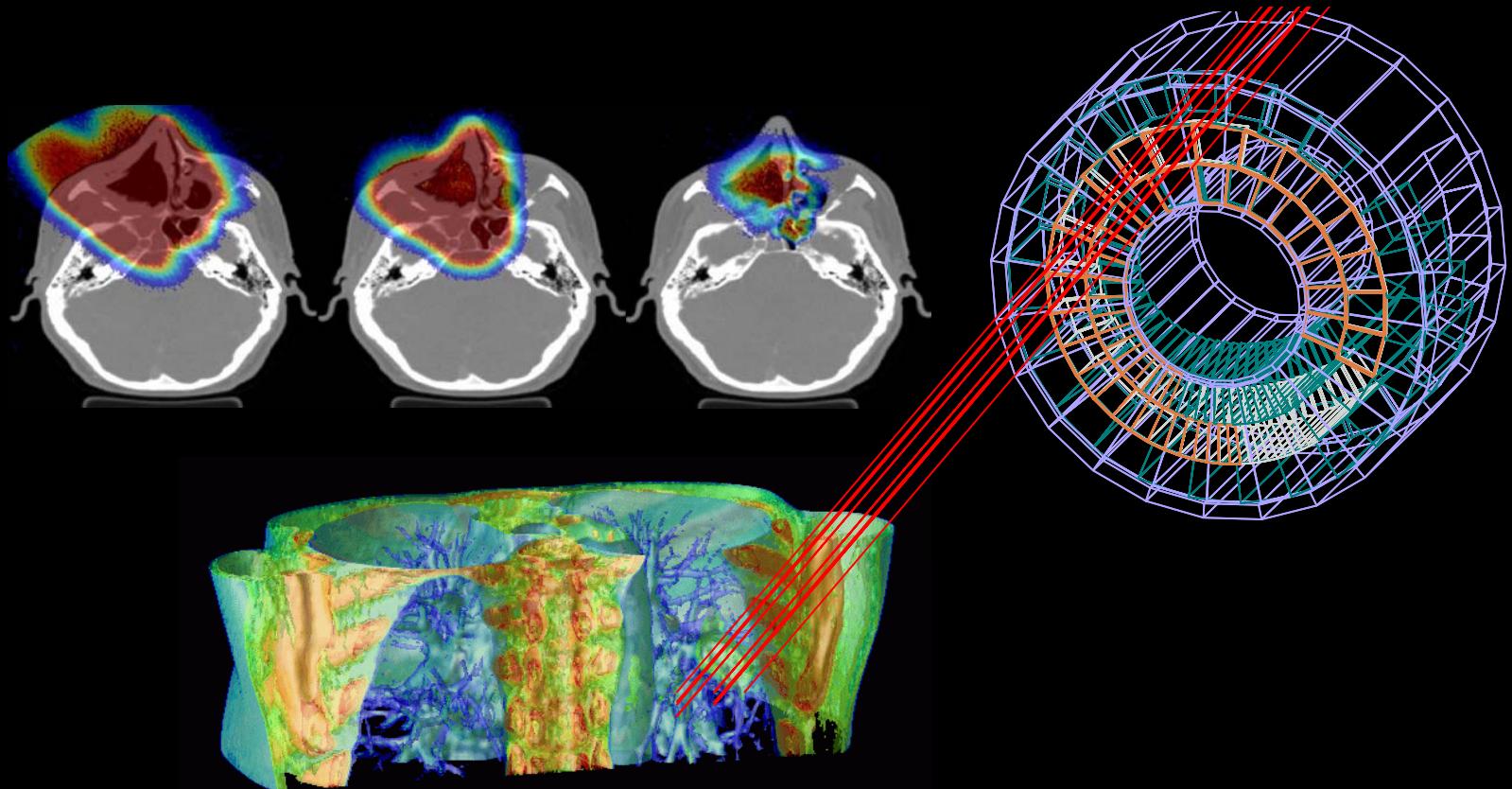


Geant4 applications to proton radiation therapy



Harald Paganetti



MASSACHUSETTS
GENERAL HOSPITAL

HARVARD
MEDICAL SCHOOL



Geant4 application to proton radiation therapy

- Proton therapy techniques in a nutshell

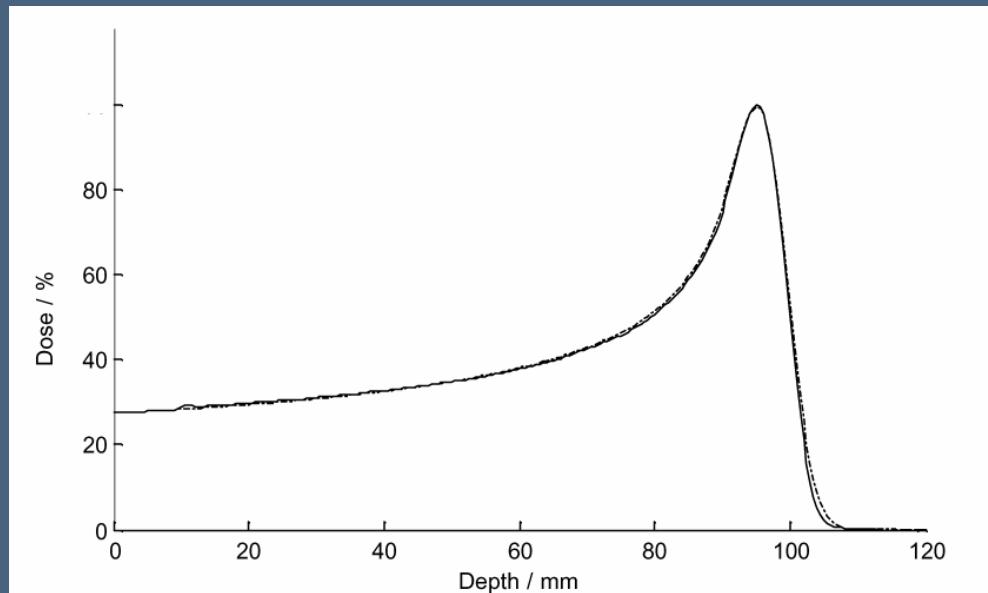
Monte Carlo applications:

- Treatment head developments
- Quality assurance
- Phase space calculations
- Patient simulations
- Clinical use
- Time dependent patient geometries
- Neutron dose in proton beam therapy
- PET imaging for quality assurance

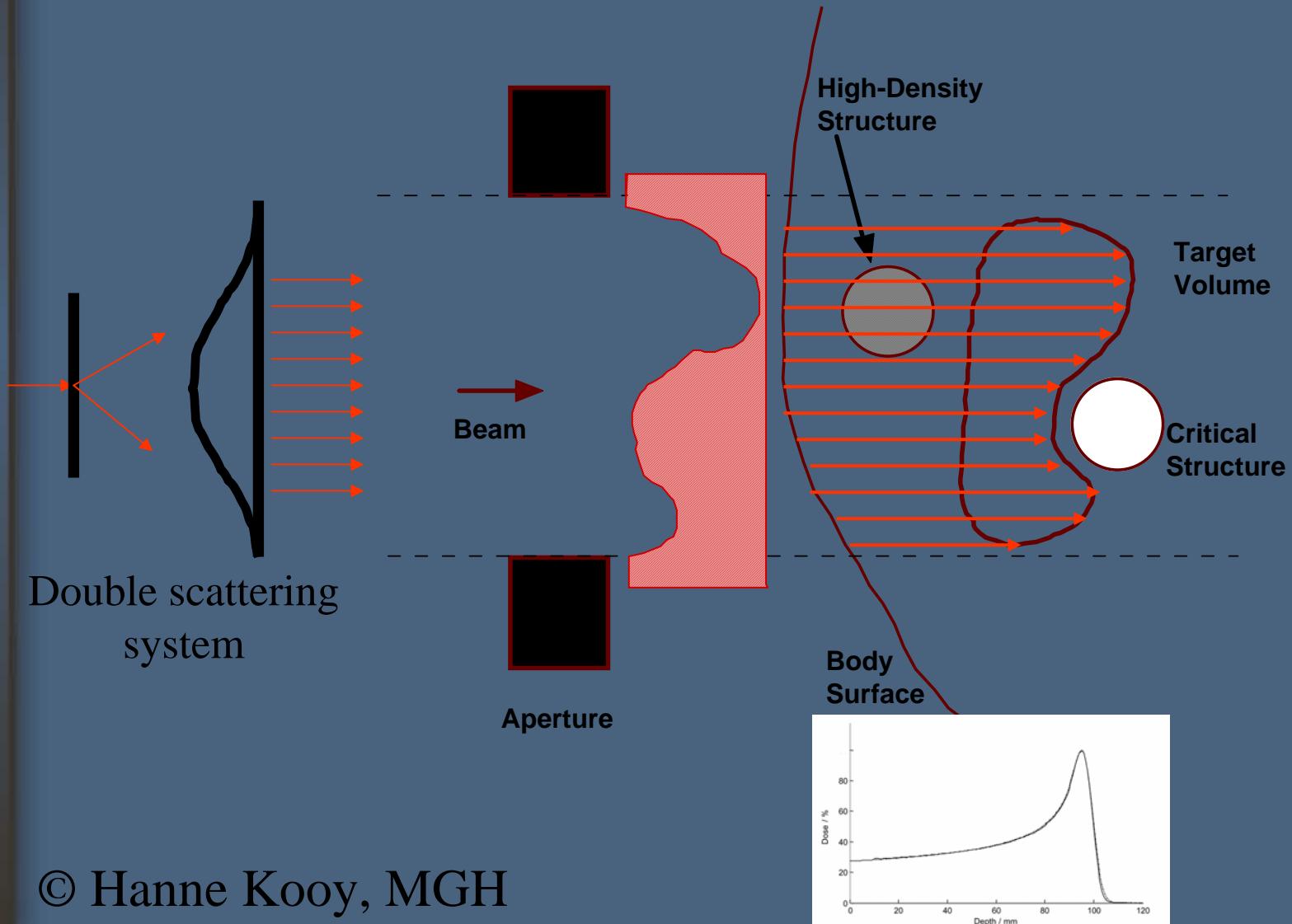


Geant4 application to proton radiation therapy

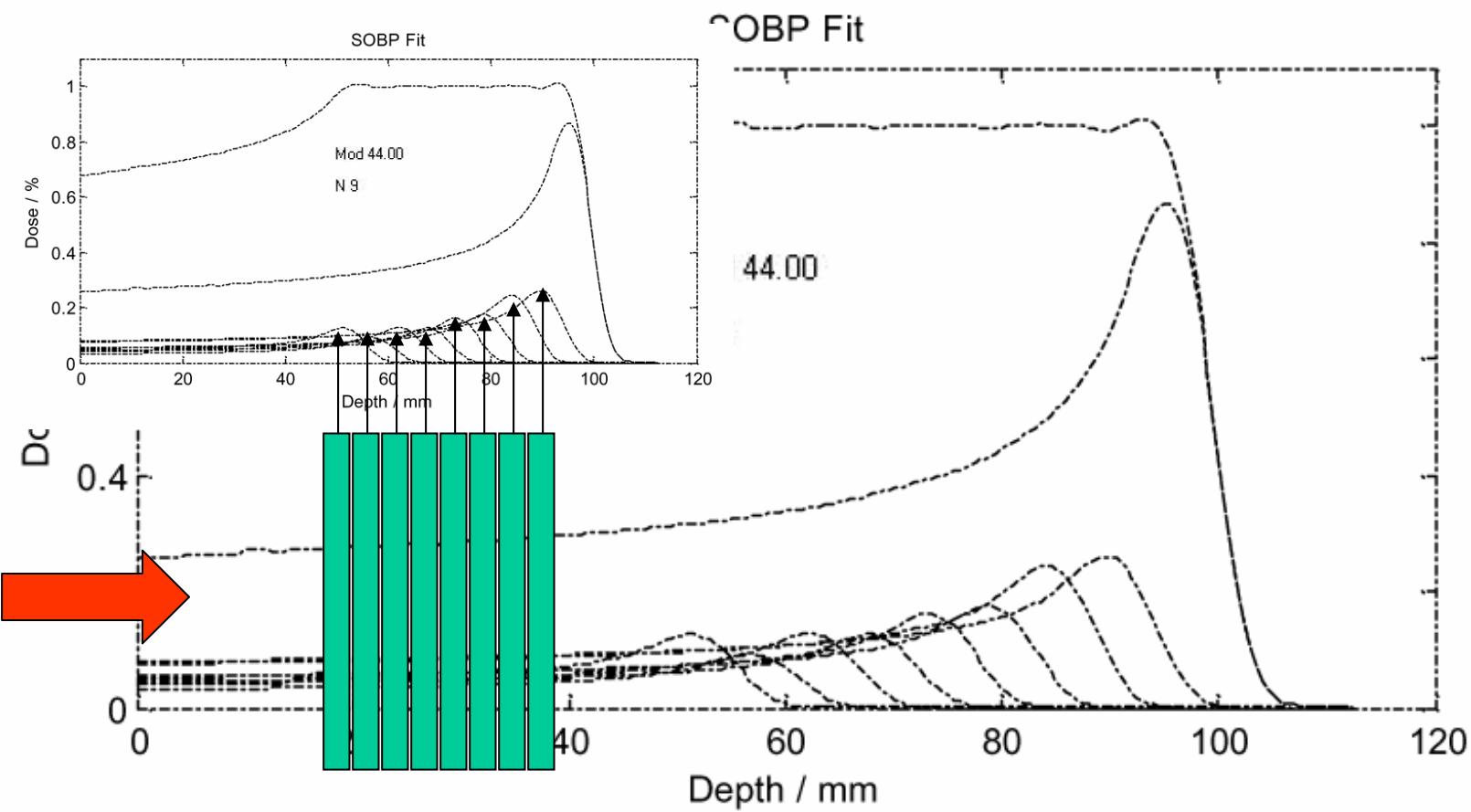
- Proton therapy techniques in a nutshell



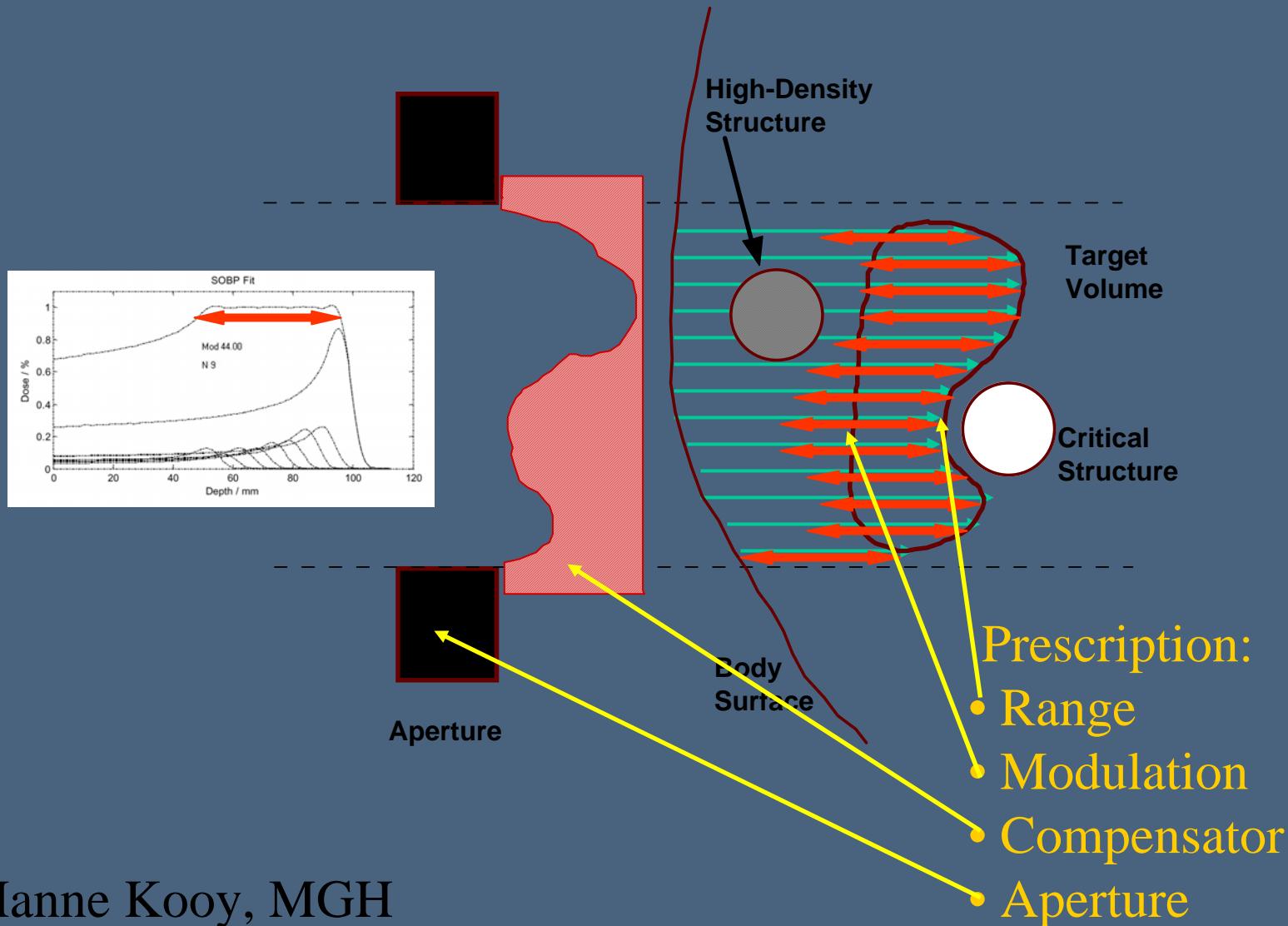
Dose shaping for passive scattered protons



