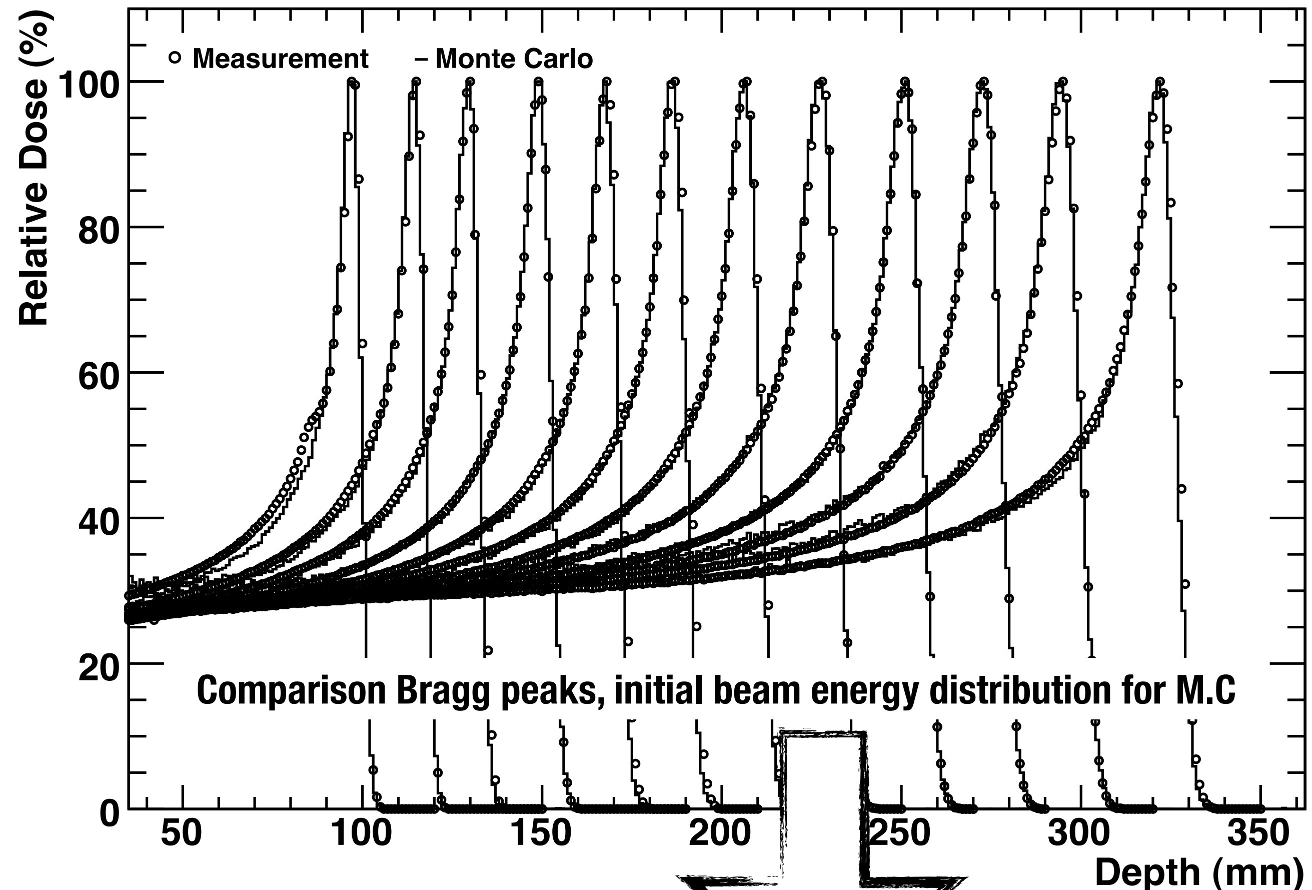
```
#the set-up to be set before initialization
/GTR2/SNT/type 250
/GTR2/SNT/aperture/rectangle open
/GTR2/SNT/aperture/rectangle Lx Ly Ox Oy
#Geant4 kernel initialize
/run/initialize
/GTR2/FS/lollipops 2 5
/GTR2/SS/select 2
/GTR2/RM/track 5
/GTR2/VC/setVxVy cm 15.6 15.7
```

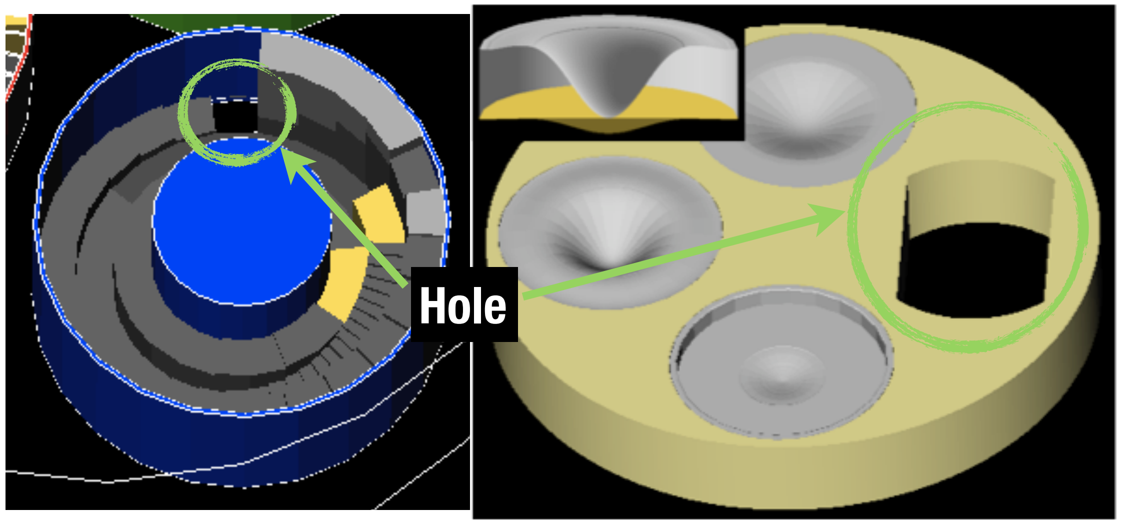
for case, --tr=**FBTR**,"/GTR2/ -> /FBTR/"

Control

```
/TCS/passive/bcm TR2_B4_1 141 1000
/TCS/StartIrradiation
```

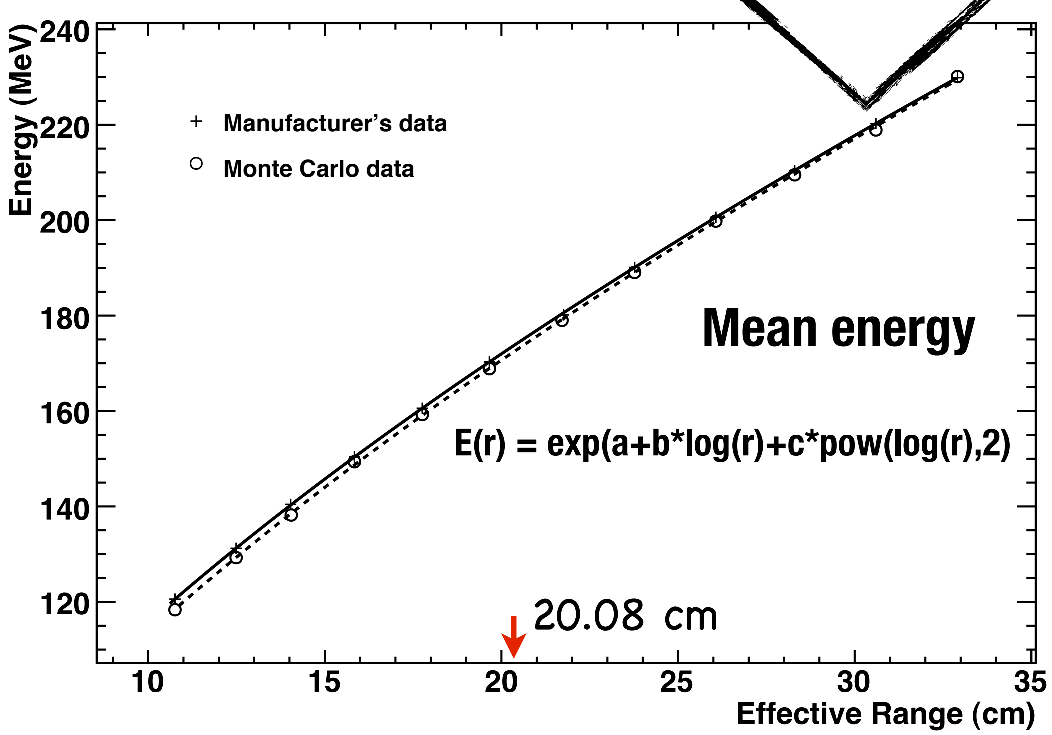
TCS ~ "Treatment Control System"
TR2_B4_1 ~ Beam current pattern
141 ~ Stop digit
1000 ~ baseline of incident particle

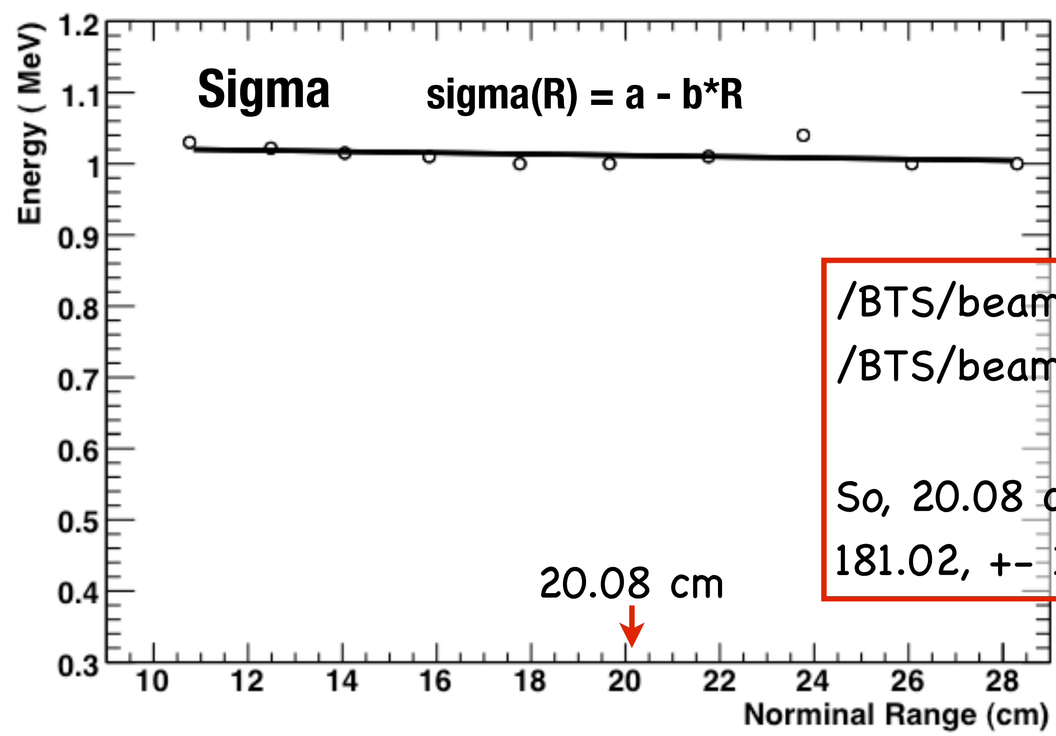




Exp and M.C simulation were performed in same condition which every scatter element were opened.