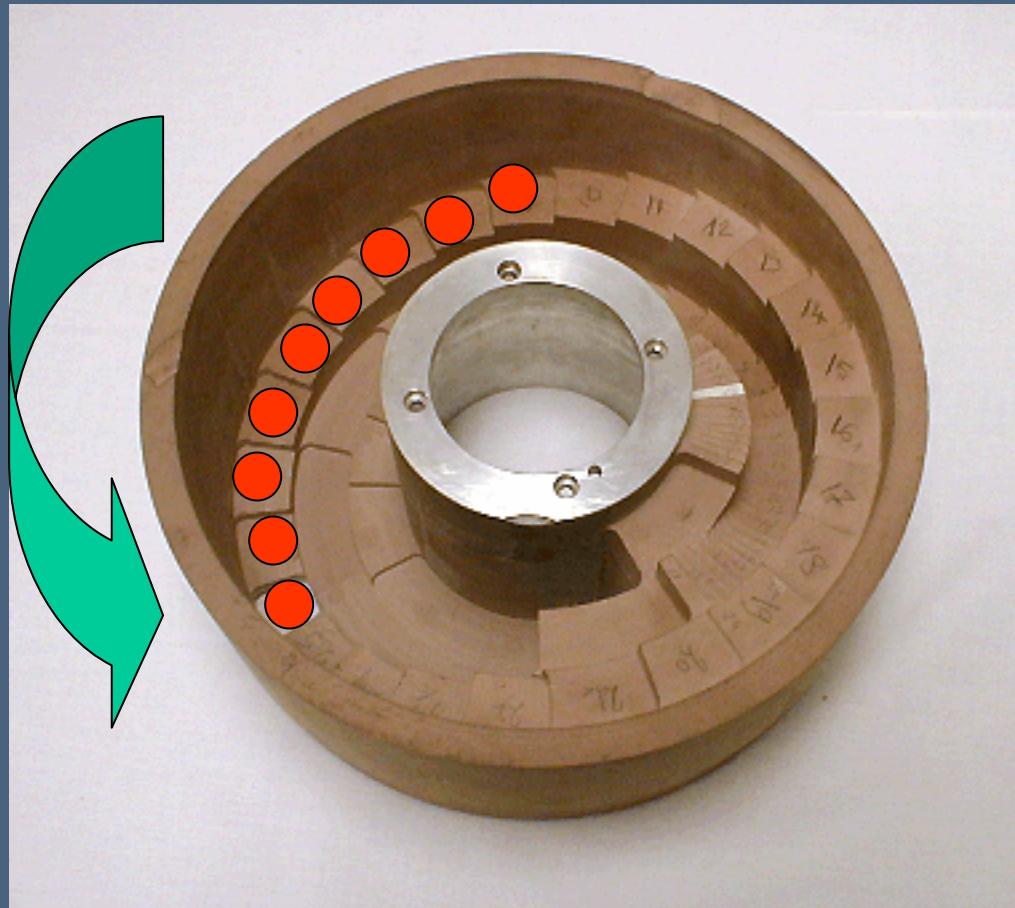
SOBP: Spread-Out Bragg Peak



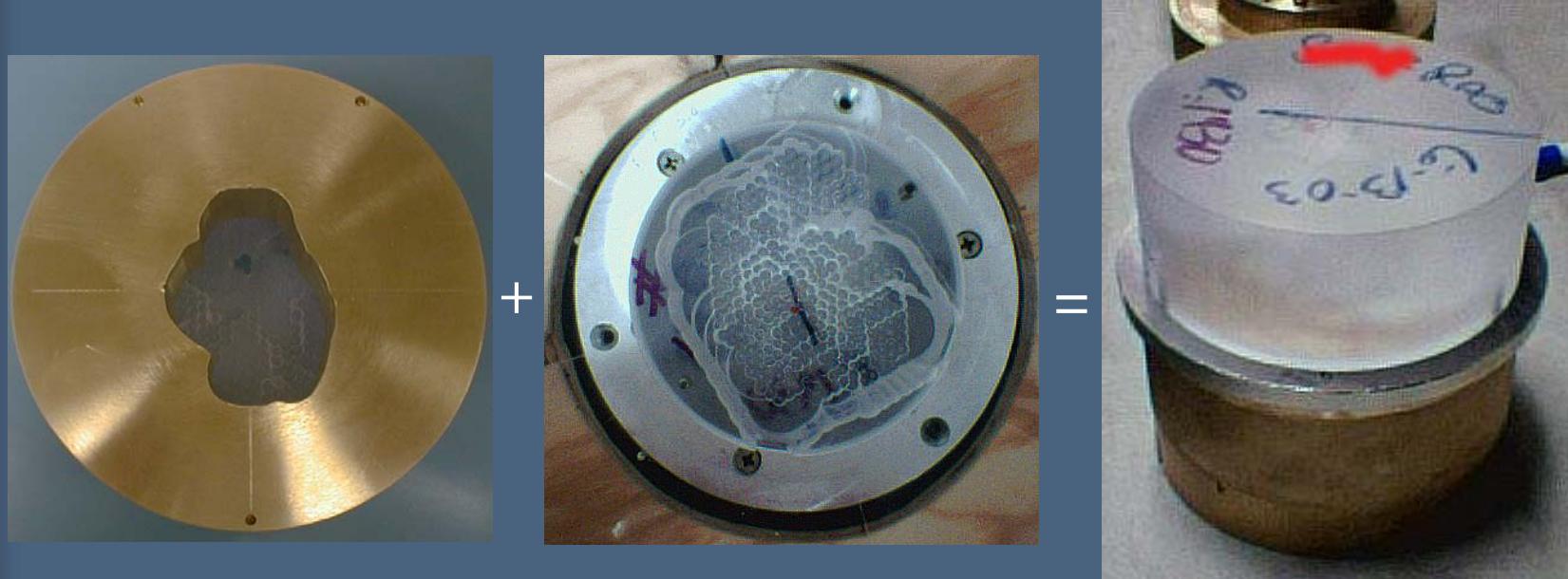
SOBP Modulation



Range Modulator Wheel

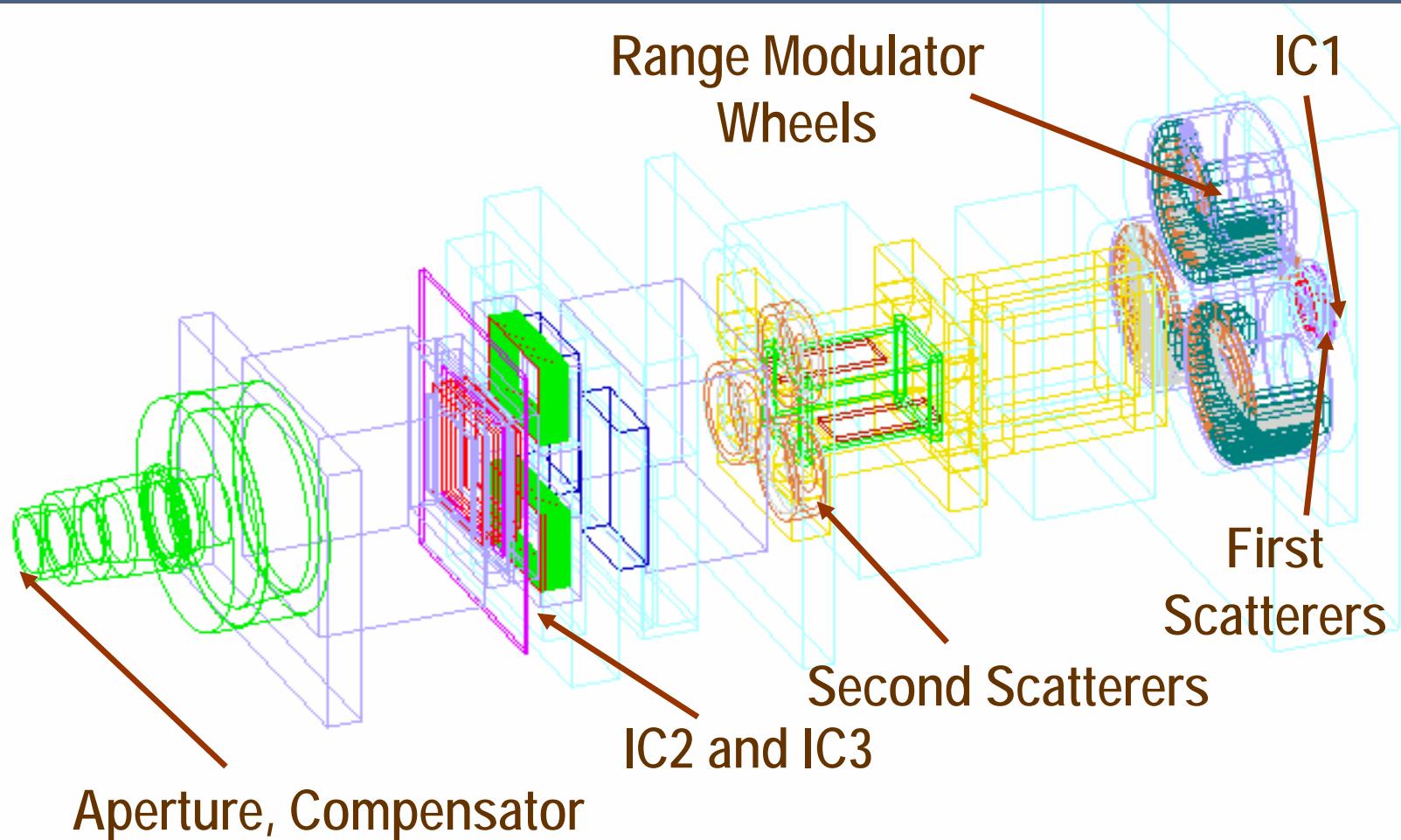


Aperture and Range Compensator



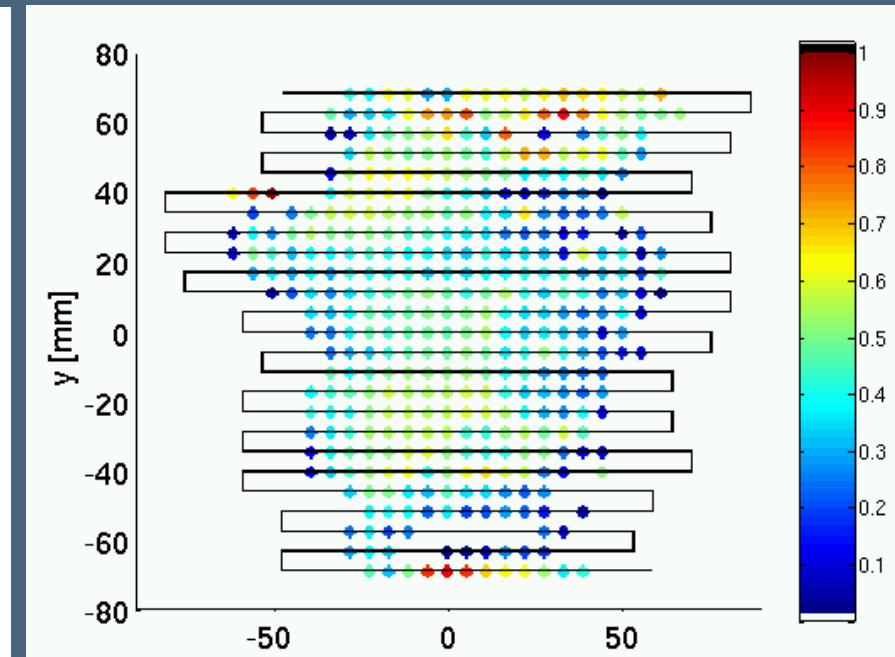
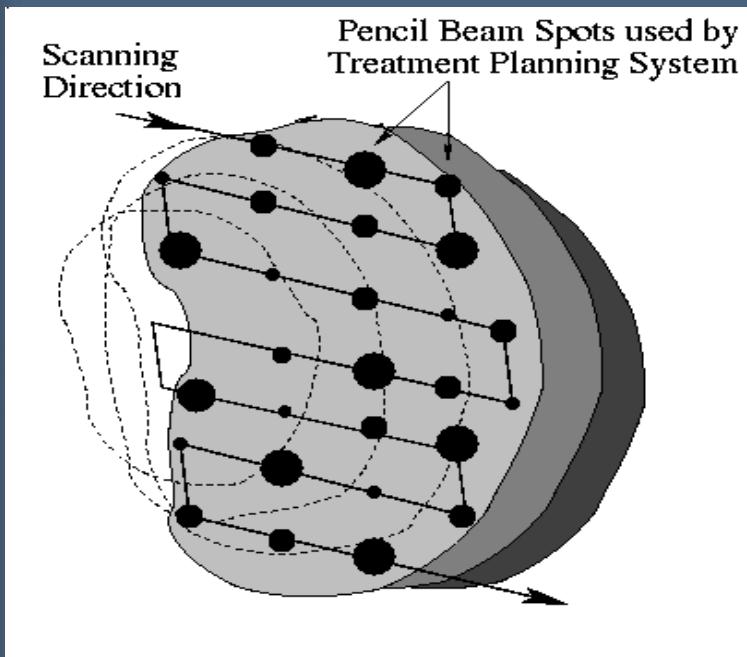
To be ‘designed’ by the planning system !

Typical treatment head

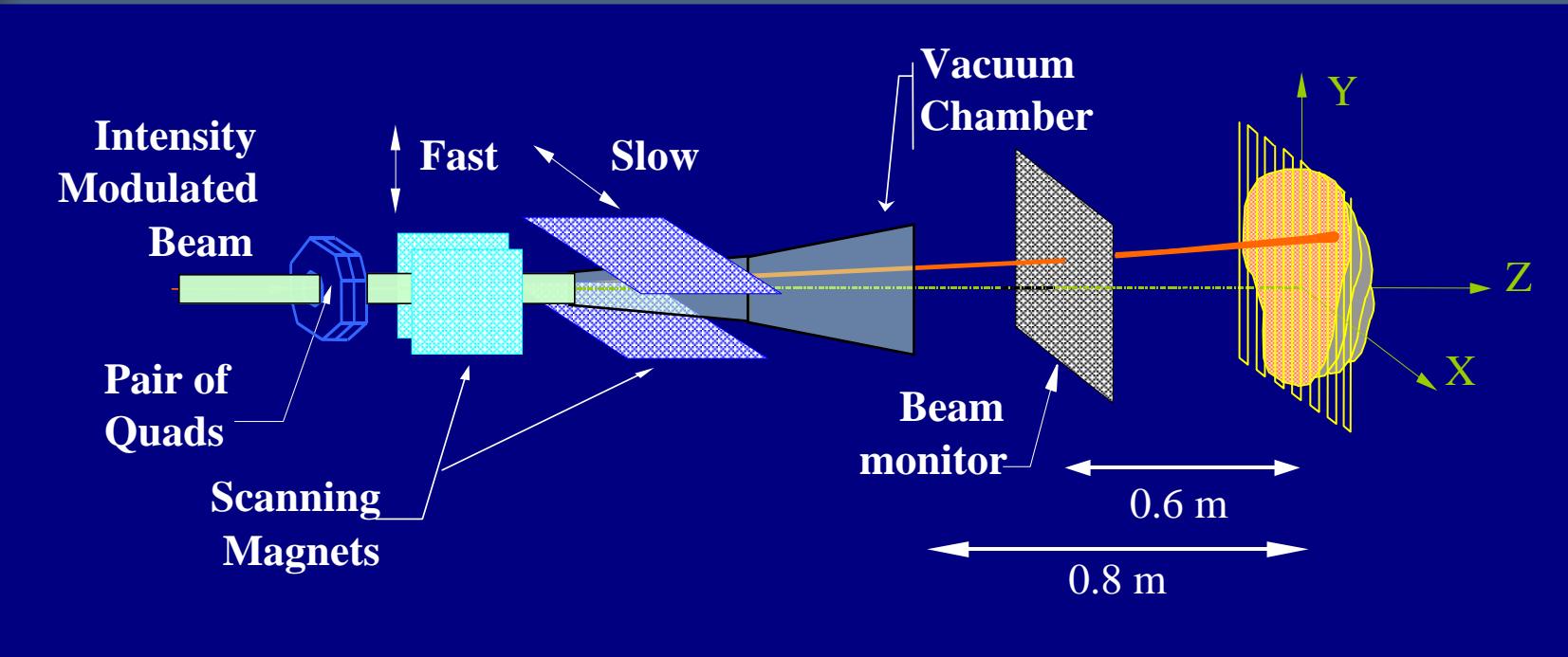


Proton beam scanning

- Bragg peaks of pencil beams are distributed throughout the planning volume
- Pencil beam weights are optimized for several beam directions simultaneously (inverse planning)

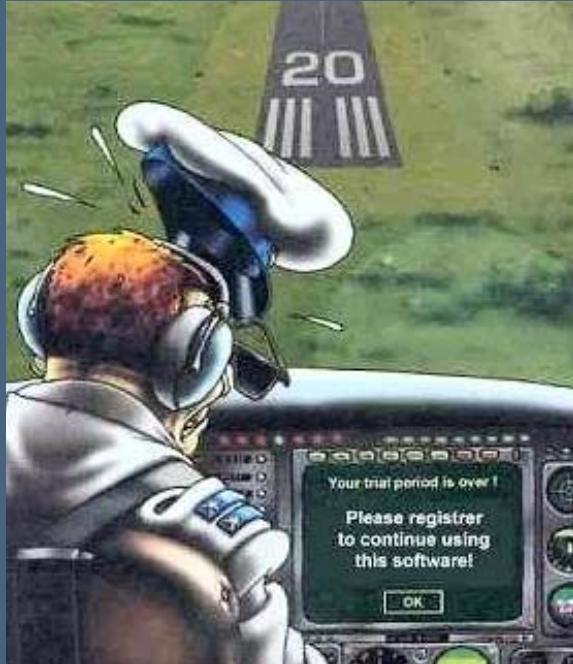


Proton beam scanning



Monte Carlo for proton therapy simulations

Monte Carlo code



Physics Setup

Geant 4
is not a Monte Carlo
simulation executable

Geant 4
is an

Object Oriented Simulation Toolkit in C++
→ advantage over other codes: flexibility



Monte Carlo for proton therapy simulations

Geant4: A toolkit for the simulation of the passage of particles through matter - Mozilla Firefox

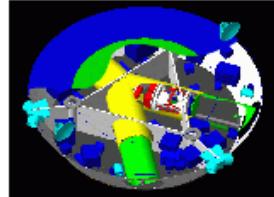
File Edit View History Bookmarks Tools Help

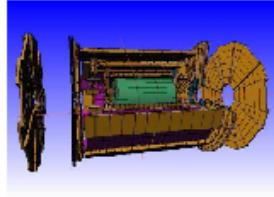
http://geant4.web.cern.ch/geant4/ Google

Geant 4

Geant4 is a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science. The two main reference papers for Geant4 are published in *Nuclear Instruments and Methods in Physics Research A* 506 (2003) 250-303, and *IEEE Transactions on Nuclear Science* 53 No. 1 (2006) 270-278.

Applications  A sampling of applications, technology transfer and other uses of Geant4

User Support  Getting started, user guides and information for developers

Results & Publications  Validation of Geant4, results from experiments and publications

Collaboration  Who we are: collaborating institutions, members, organization and legal information

Do



<http://geant4.web.cern.ch/geant4/>

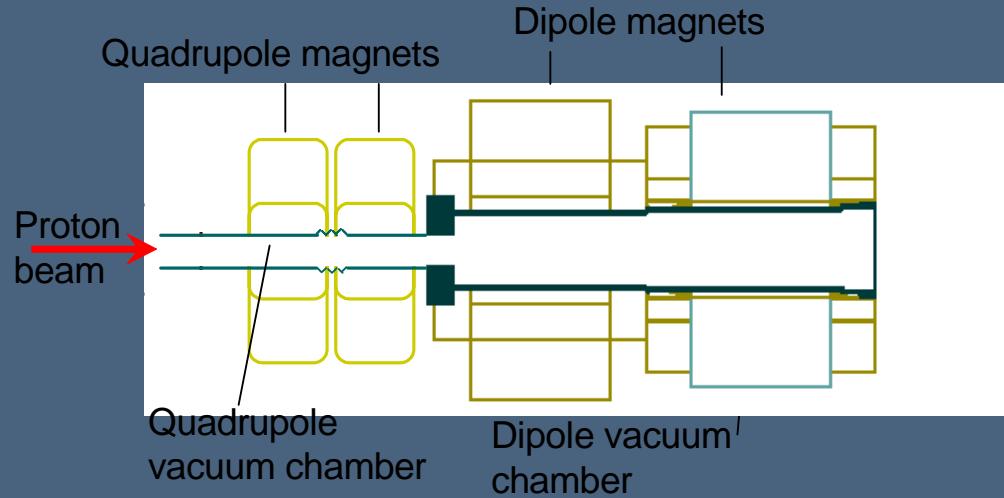
Geant4 application to proton radiation therapy

- Treatment head developments

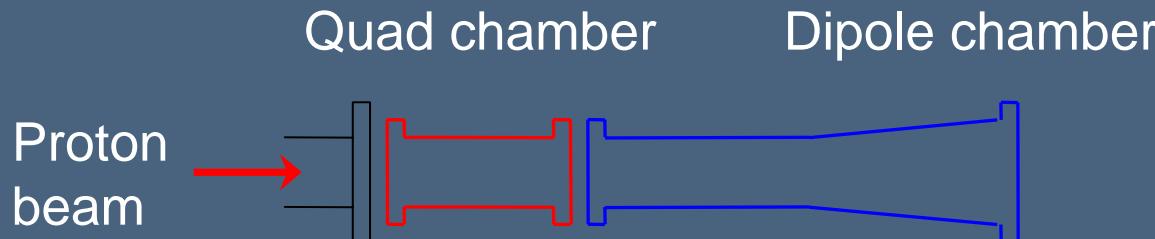


Proton therapy nozzle

- Vacuum chambers for scanned beam delivery

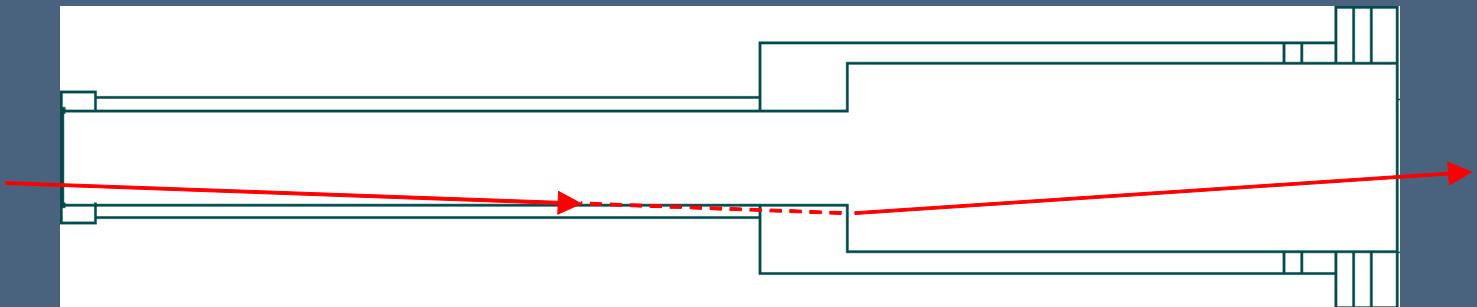


- Schematic of the chamber positions

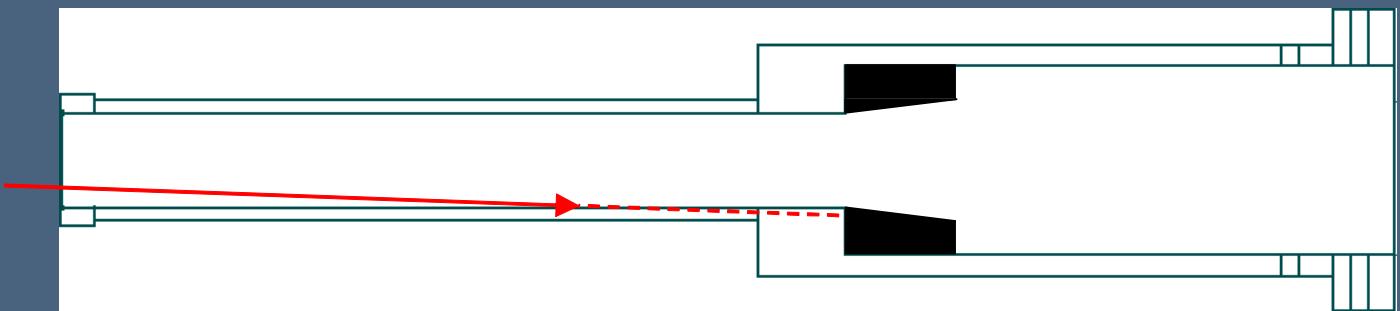


Possible design improvement

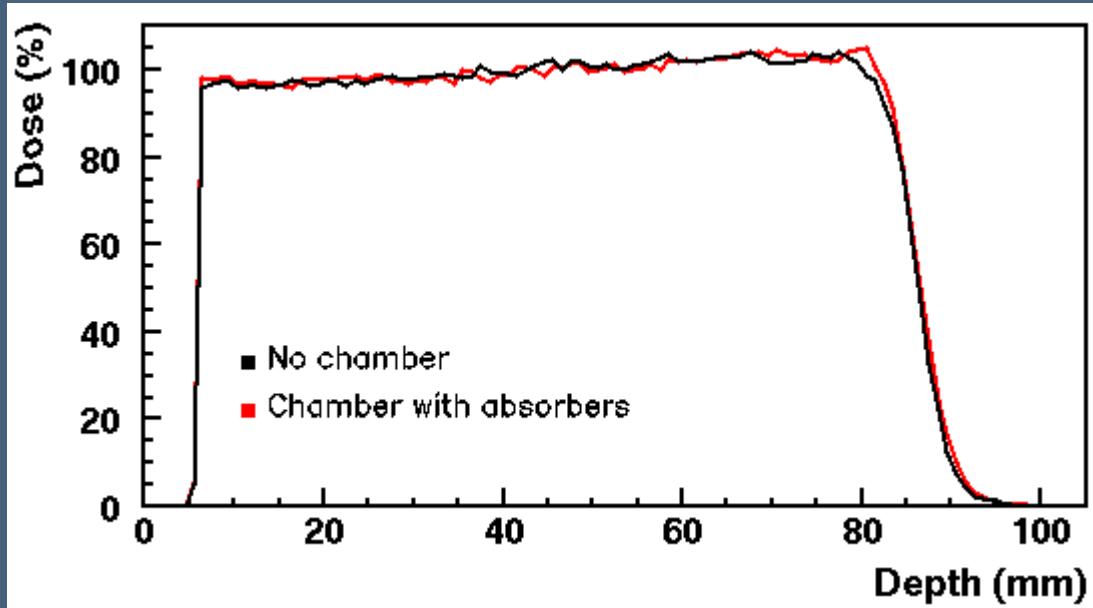
- Contamination comes from protons with reduced energy



- Smoothing edges and high-density absorbing material reduces contamination



Possible design improvement

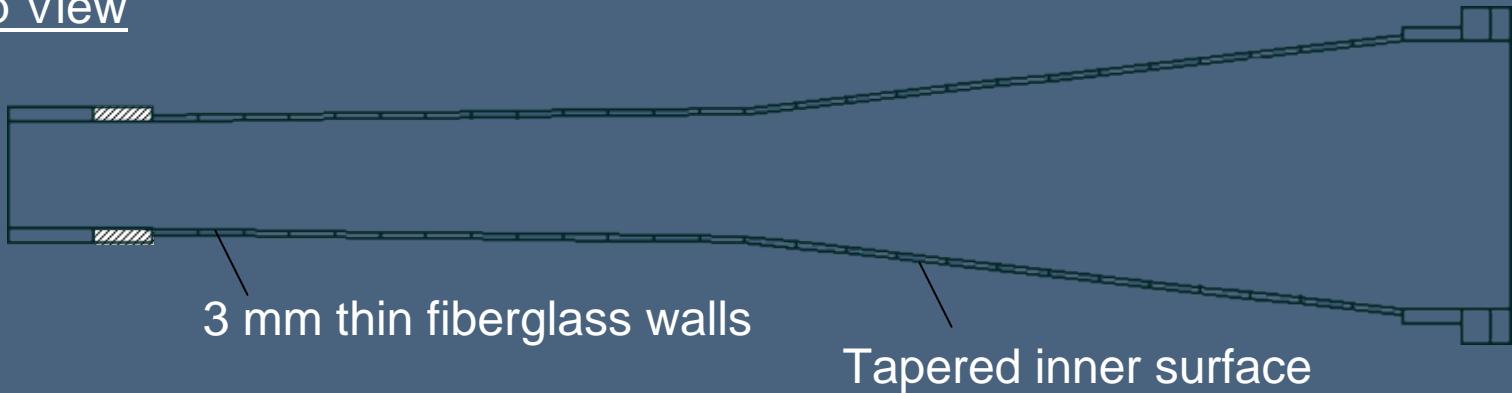


Better agreement in the slope
1.5% change in the output factor

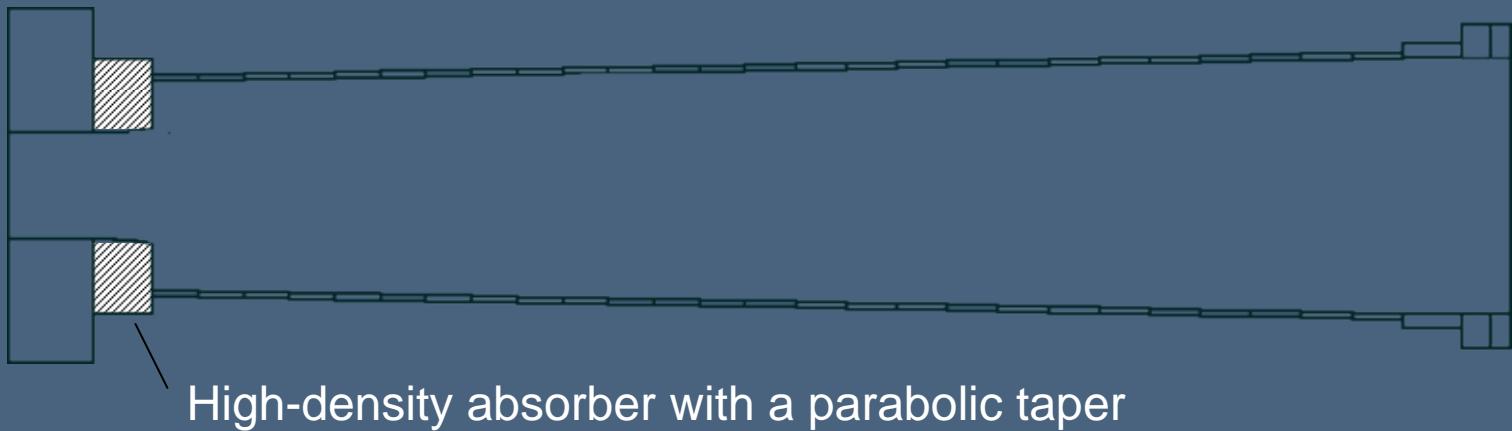


New chamber solution

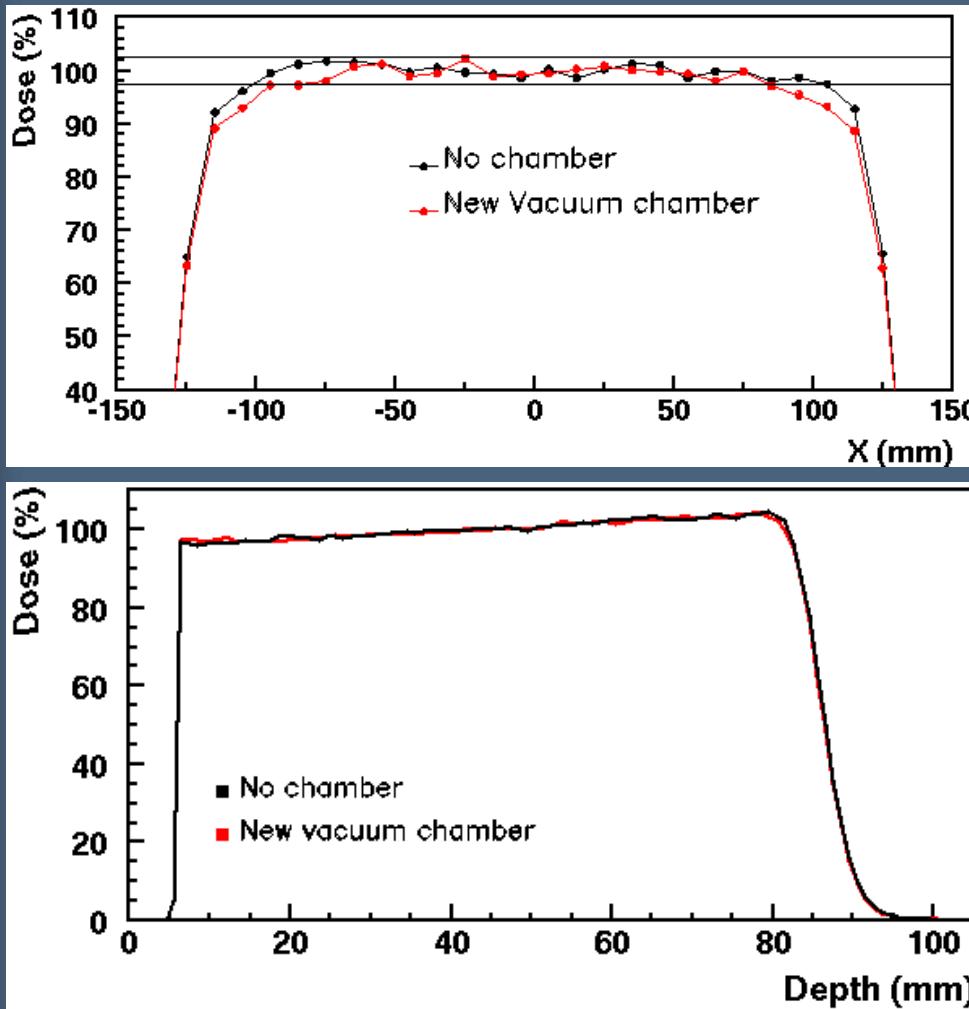
Top View



Side view



New chamber solution



Monte Carlo simulations

Field flatness is greatly improved, but there is still a reduction in the field diameter