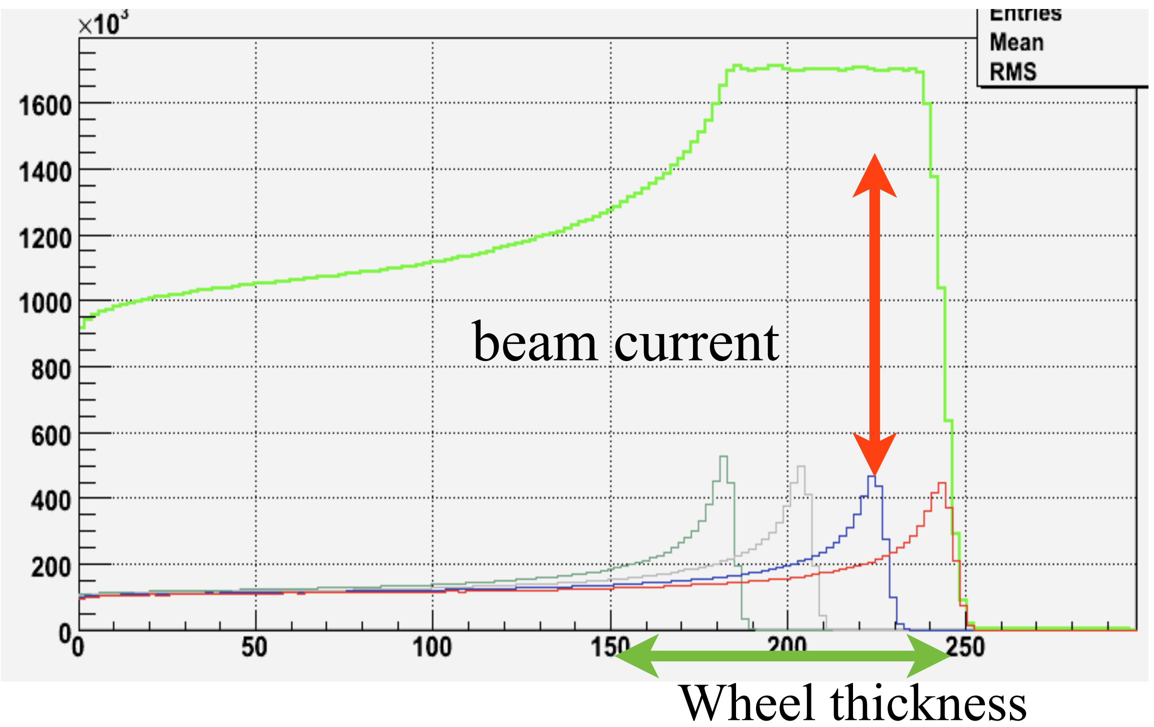
1, All first scatterers were positioned out of beam path
2. Beam passes through a hole of range modulator
3. Beam passes through a hole of second scatter

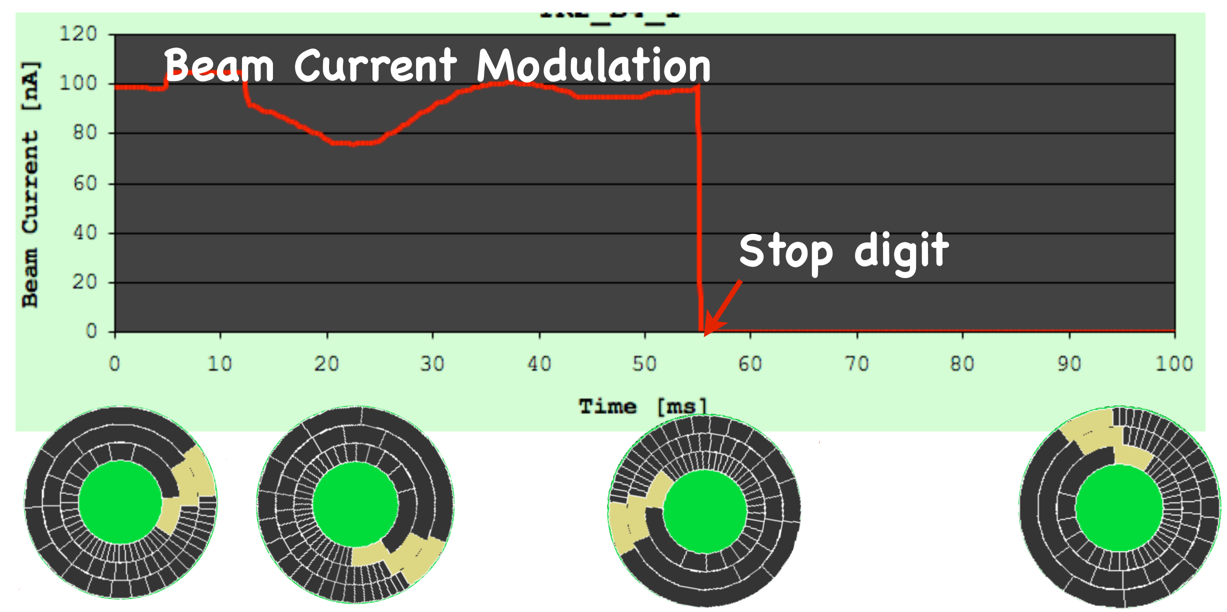





```
/BTS/beam/particle proton
/BTS/beam/energy L cm 20.08
```

So, 20.08 cm will be converted to 181.02, +- 1.014 MeV in M.C





Range modulator rotates and produce Bragg Peaks ..

```
/TCS/passive/bcm TR2_B4_1 141 1000
/TCS/StartIrradiation
```

equivalent

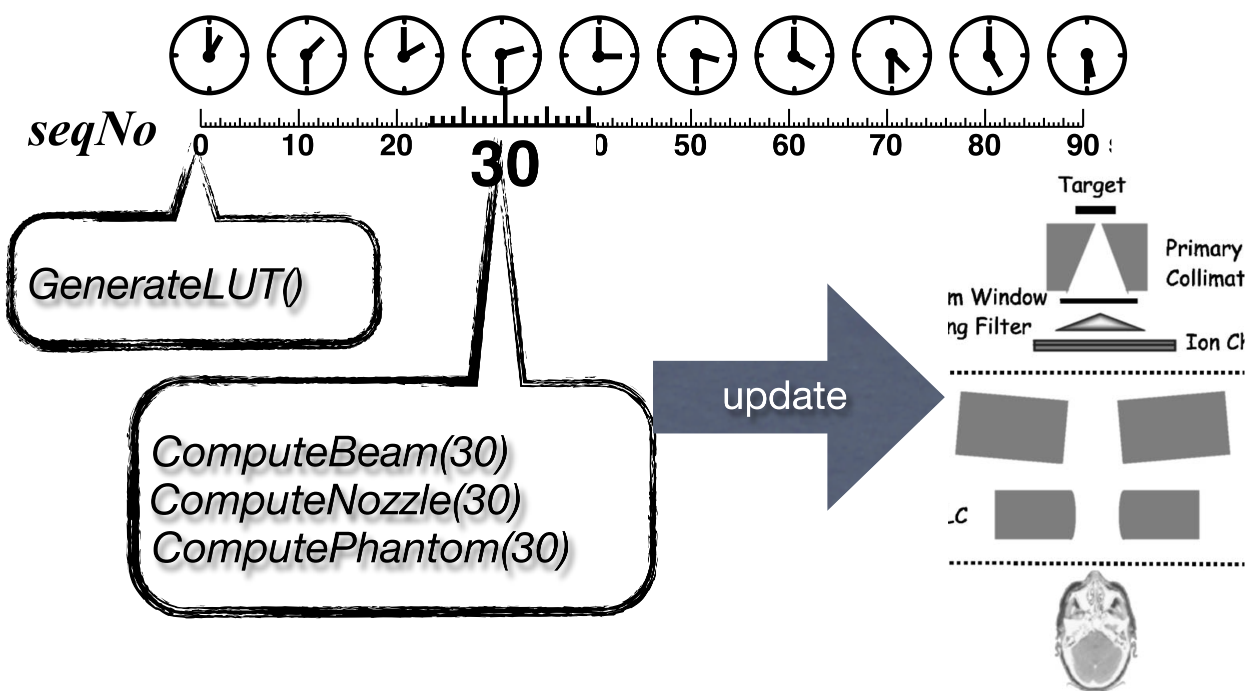
```
#start simulation
...
/GTR2/RM/angle deg 30.0
/run/beamOn 960
/GTR2/RM/angle deg 30.5
/run/beamOn 950
/GTR2/RM/angle deg 31.0
/run/beamOn 930
/GTR2/RM/angle deg 31.5
/run/beamOn 935
... ( more than 100 lines up to stop-digit)
# end of simulation
```

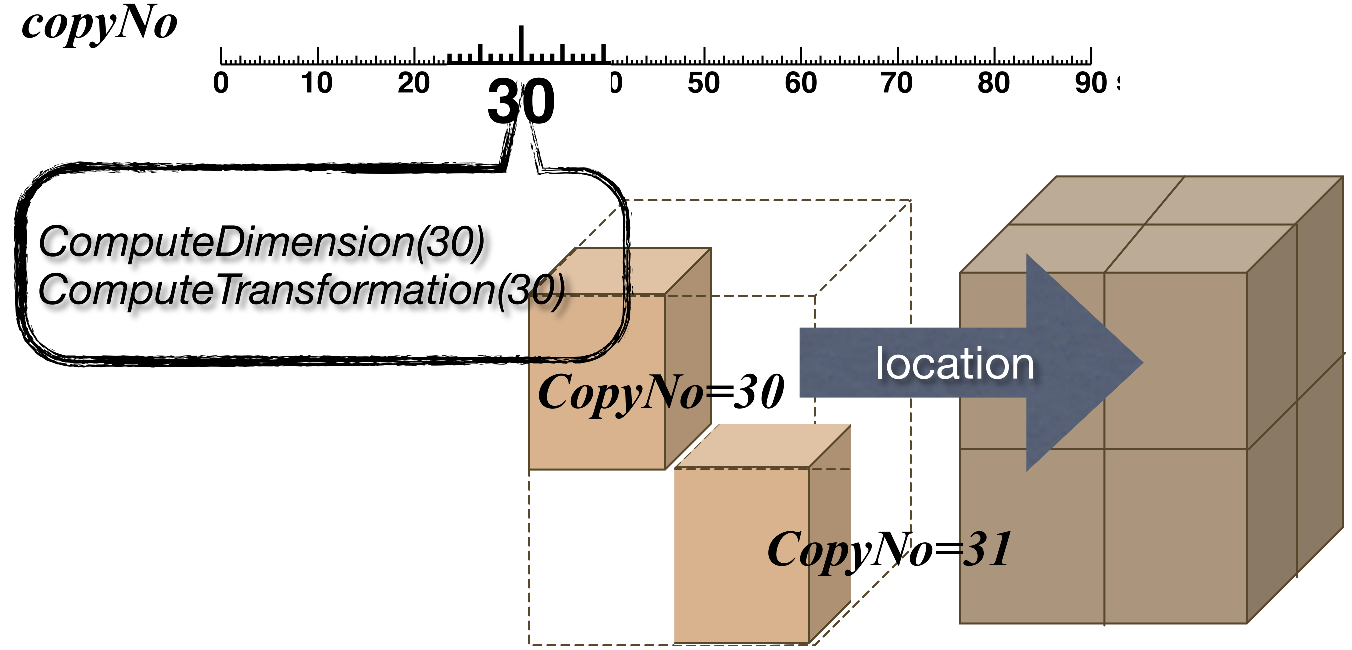
TR2_B4_1 : one of beam current modulation prepared by manufacturer