Slope has good agreement
0.3% change in output factor



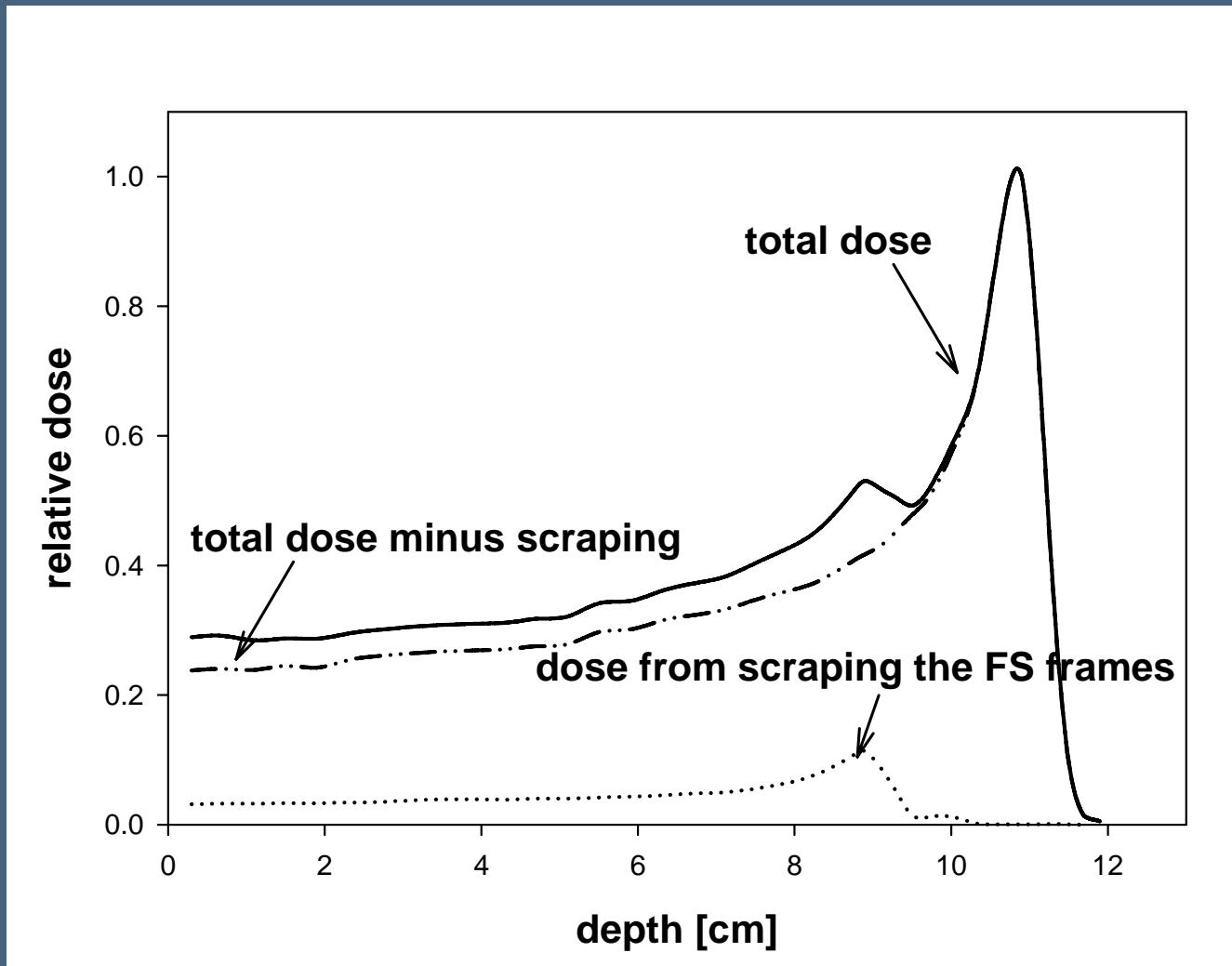
Geant4 application to proton radiation therapy

- Quality assurance



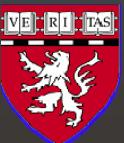
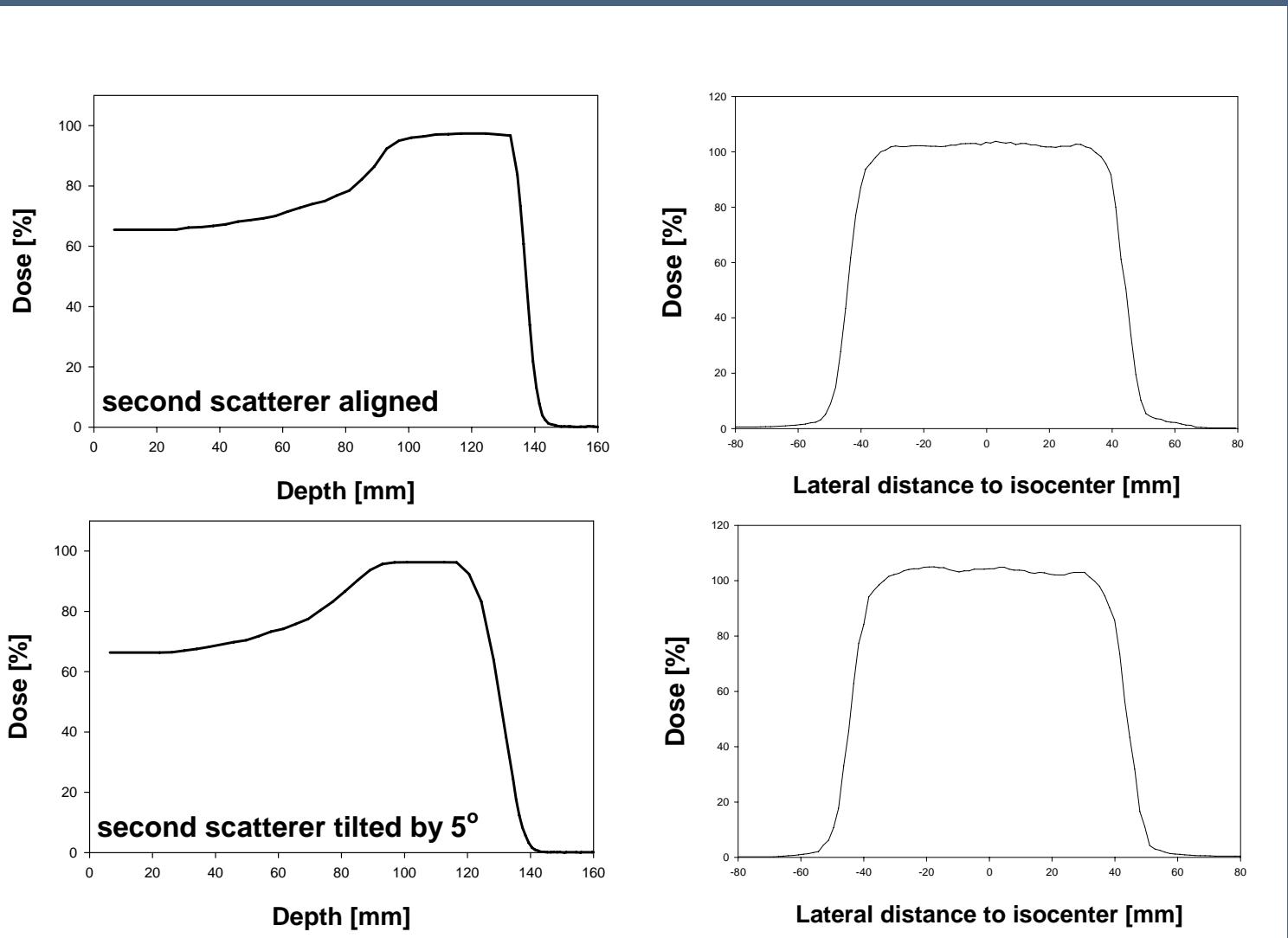
Examples: Quality Assurance / Tolerance Studies

Beam scraping (device alignment sensitivity)



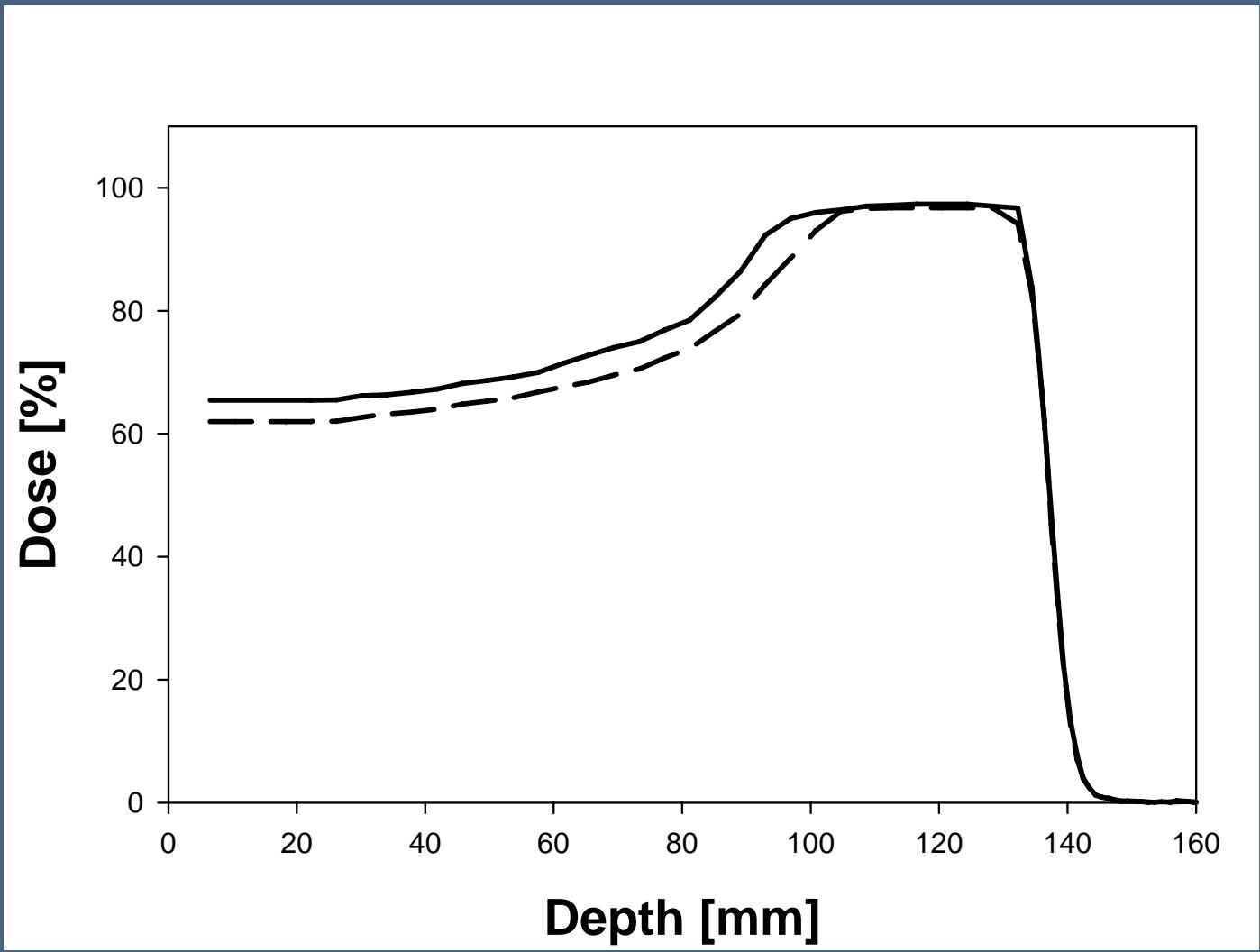
Examples: Quality Assurance / Tolerance Studies

Alignment of second scatterer



Examples: Quality Assurance / Tolerance Studies

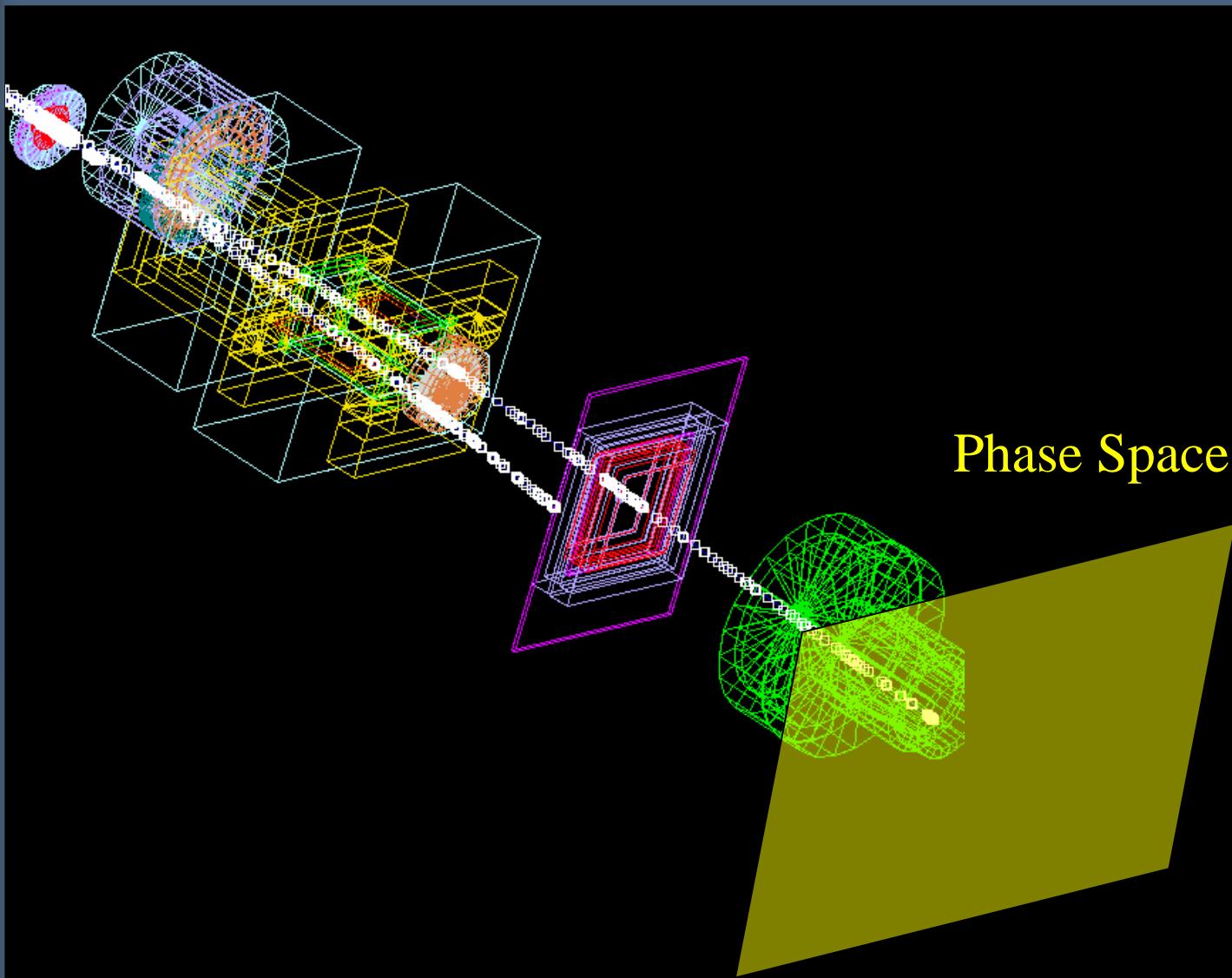
Wheel rotation potentiometer setting



Geant4 application to proton radiation therapy

- Phase space calculations



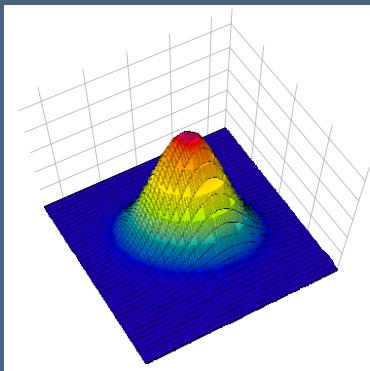


Phase Space Format Example: (part, x, y, p_x, p_y, p_z, flags ...)



Parameters to characterize the beam at nozzle entrance

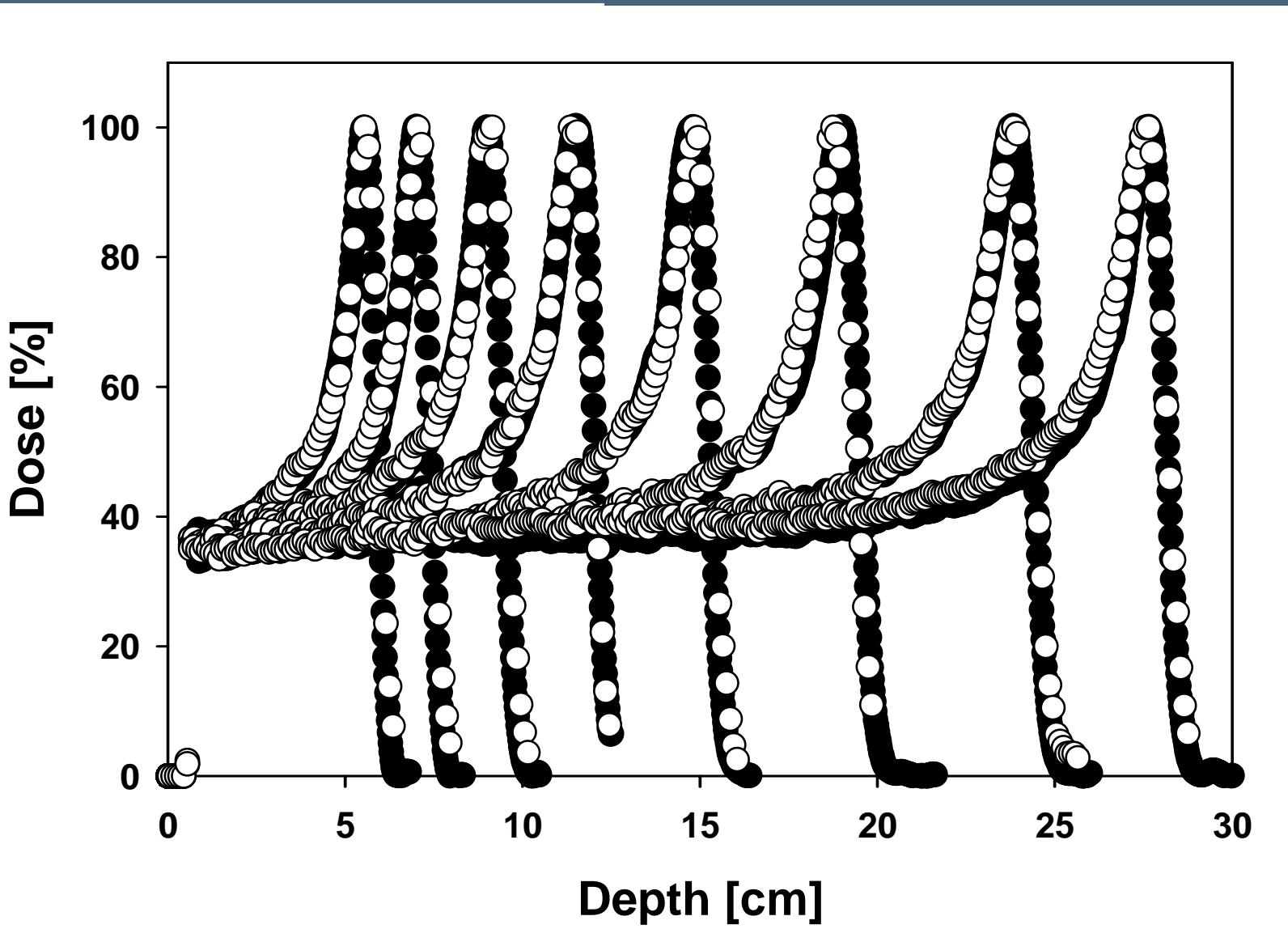
1. Beam size and spread (IC measurement)
2. Beam angular spread (manufacturer info)
3. Beam energy (control system)
4. Beam energy spread (manufacturer info, measured)

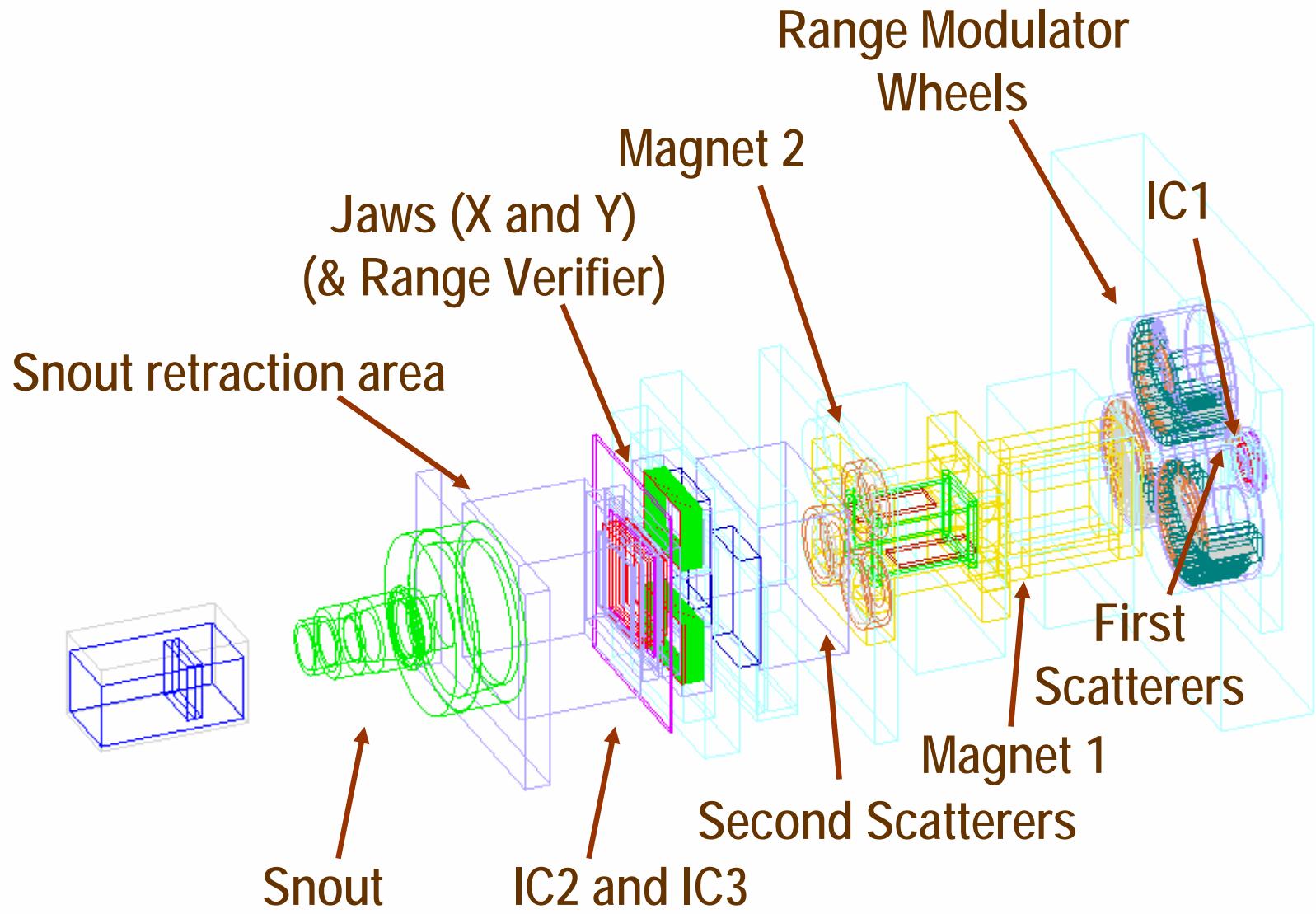


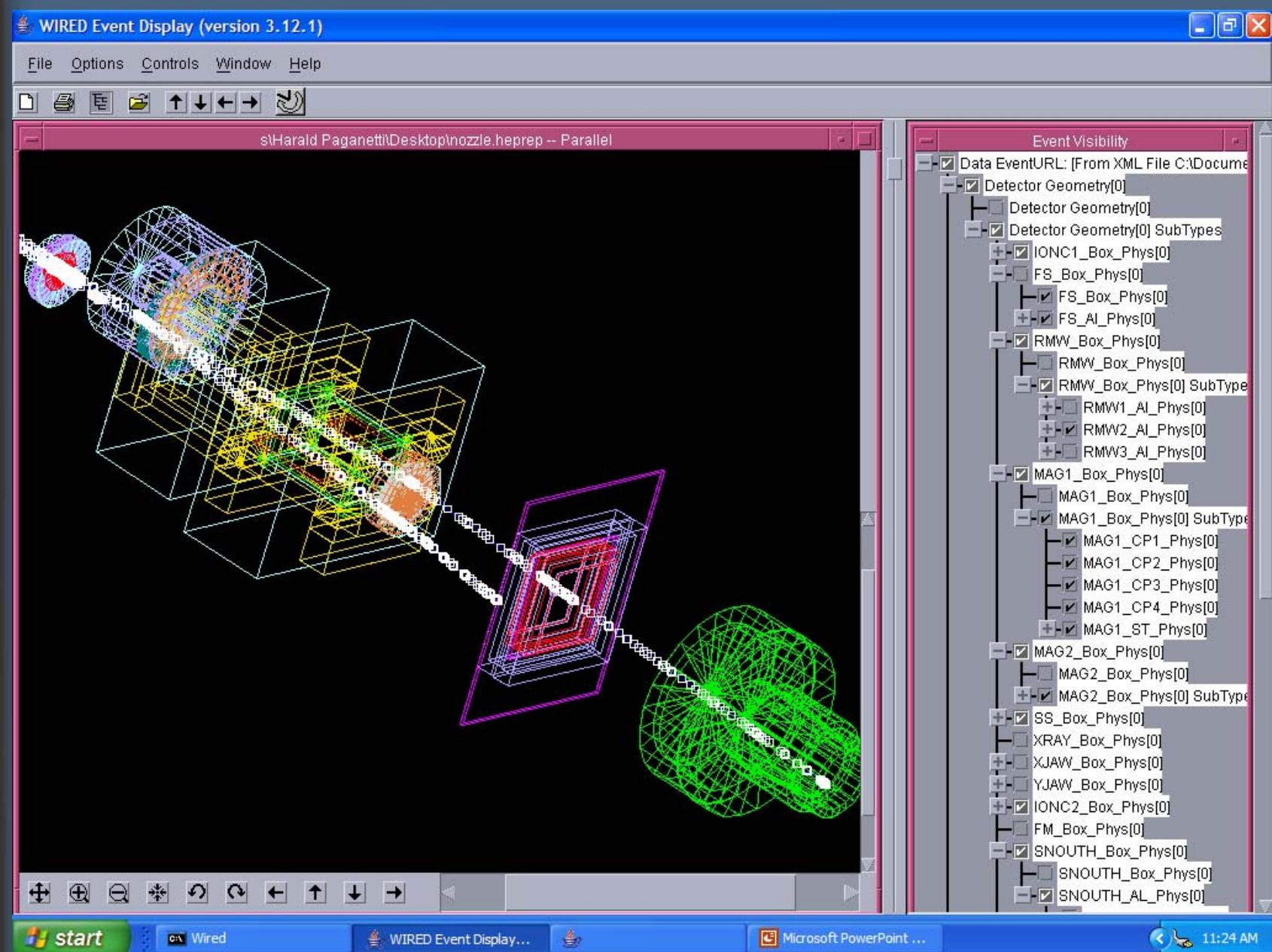
Are these parameters correlated ?



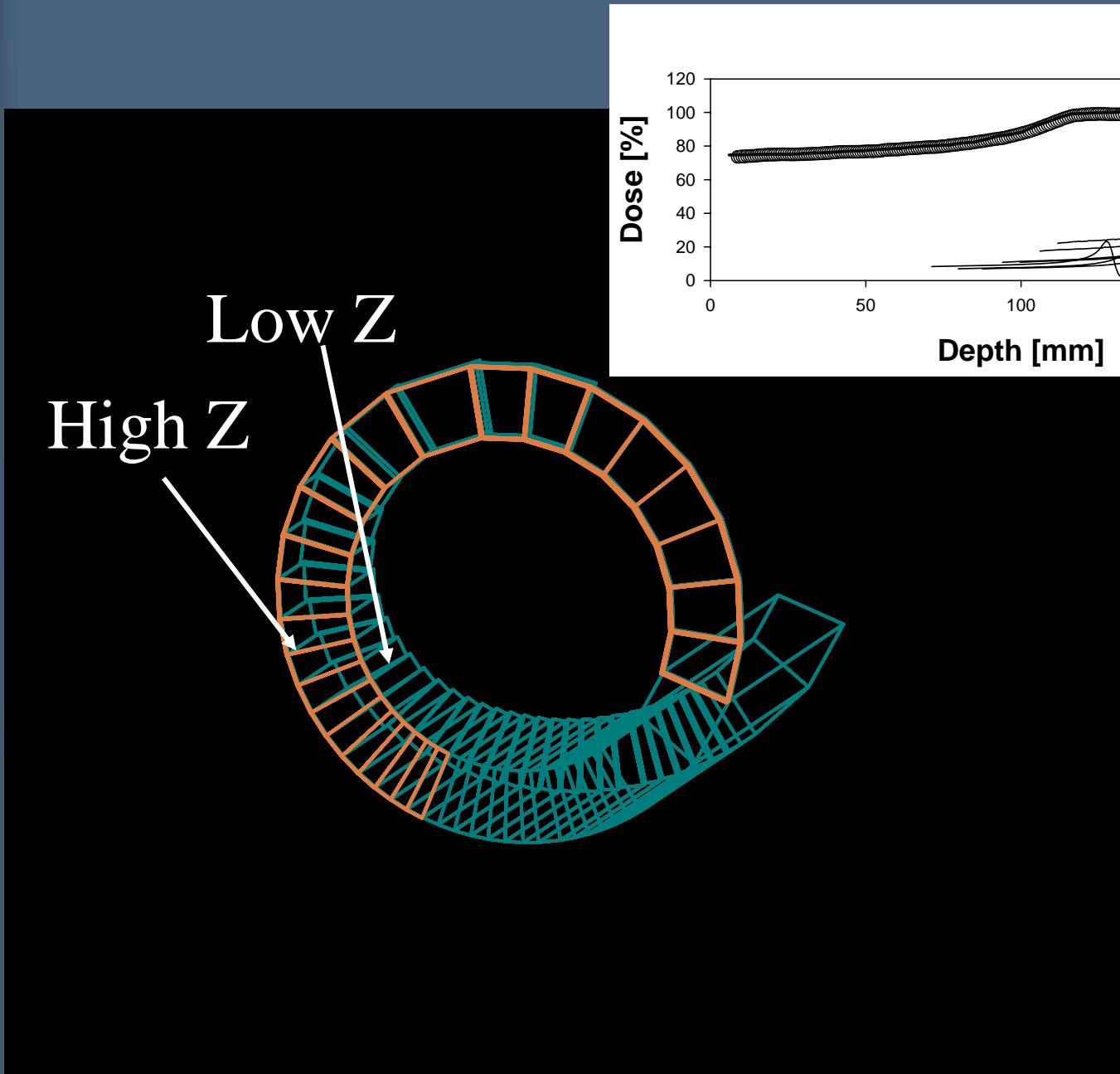
“Commissioning” of the Monte Carlo







Monte Carlo model of the nozzle (~1000 objects)
- Not patient specific -



Modeling time dependent geometrical setups

Key to 4D Monte Carlo:

Geometry changes during the simulation
via C++ class architecture based on **GEANT4**

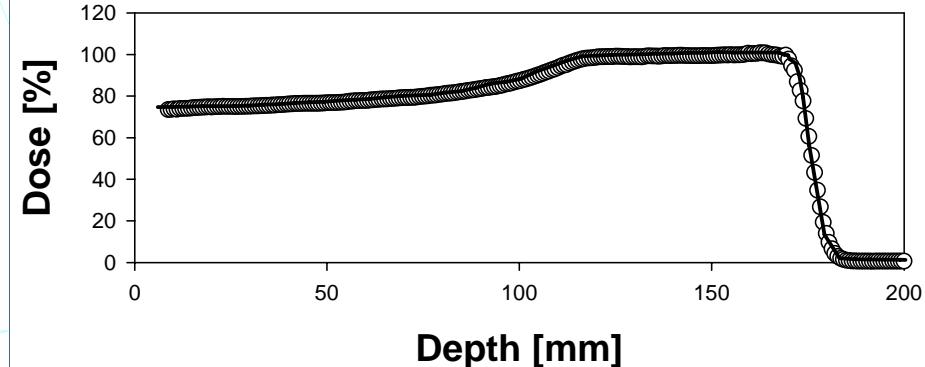
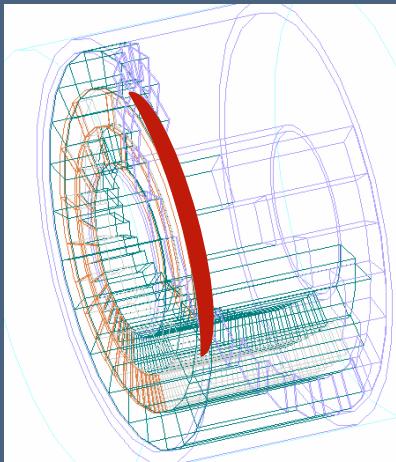
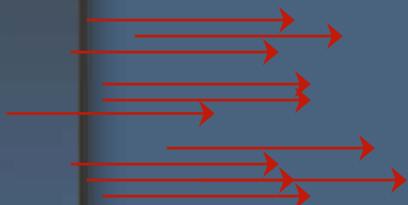
Geometry update command in *DetectorMessenger*
DetectorConstruction:

```
rot_RMW = new G4RotationMatrix();
rot_RMW->rotateZ(Wheel_angle*degree);
RMW_Phys -> SetRotation(rot_RMW);
G4RunManager* theRunManager = G4RunManager::GetRunManager();
theRunManager->DefineWorldVolume(WorldPhys);
theRunManager->GeometryHasBeenModified();
theRunManager->ResetNavigator();
```