141: stop digit, determines the width of SOBP

1000: base number of particles

*% The **sequence number** (seqNo) : a moment on time-sequence <=> the **copy number** of G4PVParameterisation : an identifier as a part of geometrical structure.*



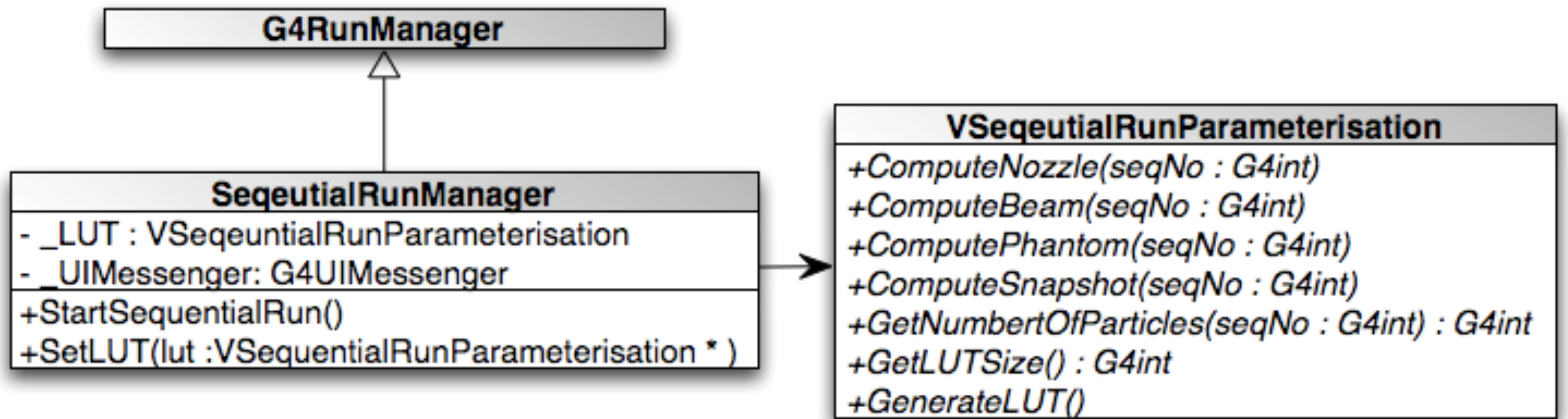


The ***VSeqentialRunParameterisation*** class was devised to

- generate a **<u>look-up table</u>** having dynamical information of constituent **as function of time-sequence**
- provide the Geant4 kernel with **<u>interfaces</u>** to change the conditions by referring the look-up table

The pure virtual methods of ***VSequentialRunParameterisation***

GenerateLUT()	generates Look-Up table
GetLUTSize()	returns the size of Look-Up table
GetNumberOfParticles(G4int seqNo)	returns number of particles per individual simulation
ComputeNozzle(G4int seqNo)	changes nozzle set-up
ComputeBeam(G4int seqNo)	changes beam condition
ComputePhantom(G4int seqNo)	change target phantom set-up



The ***StartSequentialRun()*** method was added to ***G4RunManager*** to automatically
1. invoke ComputeXXX methods defined in user class of VSequentialRunParameterisation
2. perform individual simulations by referring number of participant particles
until Look-up table being empty

```
G4int start_lut = 0 ;
G4int stop_lut = _LUT->GetLUTSize();
for(G4int i=start_lut; i < stop_lut ; ++i){
  _LUT->ComputeNozzle(i);
  _LUT->ComputeBeam(i);
  _LUT->ComputePhantom(i);
  …
  this->BeamOn( _LUT->GetNumberOfParticles(i));
}
```

Because SequentialRunManager is independent (no needs of re-writing) of user application,
Internally generating look-up table for specific application is our key approach.

```
#start simulation
...
/GTR2/RM/angle deg 30.0
/run/beamOn 960
/GTR2/RM/angle deg 30.5
/run/beamOn 950
/GTR2/RM/angle deg 31.0
/run/beamOn 930
/GTR2/RM/angle deg 31.5
/run/beamOn 935
... ( more than 100 lines)
# end of simulation
```

replaced by

```
/TCS/passive/BCM TR2_B6_1 144 1000
/TCS/StartIrradiation
```

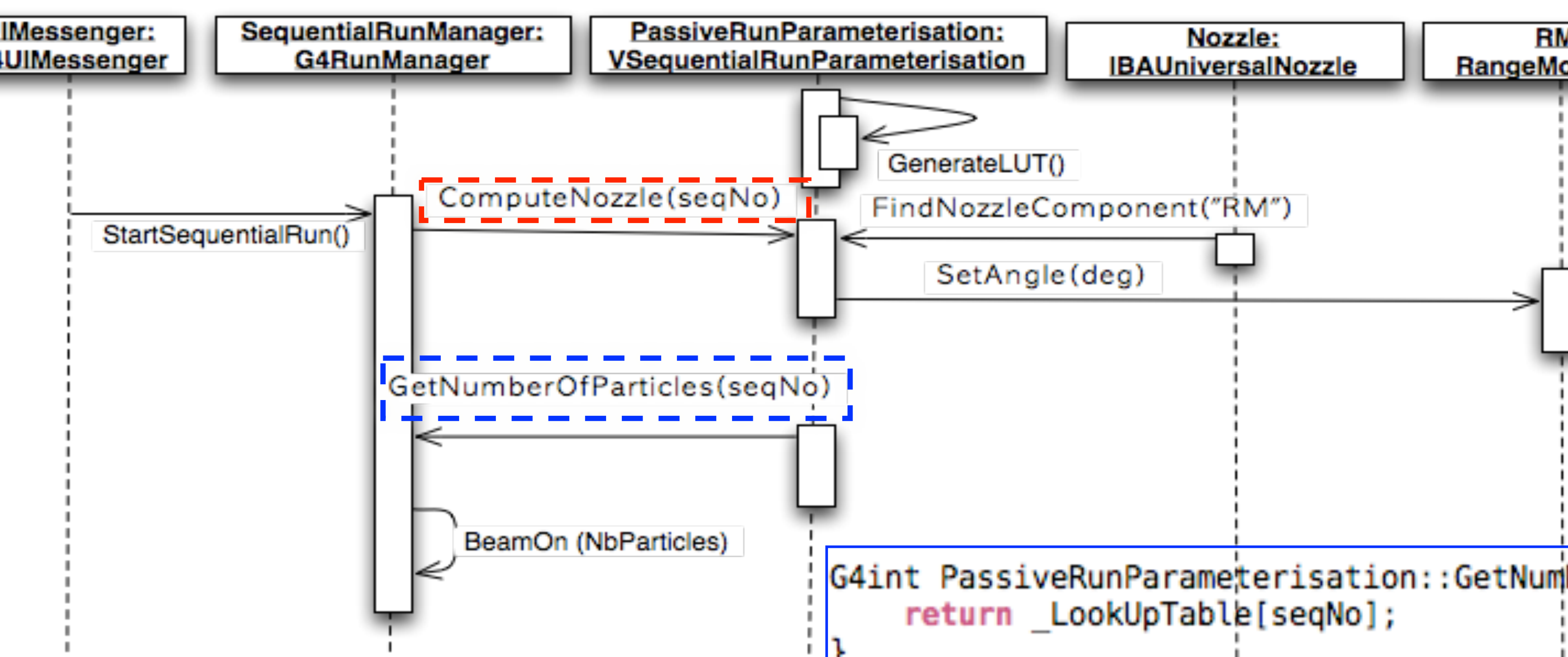
TR2_B6_1 : one of beam current modulation prepared by manufacturer

144: stop digit. it presents width of SOBP

1000: base number of particles

look-up table for passive scattering (number of particles per each individual run)