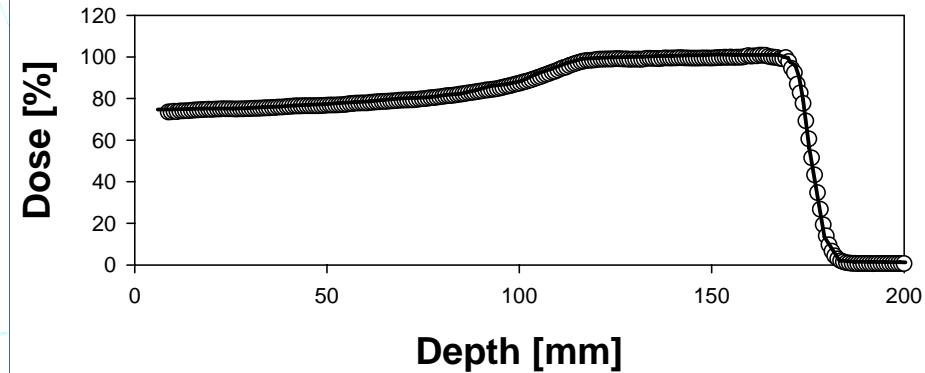
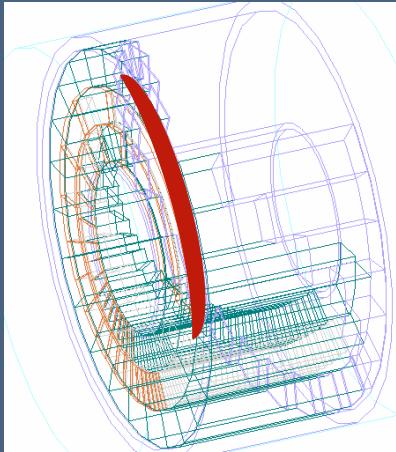
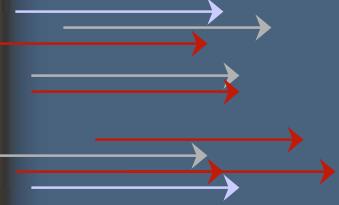


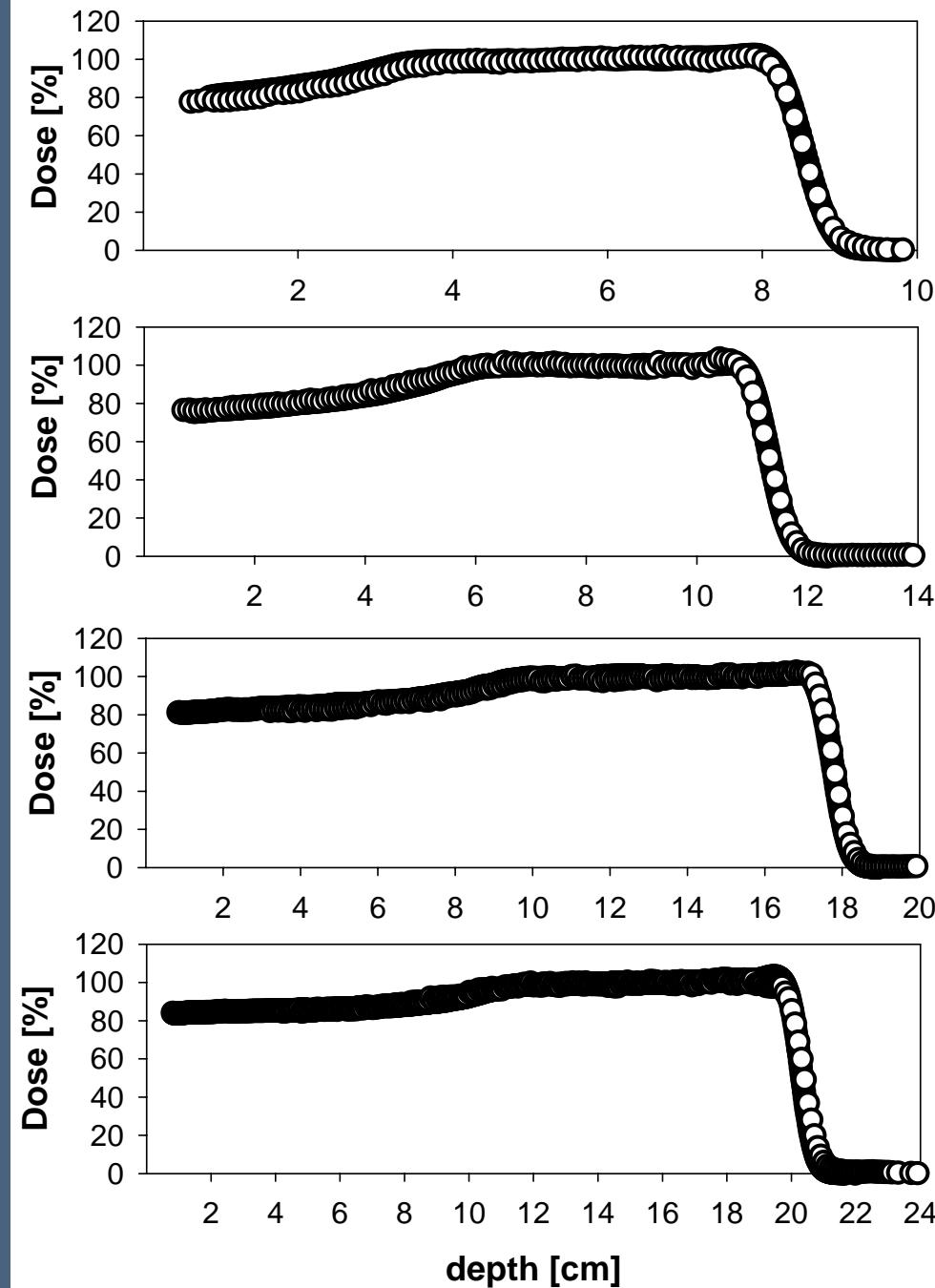
Range Modulator Wheel Issues

1. Beam Gating



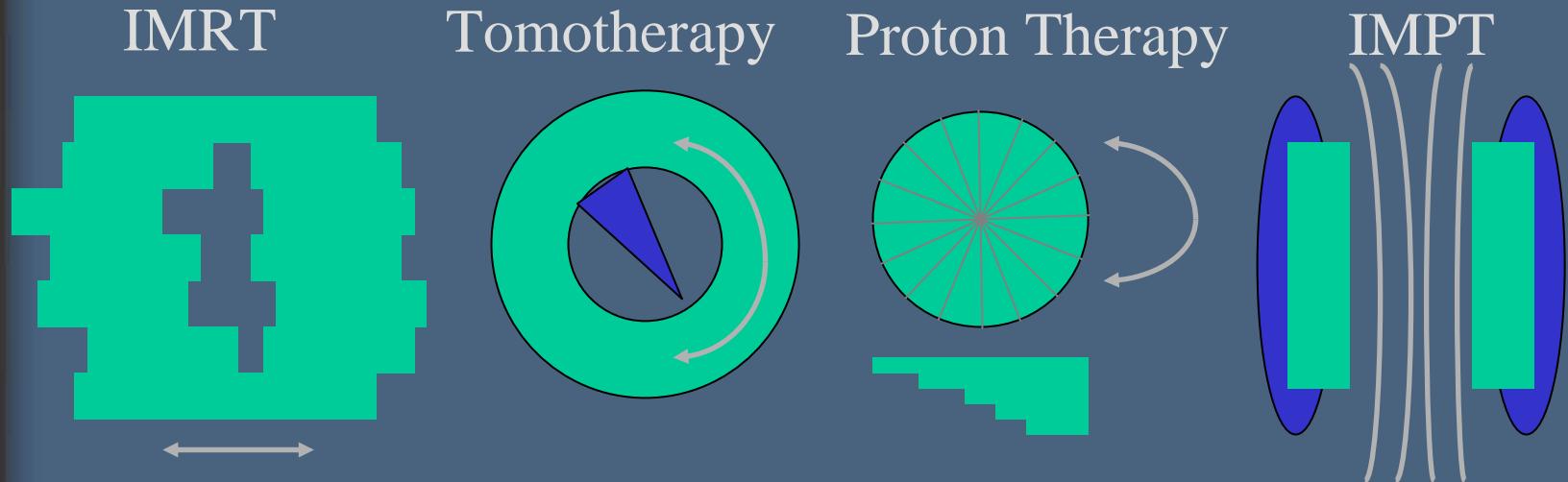
2. Beam Current Modulation





Dynamic Systems in Radiation Therapy

- Beam Delivery -



Types of variations:

IMRT: moving leafs

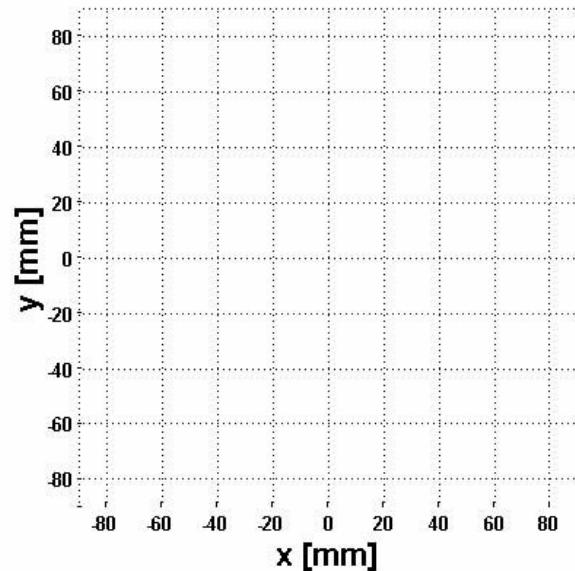
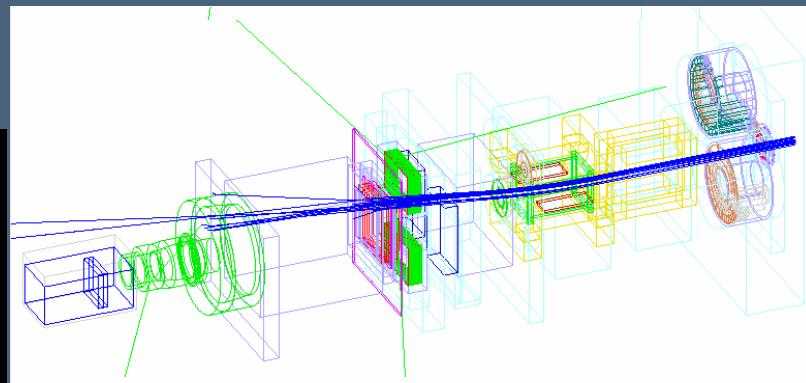
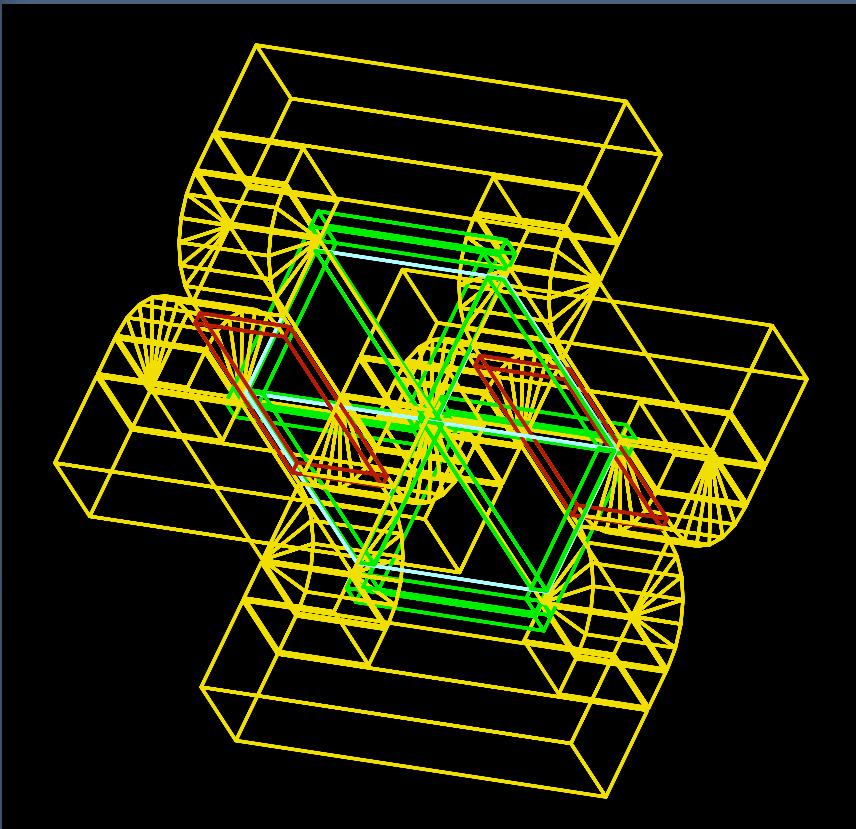
Tomotherapy: rotating beam

Protons: rotating wheel

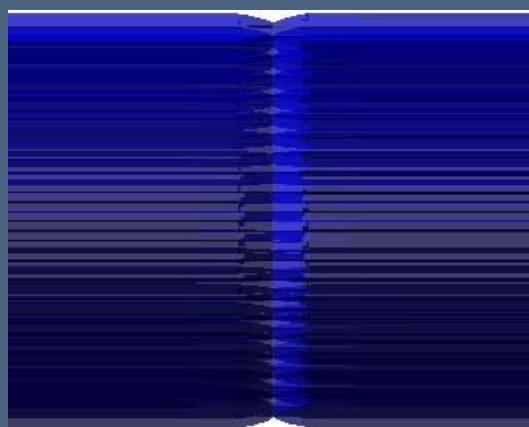
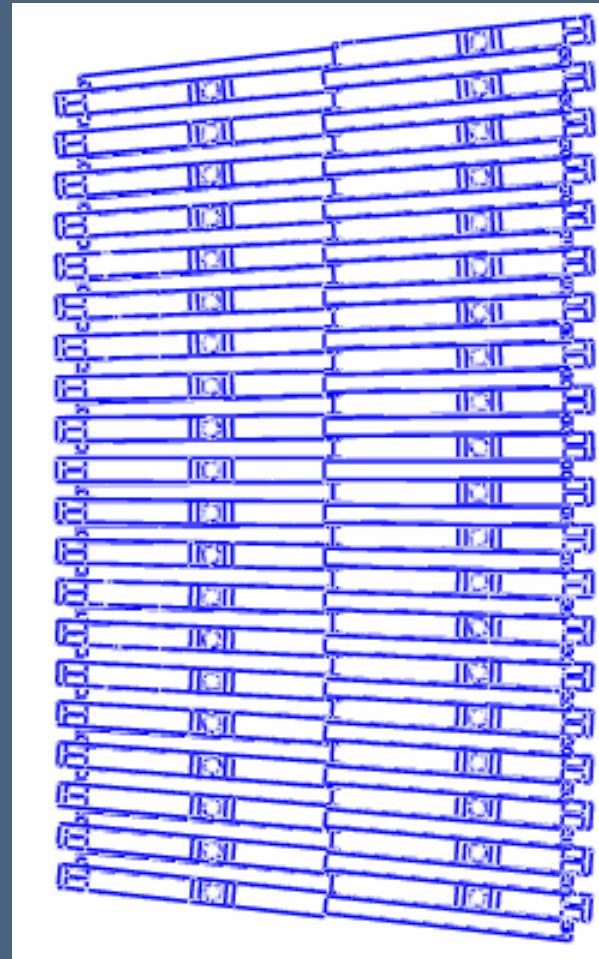
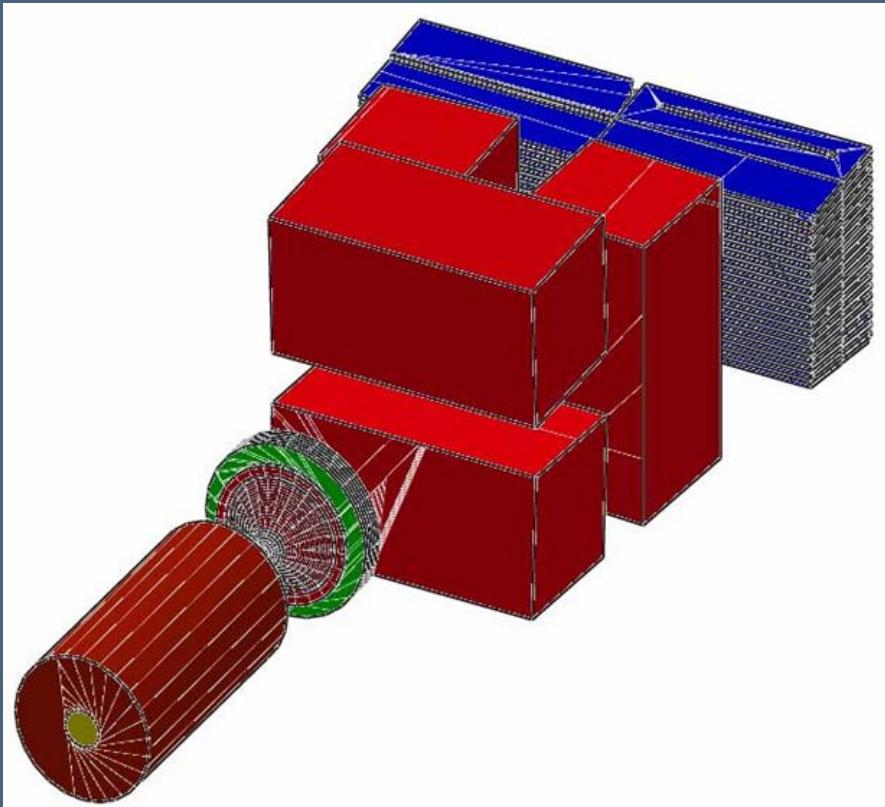
IMPT: changing magnetic field



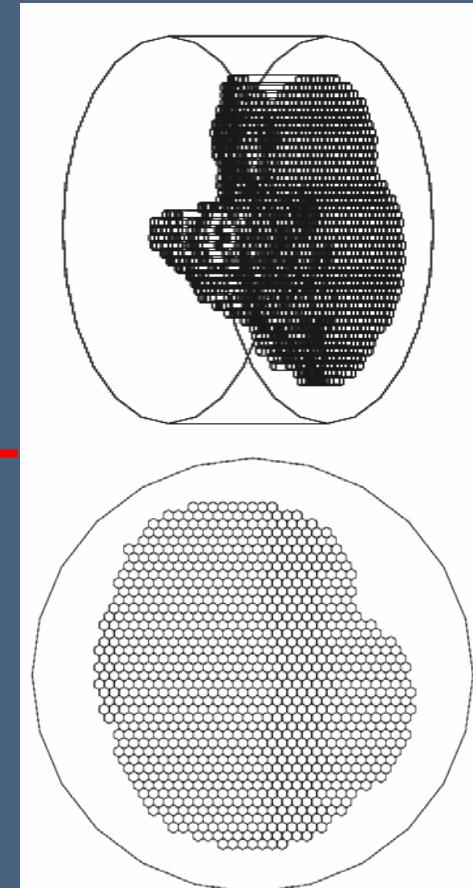
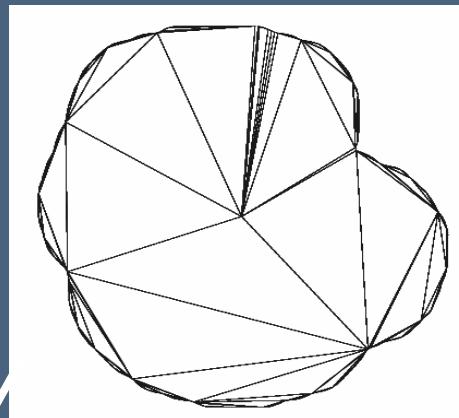
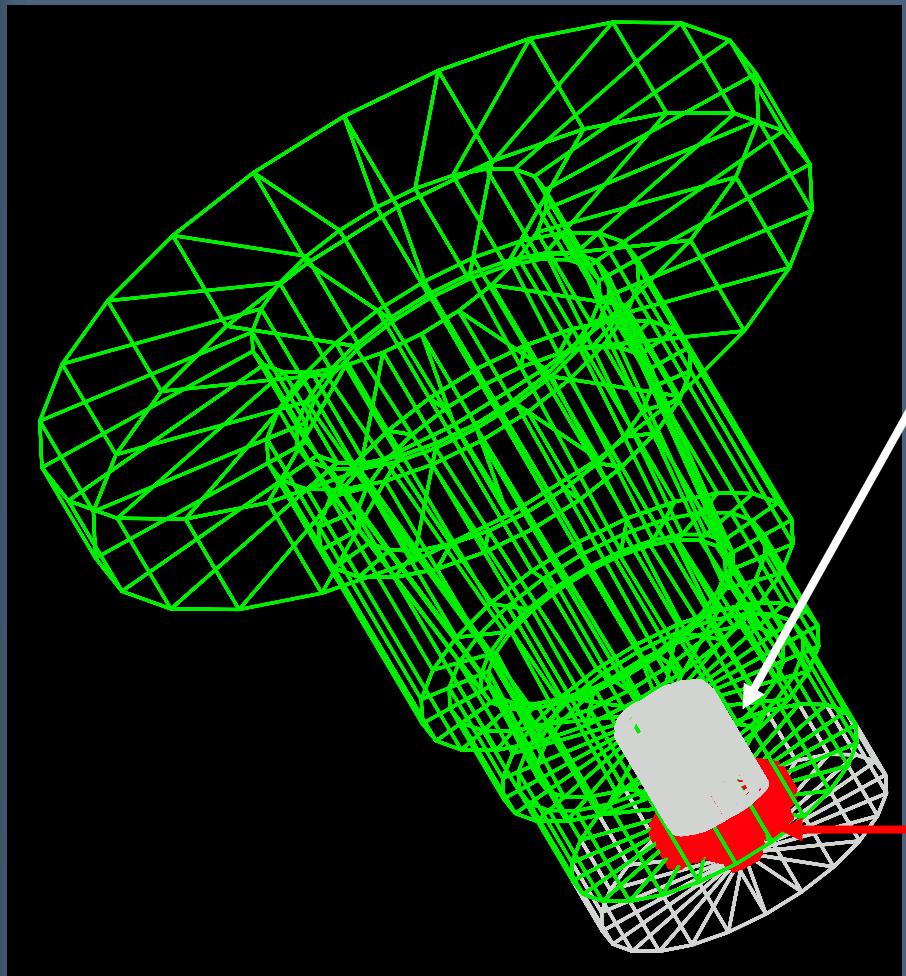
Scanning Magnet simulation



IMRT simulation



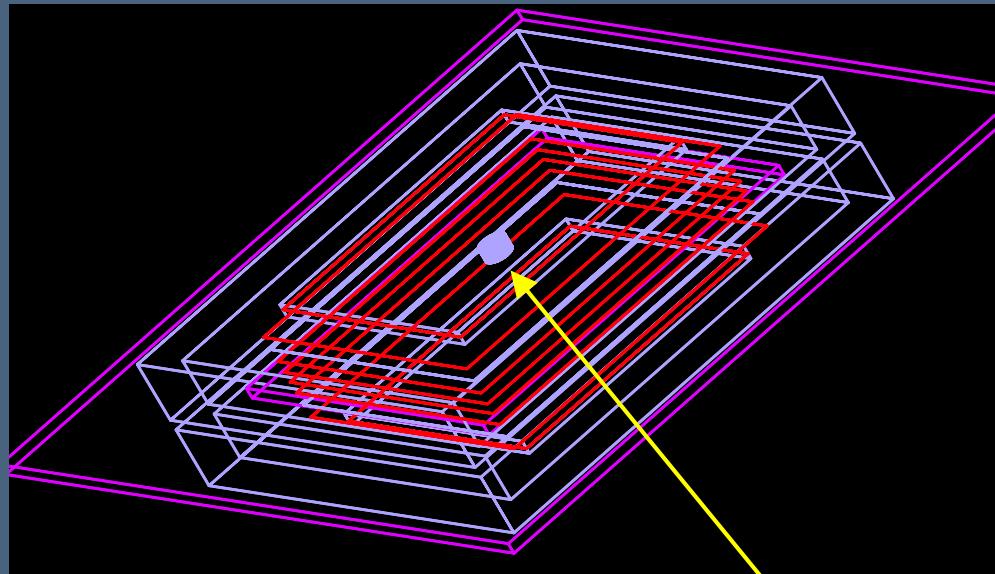
Aperture and Compensator



Monte Carlo simulation based
on milling machine files



Simulation of ionization chambers

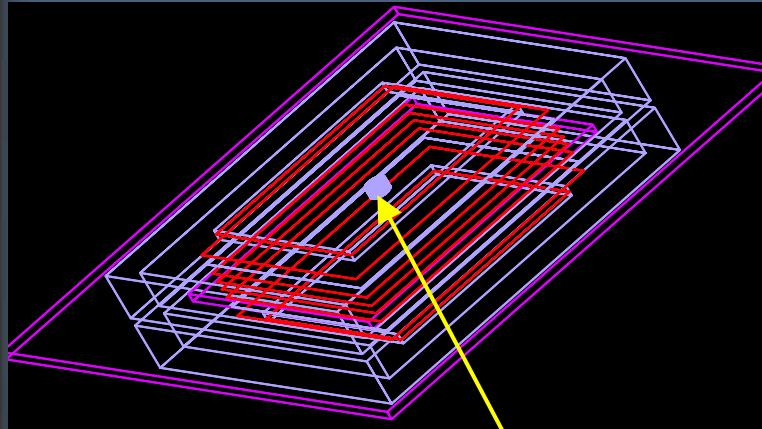


Volume for absolute dosimetry

$$\text{Output - Factor} \quad \simeq \quad \frac{D_{\text{cal}}}{i_{ic}} \left[\frac{cGy}{MU} \right]$$



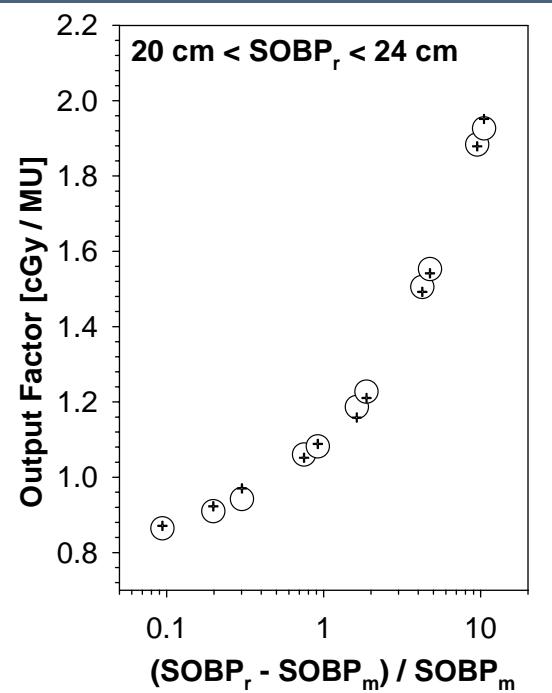
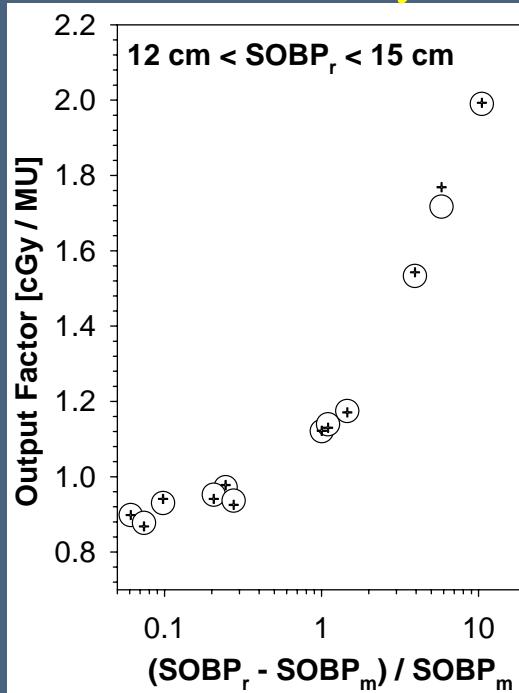
Absolute dosimetry (output factor prediction) by simulating the ionization chamber output charge



Volume for absolute dosimetry

$$\text{Output-Factor} \quad \equiv \quad \frac{D_{\text{cal}}}{i_{ic}} \left[\frac{\text{cGy}}{\text{MU}} \right]$$

$$i_{ic} = \frac{e \cdot \epsilon_{ic}}{W_{air}} \times \int \int \left(\frac{dE}{dx} \right)_{air} p \cdot d\xi dF$$



Geant4 application to proton radiation therapy

➤ Patient simulations



Patient information

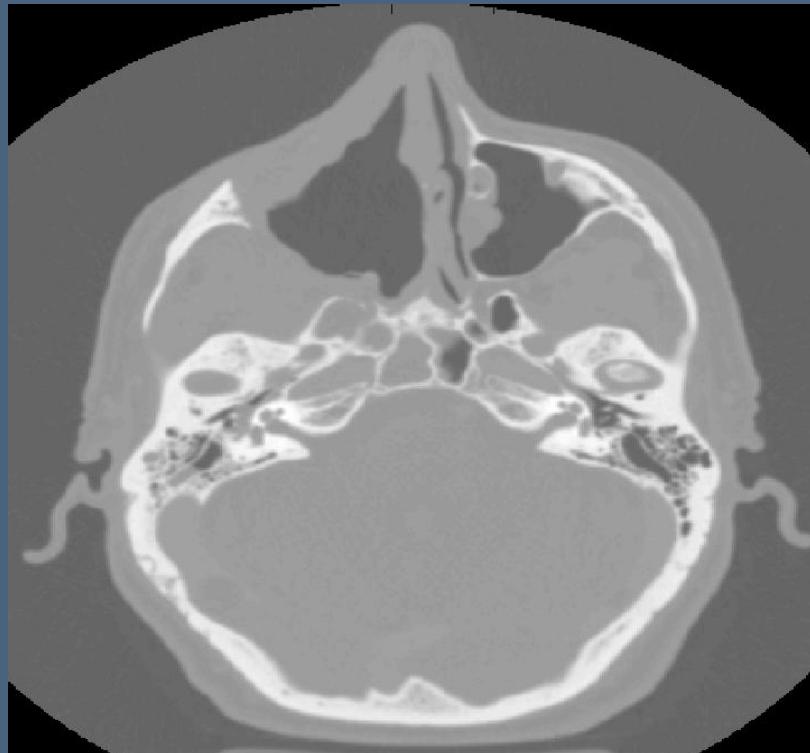
Example:

CT scan:

**134 CT slices, 512×512 voxels/slice
 $0.488 \text{ mm} \times 0.488 \text{ mm} \times 1.25/2.5 \text{ mm}$**

Treatment planning grid:

$2.0 \text{ mm} \times 2.0 \text{ mm} \times 2.5 \text{ mm}$



Issues related to dose calculations on CT data:

- Memory Consumption -

Solution within the Geant4 framework

- Parameterized volume:
allows the least computer memory usage for CT voxels (two bytes per voxel)

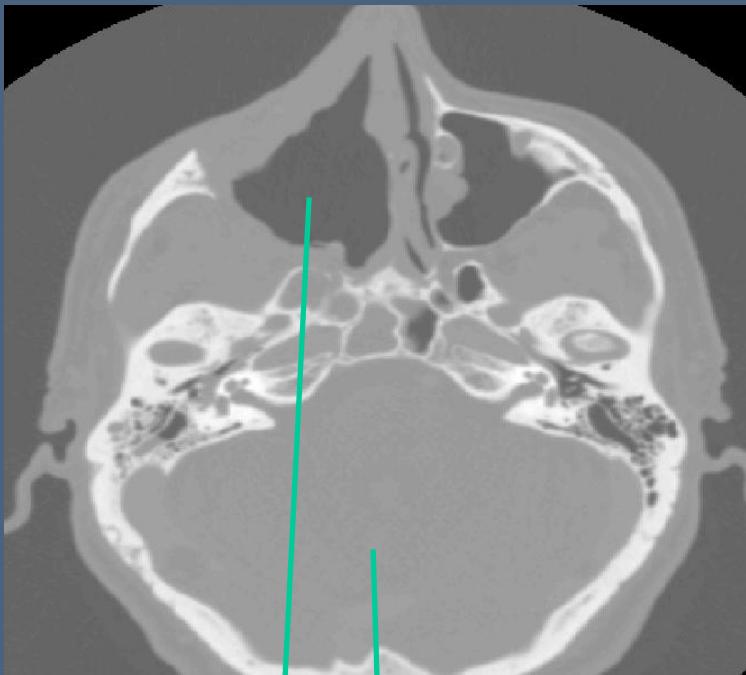
Modification of the Geant4 source code

Slow tracking through

- Much faster way to transport particles in CT voxels
Abandoning the general, but low-efficient algorithm in GEANT4.