seqNo	# particles
0	960
1	950
2	930
3	935
...	
143	900

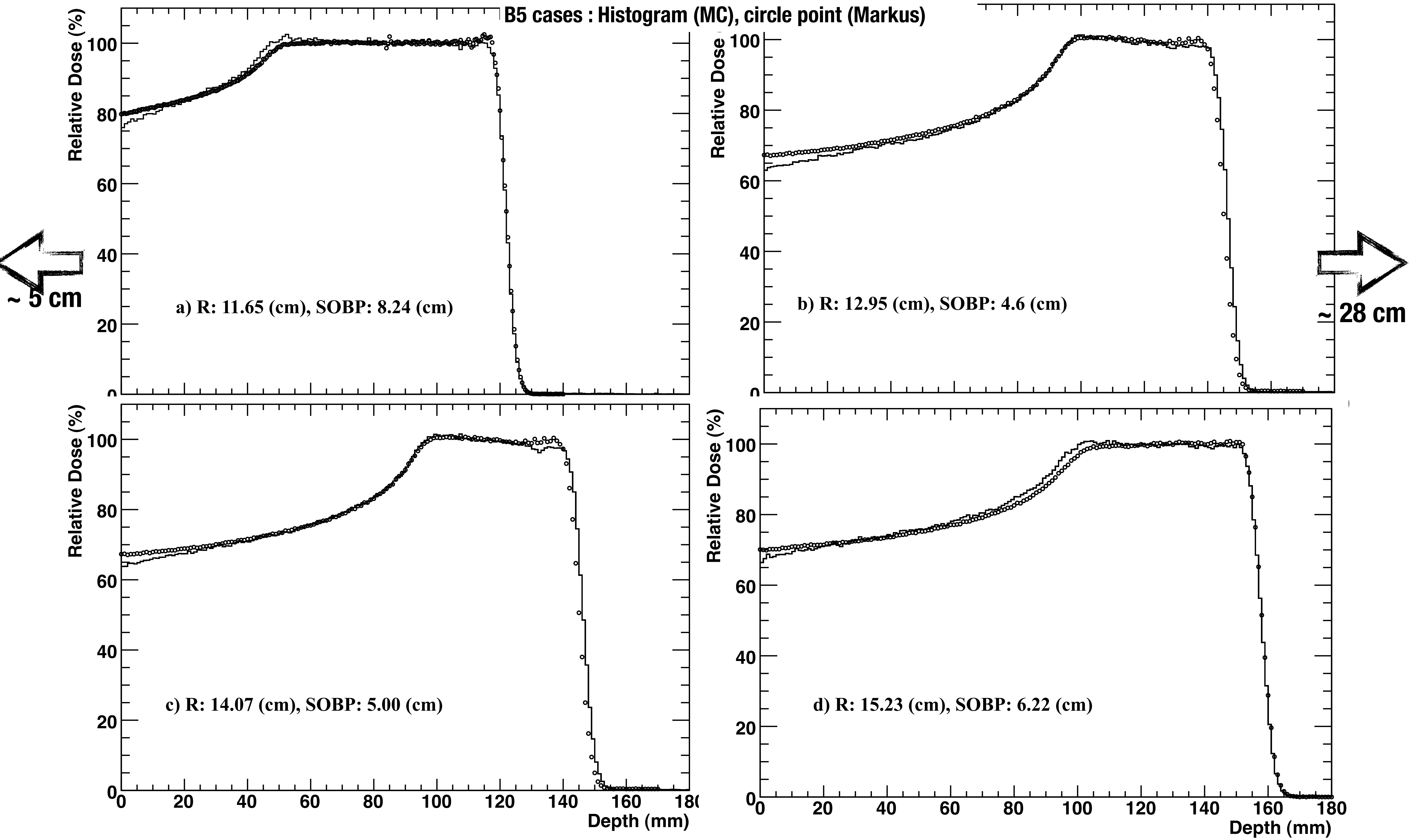



```
void PassiveRunParameterisation::ComputeNozzle(G4int seqNo){
    static G4String RMstring("RM");
    static N03_RM* pRM = static_cast<N03_RM*>
            ( _pNozzle->FindNozzleComponent(RMstring) );

    G4double ZeroAngle = pRM->GetZeroAngle();
    pRM->SetAngle( seqNo*(_THDIGIT_) + ZeroAngle );
}
```

```
G4int PassiveRunParameterisation::GetNumberOfParticles(G4int seqNo){
    return _LookUpTable[seqNo];
}
```

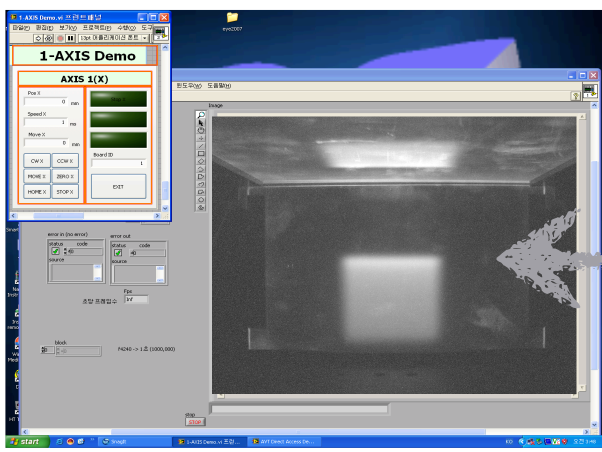
Because the initial beam information does not change during passive scattering simulation, so only nozzle set-up was changed as function of sequence number.


B5 cases : Histogram (MC), circle point (Markus)
~ 5 cm
~ 28 cm
a) R: 11.65 (cm), SOBP: 8.24 (cm)
b) R: 12.95 (cm), SOBP: 4.6 (cm)
c) R: 14.07 (cm), SOBP: 5.00 (cm)
d) R: 15.23 (cm), SOBP: 6.22 (cm)
Relative Dose (%)
Depth (mm)

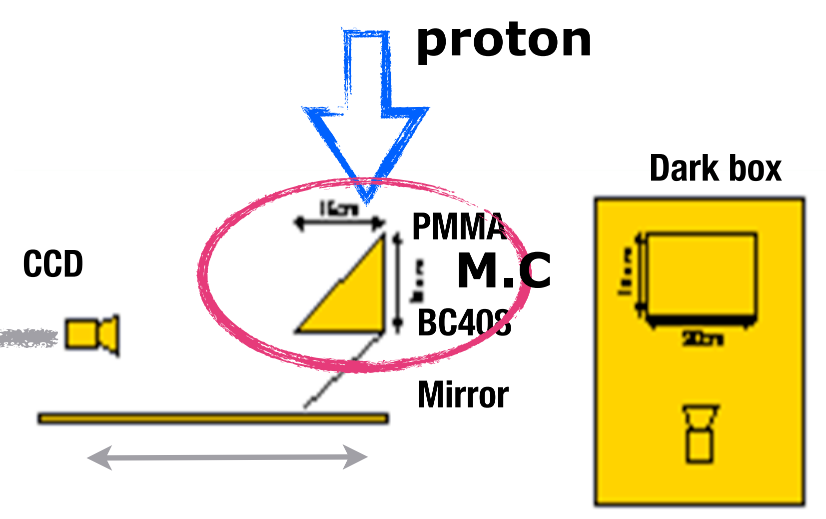
The accurate simulation study can help to design and construct a dosimetry device utilizing the BC408 scintillator.

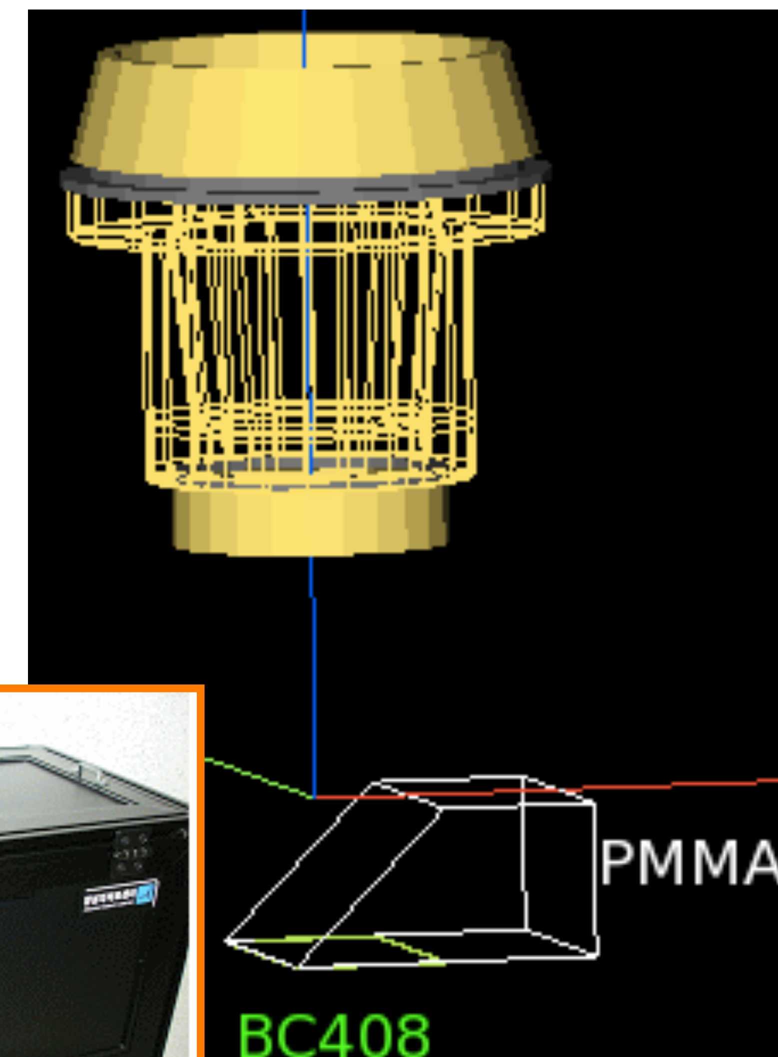
we have simulated ...

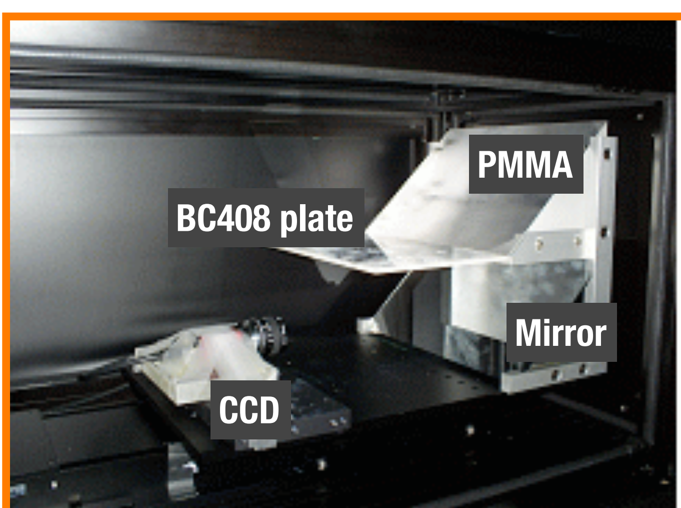
- optical photon emission spectrum
- total light output vs proton energy
- quenching effect

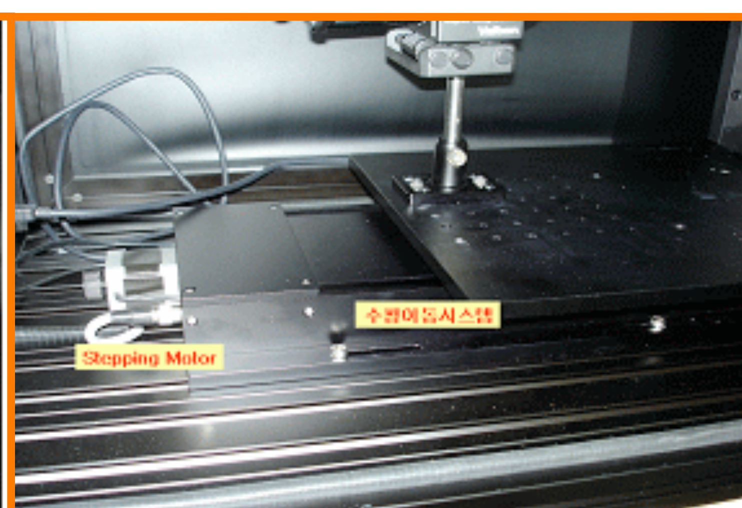


Remote control PC







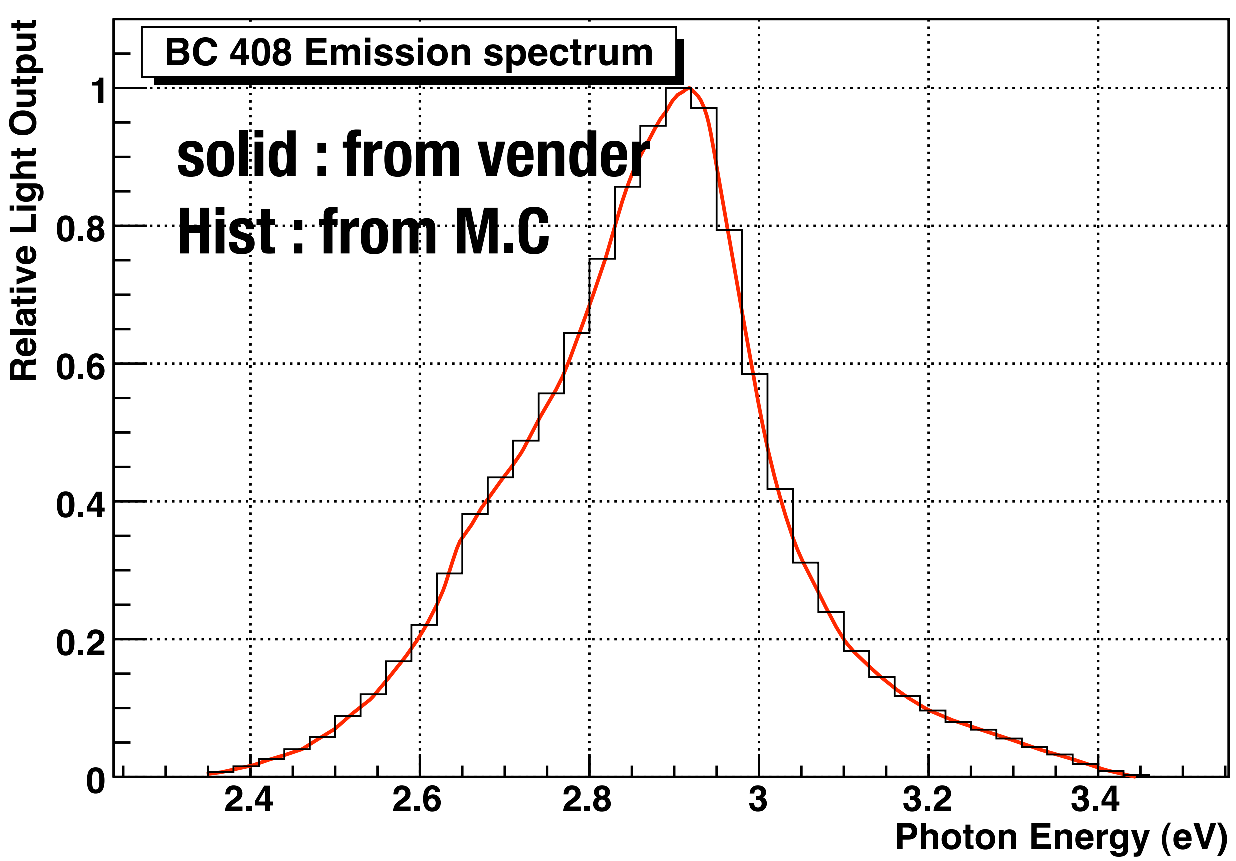


SCINTILLATOR (2/4): MATERIAL PROPERTIES

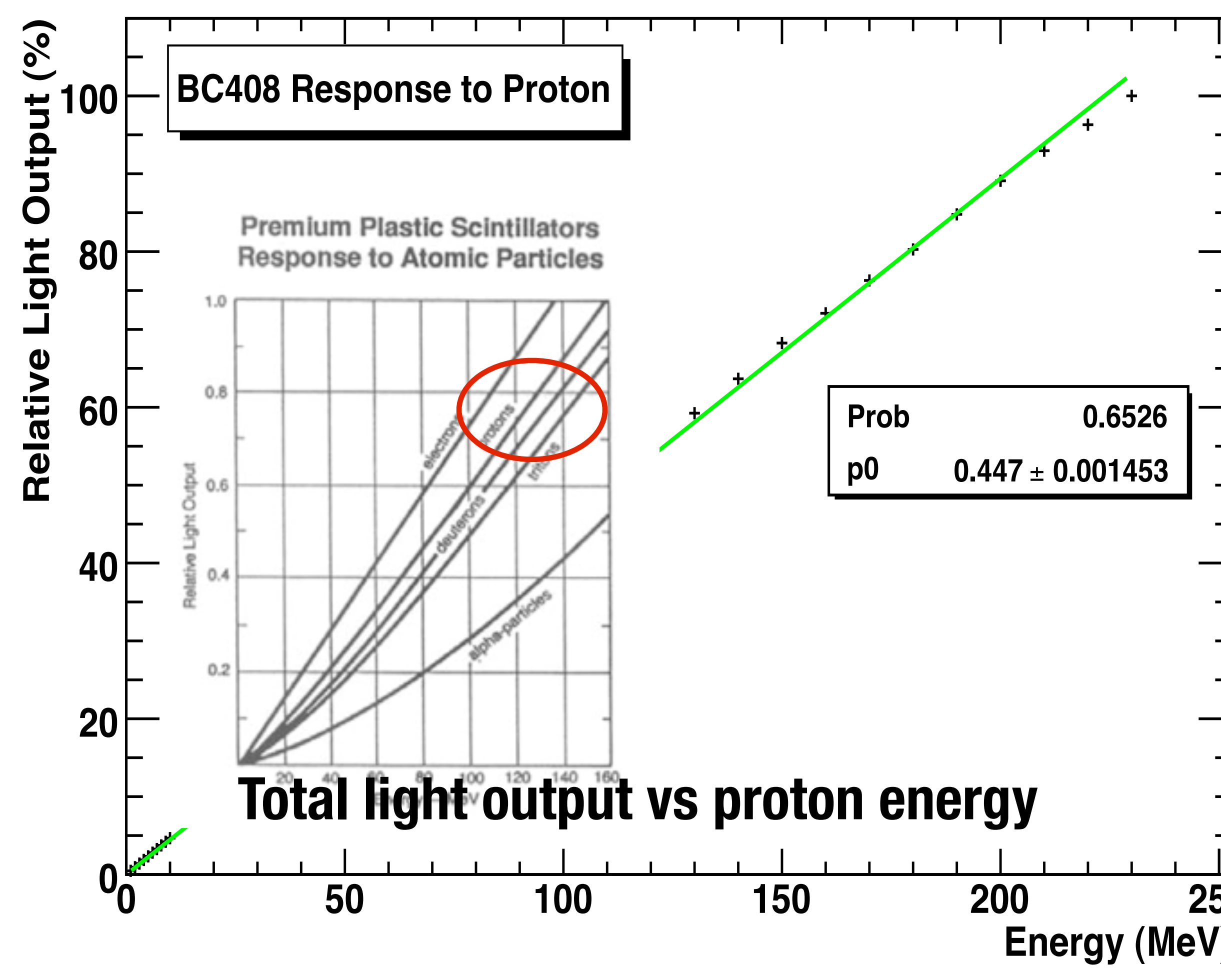
BC408 input parameters for G4Scintillation process		
Basic infomation *G4Material*	Chemical name	Polyvinyl Toluene & Organic Flours
	Chemical formula	$C_{10}H_{11}$ or H:C atoms = 1.104
	Density	1.032 g/cm^3
Additional Properties *G4MaterialPropertiesTable*	R Index	1.58
	Light Yield Factor	500.0/MeV
	Photon Energy	
	Spectrum(E_i)	

```
G4double OptEnergyBC408[numentries] = {
      3.44439*eV, 3.40654*eV, 3.36951*eV, 3.33328*eV, 3.29782*eV,
      3.26310*eV, 3.22911*eV, 3.19582*eV, 3.16321*eV, 3.13126*eV,
      3.09995*eV, 3.06926*eV, 3.03917*eV, 3.00966*eV, 2.98072*eV,
      2.95233*eV, 2.93834*eV, 2.93139*eV, 2.92448*eV, 2.91760*eV,
      2.91075*eV, 2.90393*eV, 2.89715*eV, 2.89040*eV, 2.88367*eV,
      2.87032*eV, 2.85710*eV, 2.84399*eV, 2.81814*eV, 2.79275*eV,
      2.76781*eV, 2.74332*eV, 2.71925*eV, 2.69561*eV, 2.67237*eV,
      2.66090*eV, 2.64953*eV, 2.62708*eV, 2.60500*eV, 2.58329*eV,
      2.56194*eV, 2.54094*eV, 2.52028*eV, 2.49996*eV, 2.47996*eV,
      2.46028*eV, 2.44090*eV, 2.42184*eV, 2.40306*eV, 2.38458*eV,
      2.36637*eV, 2.34845*eV, 2.34845*eV

G4double OptScintOutputBC408[numentries] ={
      0    , 0.011, 0.026, 0.039, 0.054, 0.068, 0.082, 0.1  , 0.126, 0.159,
      0.2  , 0.27 , 0.35 , 0.48 , 0.67 , 0.87 , 0.96 , 0.982, 0.993, 1    ,
      0.995, 0.99 , 0.98 , 0.966, 0.955, 0.925, 0.895, 0.855, 0.75 , 0.66 ,
      0.58 , 0.52 , 0.47 , 0.43 , 0.39 , 0.366, 0.34 , 0.27 , 0.215, 0.175,
      0.142, 0.112, 0.092, 0.07 , 0.055, 0.04 , 0.032, 0.025, 0.017, 0.012,
      0.007, 0.004, 0.004
};
```



Optical photon spectrum



Total light output vs proton energy

SCINTILLATOR (3/4): QUENCHING EFFECT

Quenching effect has not been implemented and then we added quenching formula G4Scintillation.hh/cc.

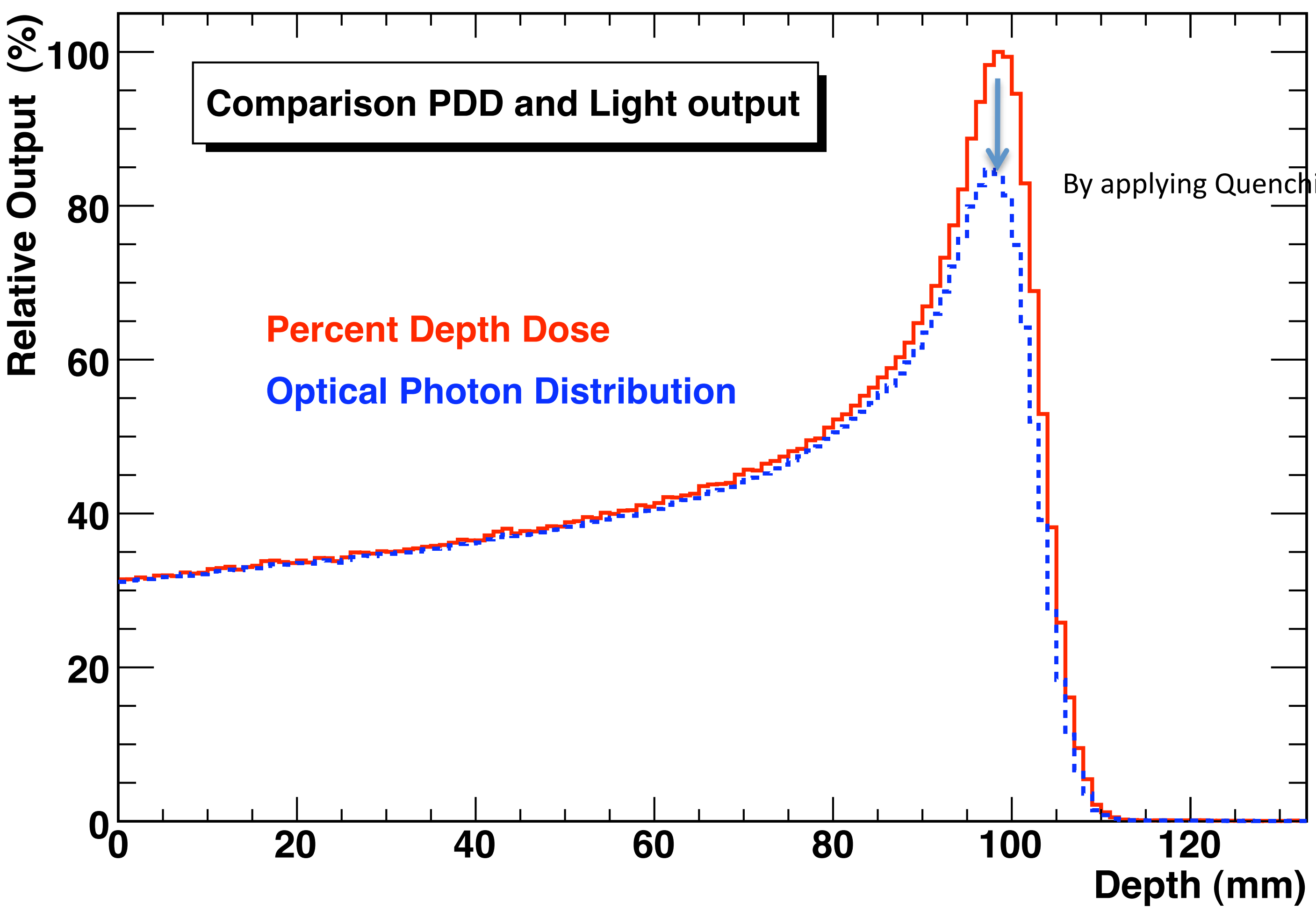
$$dN = \varepsilon dL$$

$$dL = dE$$

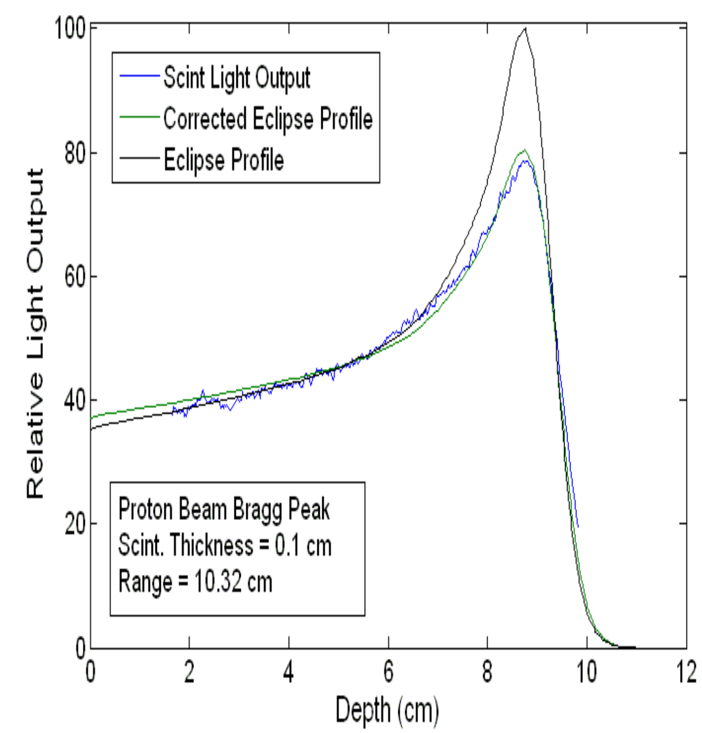
original Geant4 Scintillation

$$dL_{quenching} = \frac{dE}{(1+\frac{kB}{\rho}\cdot\frac{dE}{dx})}$$

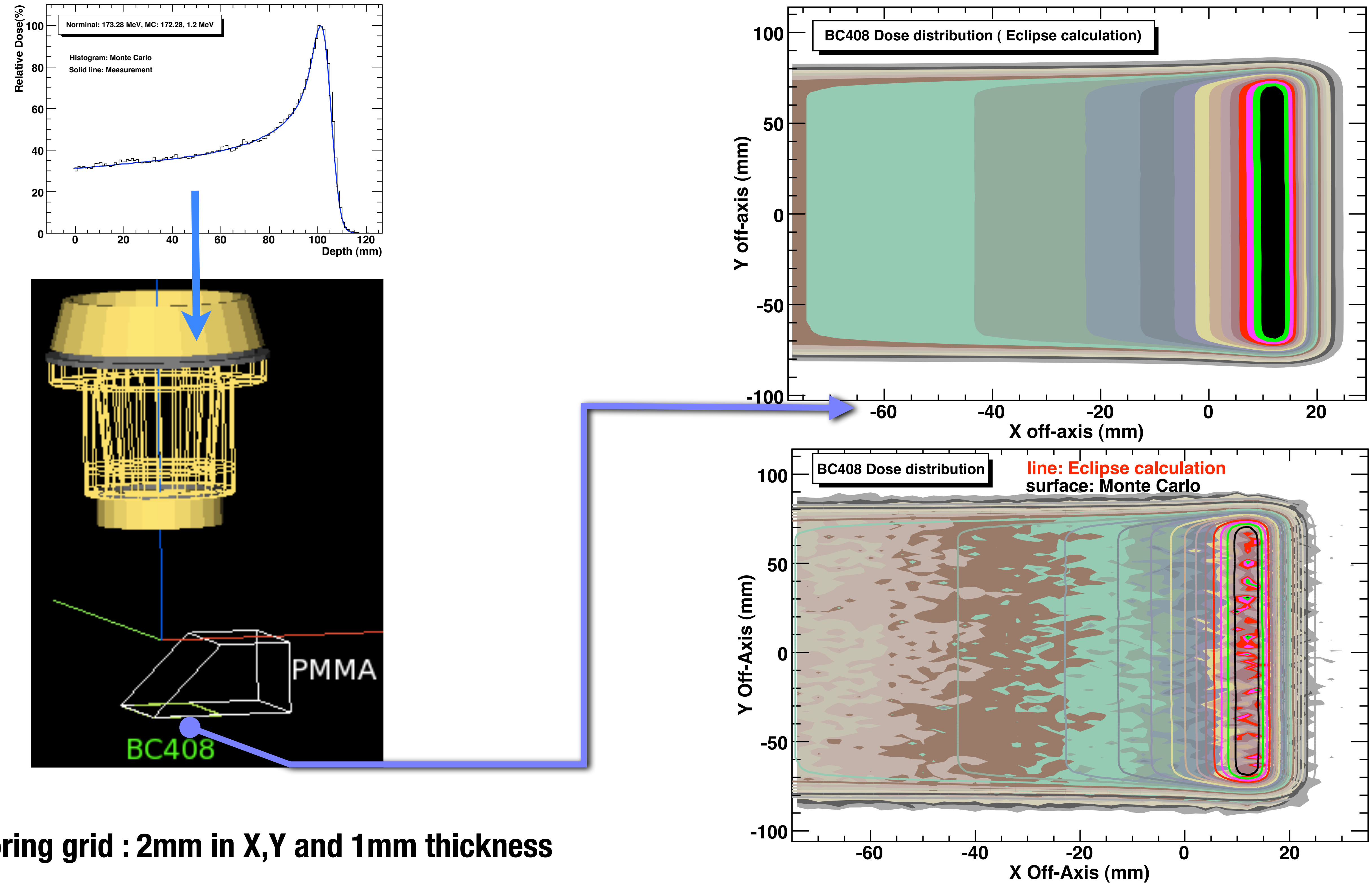
- *dN : # of generated optical photons per a step*
- *ε : Conversion efficiency.*
  - *G4MaterialPropertiesTable::GetConstProperty("SCINTILATIONYIELD")*
- *dL : Transfered energy to be converted into optical photon.*
  - *aStep.GetTotalEnergyDeposit()*
- *kB: Quenching factor.*
  - *G4MaterialPropertiesTable::GetConstProperty("QUENCHINGFACTOR")*
- *ρ: Material density . G4Material::GetDensity()*
- *dE/dX : stopping power, G4EnergyLossTable::GetDEDX()*



The input parameters for BC408 and G4Scintillation process		
Additional Properties *G4MaterialPropertiesTable*	…	
	Quenching Factor	0.00708 g/cm^{2}MeV



SCINTILLATOR (3/4): 2D DOSE DISTRIBUTION



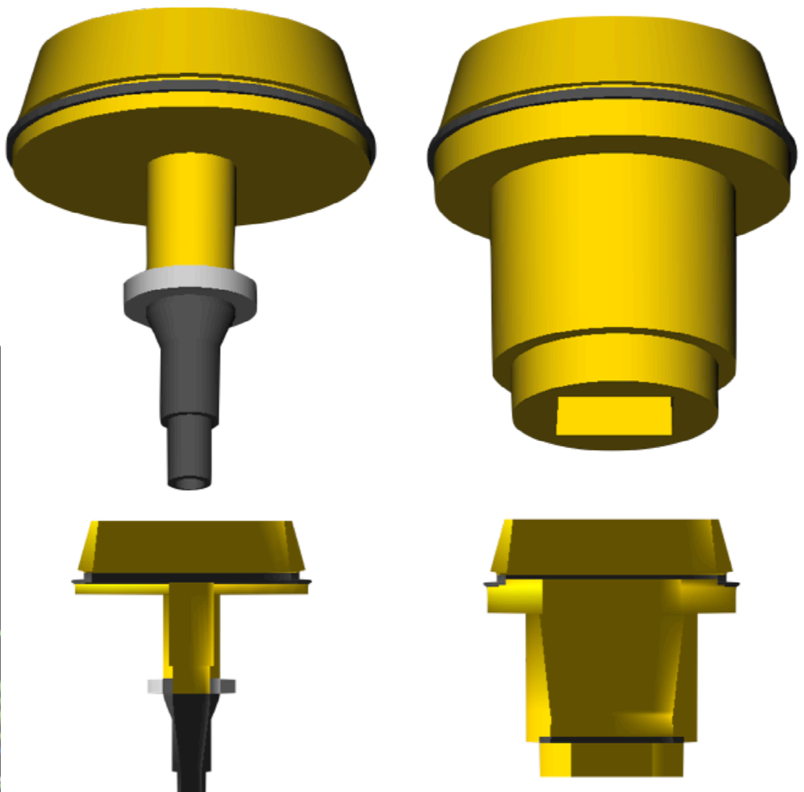
scoring grid : 2mm in X,Y and 1mm thickness

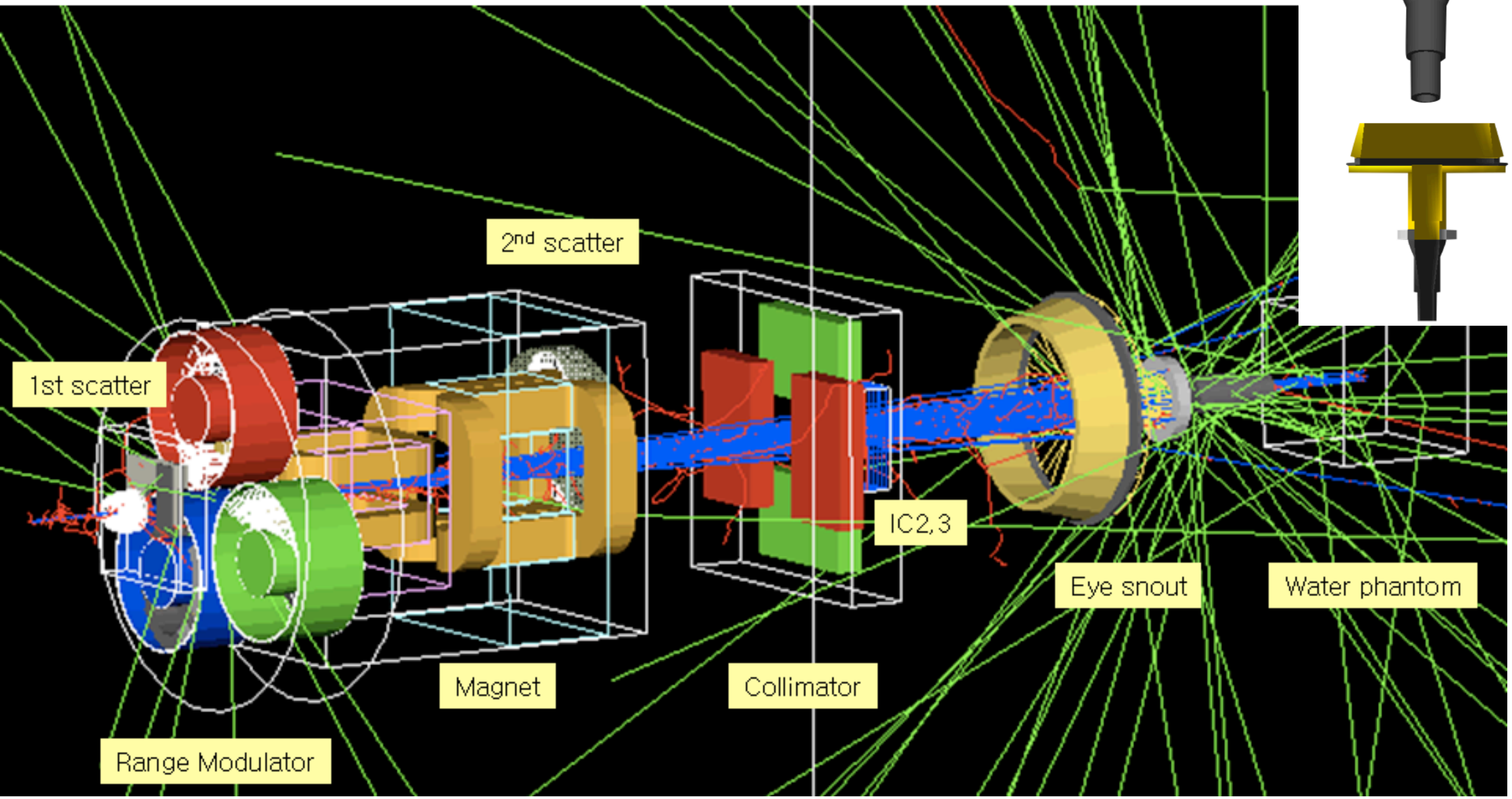
FINDING NEUTRON (1/4): INTRODUCTION

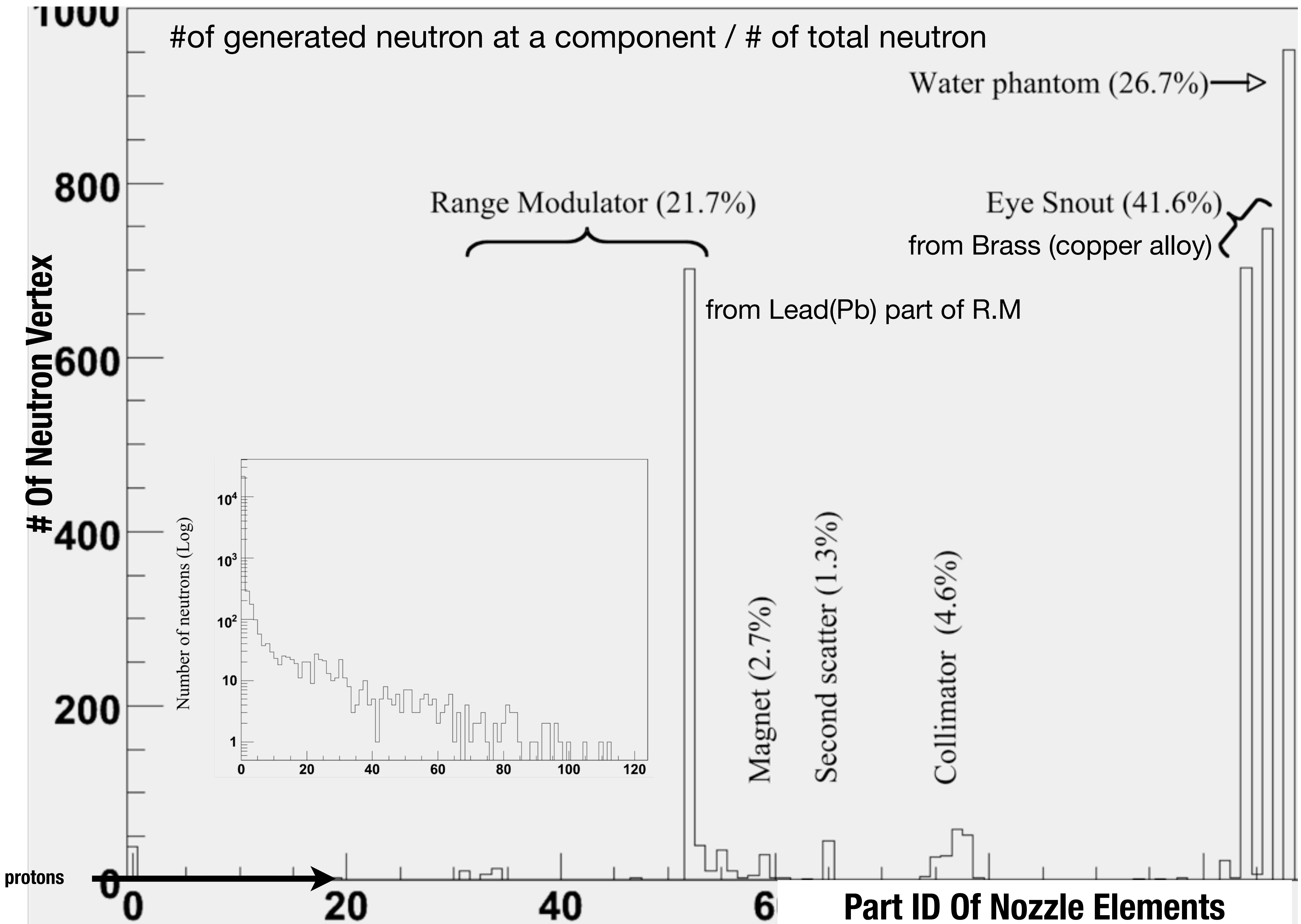
Secondary neutrons are produced during proton treatment by nuclear interaction with the materials on the beam path, including the patient's body.

We simulated to investigate

- where did neutron come from ?
- how we can reduce the neutron ?

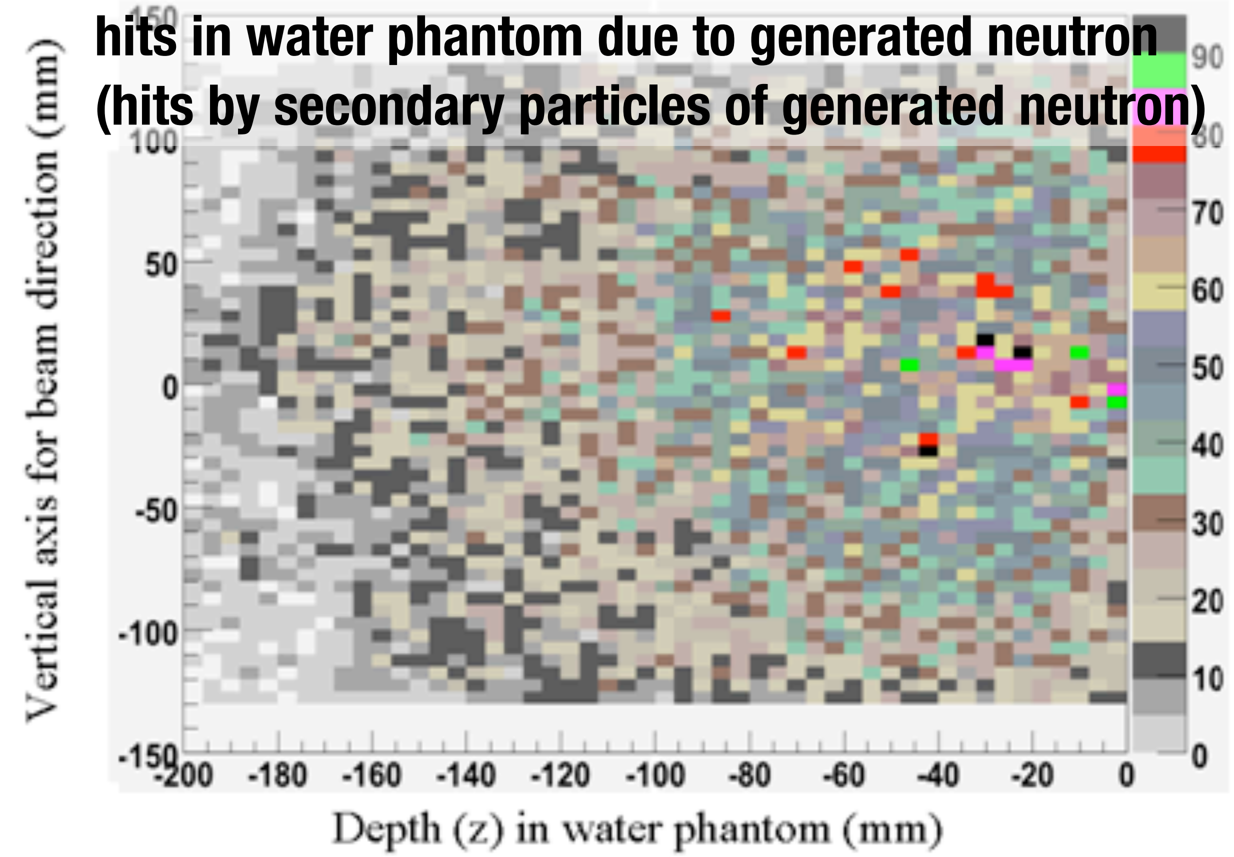




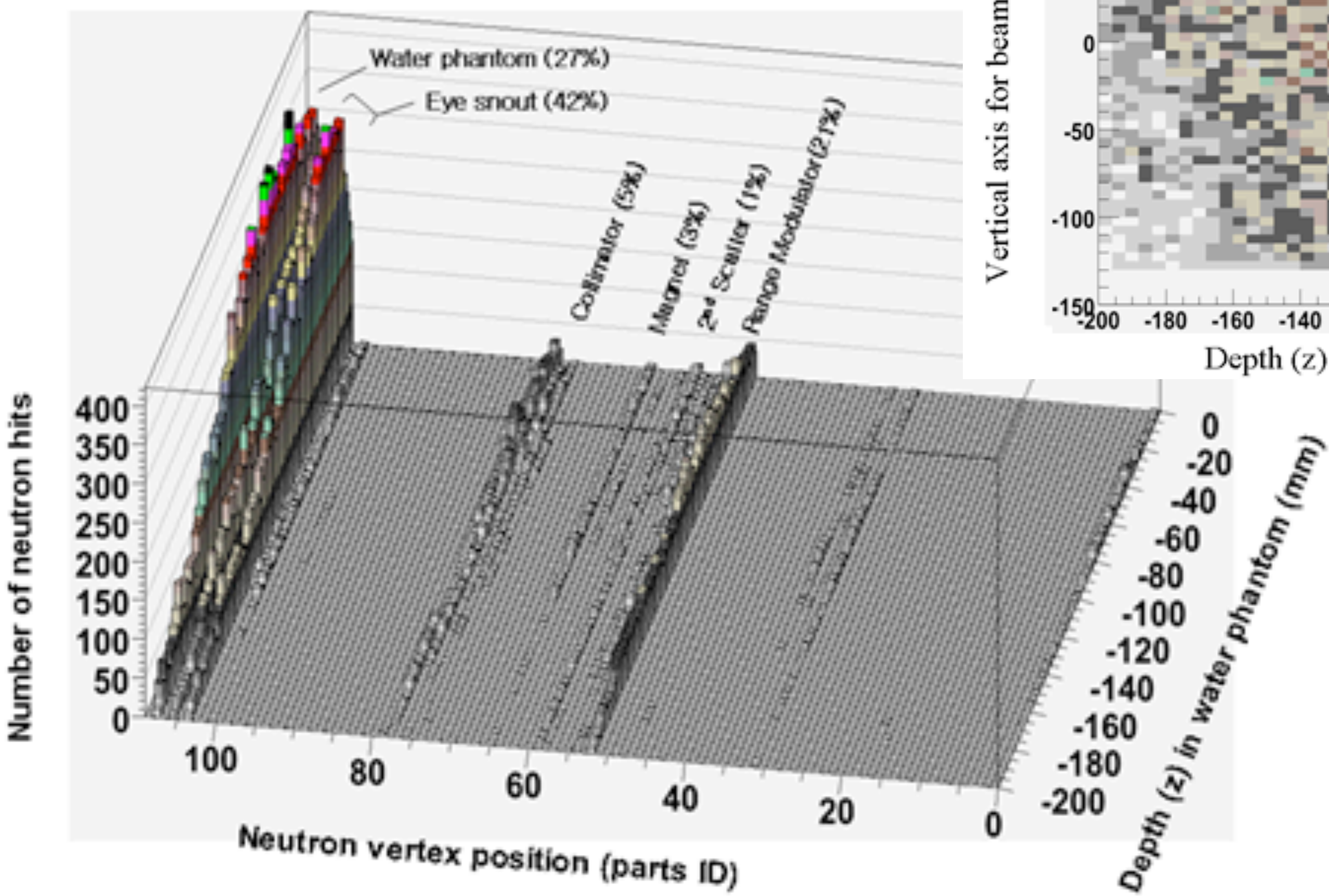

#of generated neutron at a component / # of total neutron
Water phantom (26.7%)
Range Modulator (21.7%)
Eye Snout (41.6%)
from Brass (copper alloy)
from Lead(Pb) part of R.M
Magnet (2.7%)
Second scatter (1.3%)
Collimator (4.6%)
Number of neutrons (Log)
Of Neutron Vertex
protons
Part ID Of Nozzle Elements
1000
800
600
400
200
0
0
20
40
60

FINDING NEUTRON (2/4): HIT DISTRIBUTION

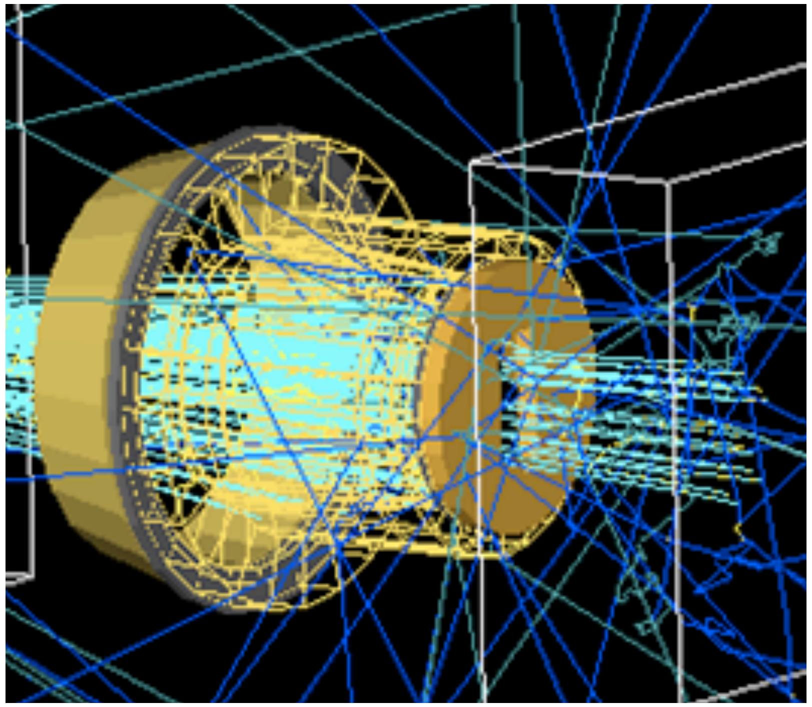
hits in water phantom due to generated neutron
(hits by secondary particles of generated neutron)

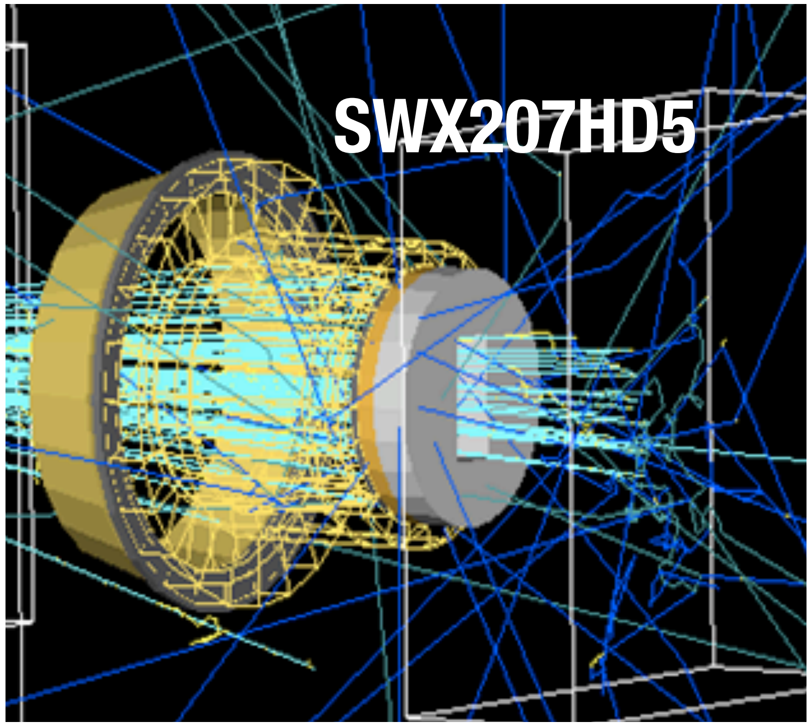


hits in water phantom vs part ID & depth



FINDING NEUTRON (4/4): TO REDUCE NEUTRON HITS



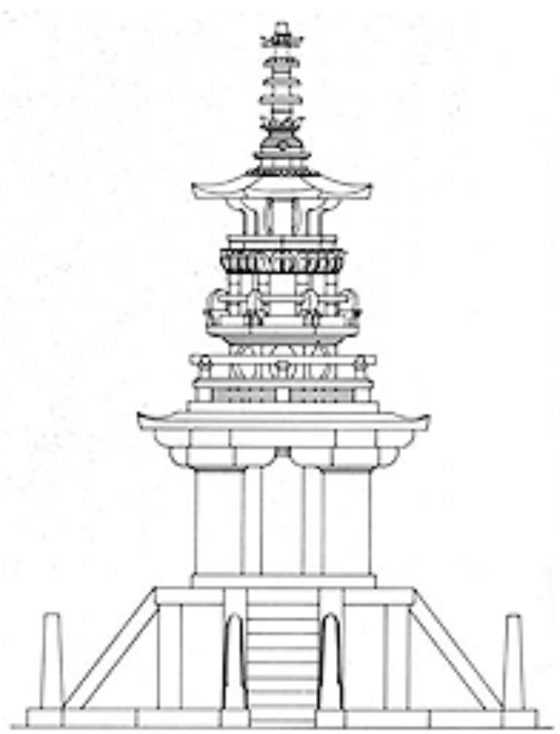


% SWX207HD5: high hydrogen-boron contaminated material

neutron from sub part	Single Brass block	Brass + SWX
Front of the Snout	0.13%	0.12%
snout	0.38%	0.24%
Brass Block	0.93%	0.43%
Phantom	0.31%	0.28%

#of neutron / # of total primary hits water phantom

Our challenge is to repeat our simulations with Geant4.9.x (currently, we are using 8.2.p02)



Algorithm

we can imagine ...

Monte Carlo

we can try ...

The real

Eventually, we honor the masterpiece

we have been enjoying our trial with ***Geant4...***
from modeling our system to user application.

Thank you for your attention!