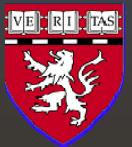


CT conversion



Density and Material composition

Density and Material composition



Issues related to dose calculations on CT data:

– CT conversion –

Solution within the Geant4 framework

- Solution:
HU space is divided into 27 groups with members of each group sharing the same element composition but differ in mass density

Modification of the Geant4 source code

- Dynamic assignment of mass density
Only one material is defined for each CT HU group.
The composition of the material is preserved, but the mass density varies



– HU conversion –

Group	HU range	Density [g/cm ³] (center of HU bin)	Density correction	Material composition weights [%]							Ca	Ti			
				H	C	N	O	Na	Mg	P	S	Cl	Ar	K	
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			0.1
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

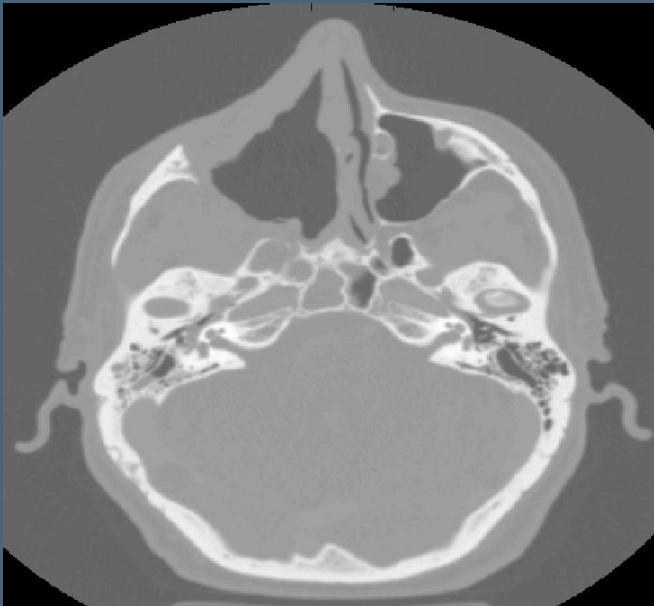


Gantry Angle



Position XYZ
Rotation
Pitch
Roll

Air Gap



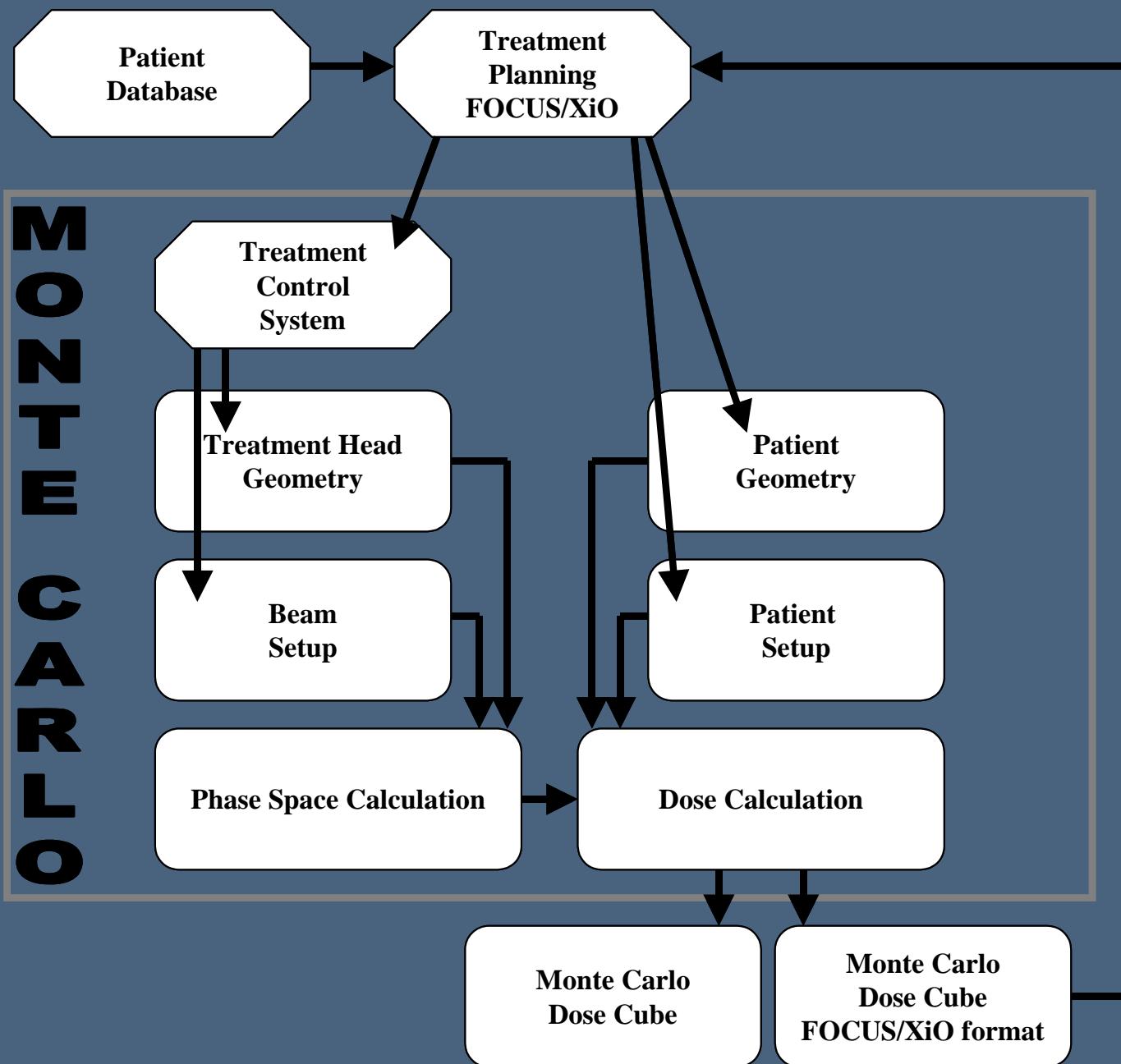
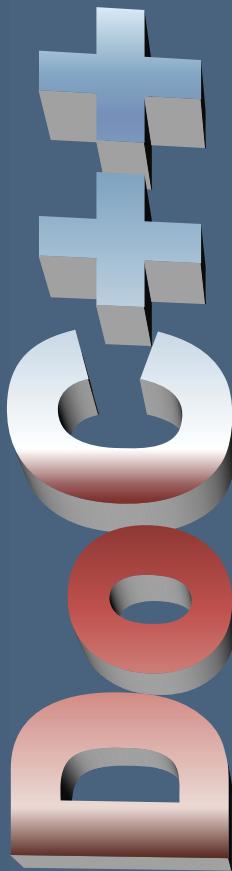
	Gantry	Couch	ISO
AP1A	0°	0°	1
AS1A	65°	270°	1
RS1A	305°	50°	1
RA1A	295°	0°	2
RS2A	300°	60°	2
AS2B	90°	270°	3



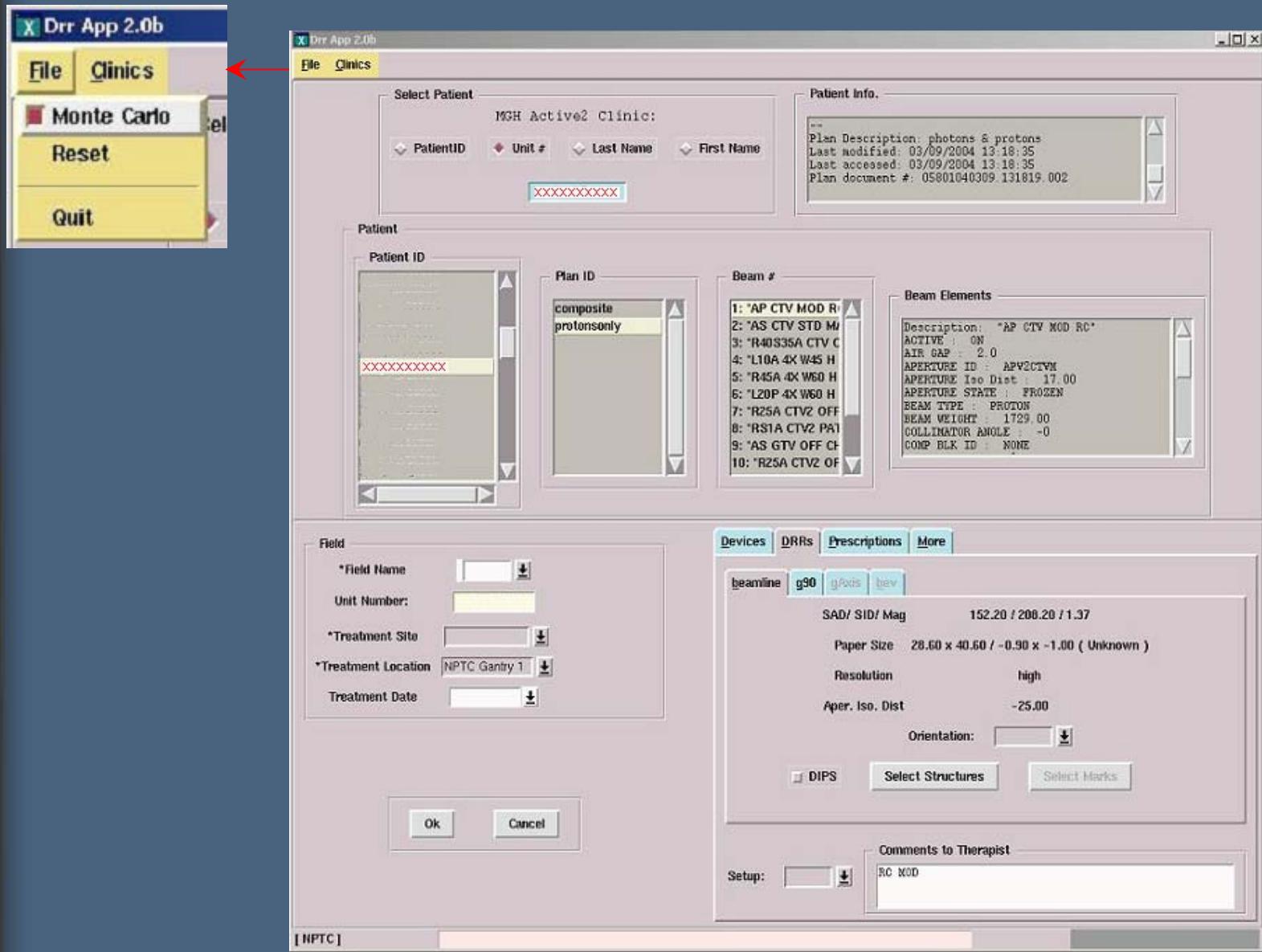
Geant4 application to proton radiation therapy

➤ Clinical use





GUI program



Logistics

Hardware @ MGH:

Linux cluster with 70 processors

Runtime per patient (using 20 processors):

5 hrs (~2.5% stat. accuracy in the GTV)

→ ~4 hrs for treatment head

→ ~1 hr for patient

based on simulation of the entire plan



No sophisticated variance reduction techniques used
Full physics

Example 1

Case 1:

Para-spinal tumor

176 x 147 x 126 slices

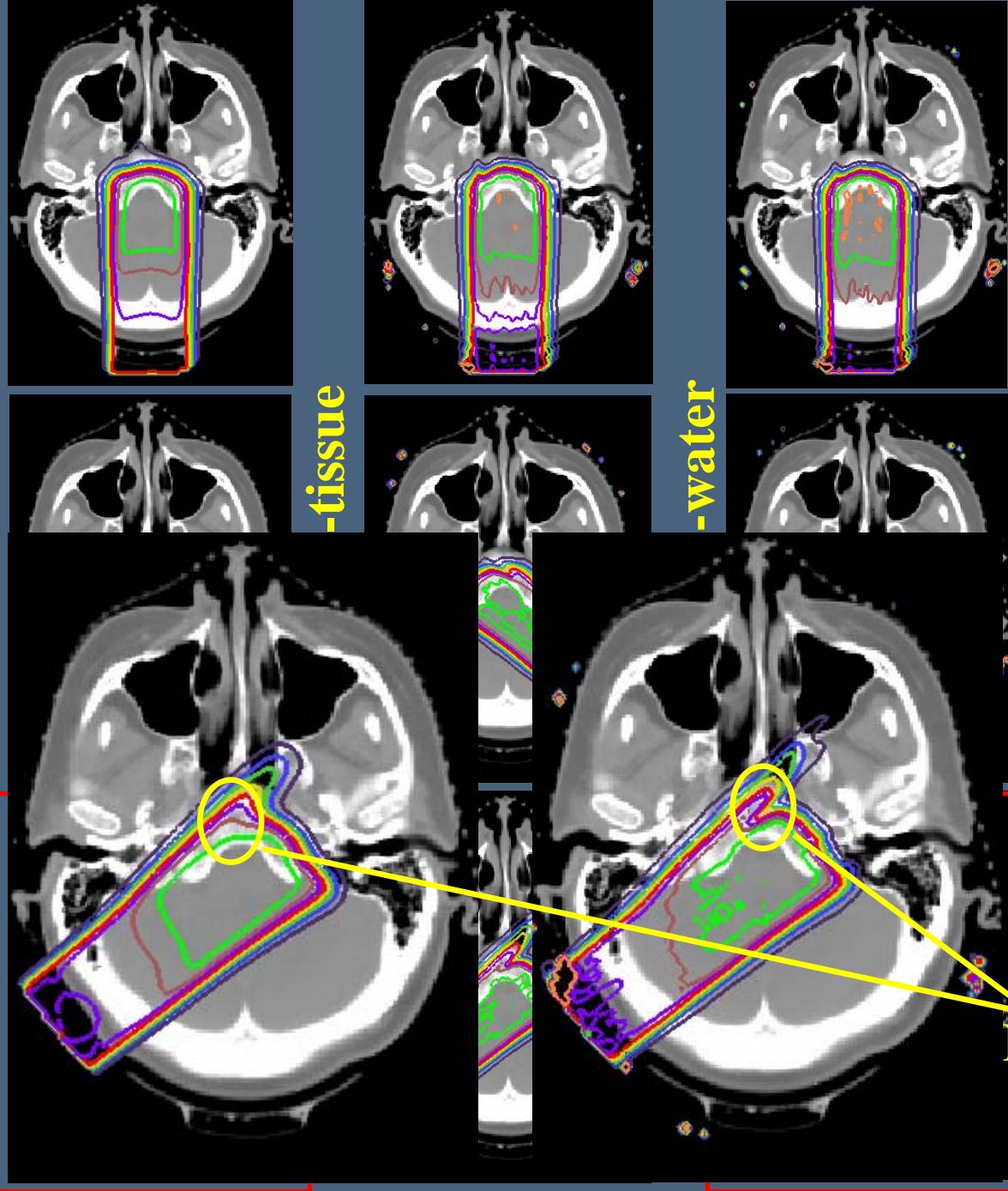
voxels: 0.932 x 0.932 x 2.5-3.75 mm³

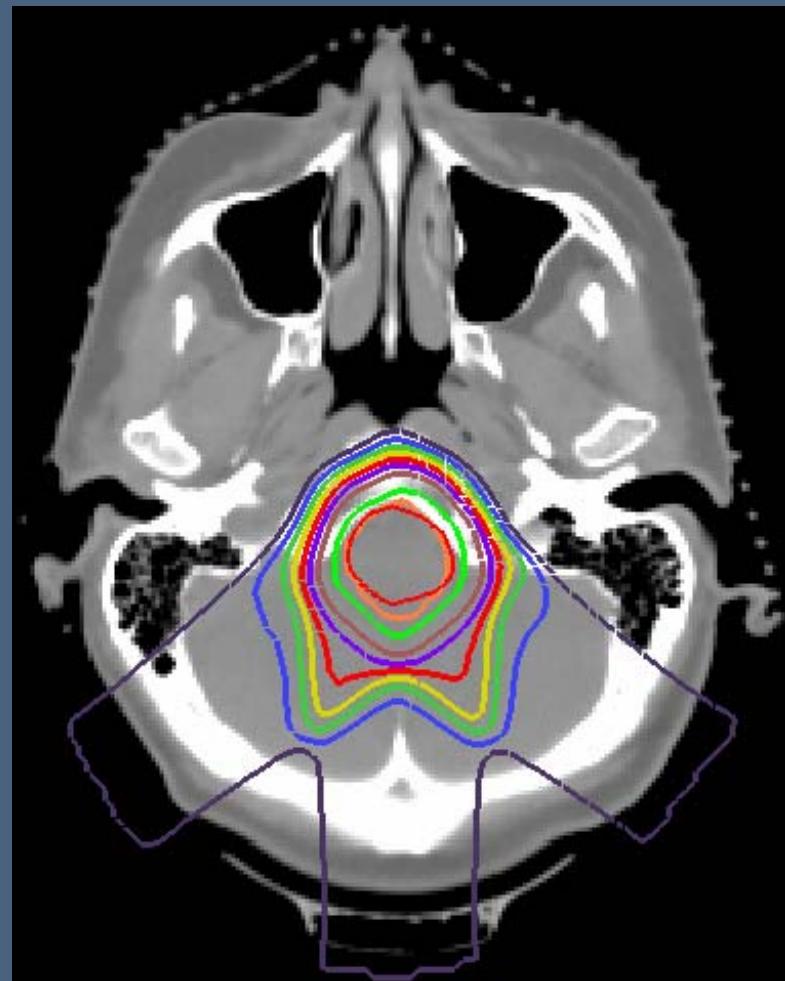
3 fields: ~15.0 Gy each





PB Dose-to-water

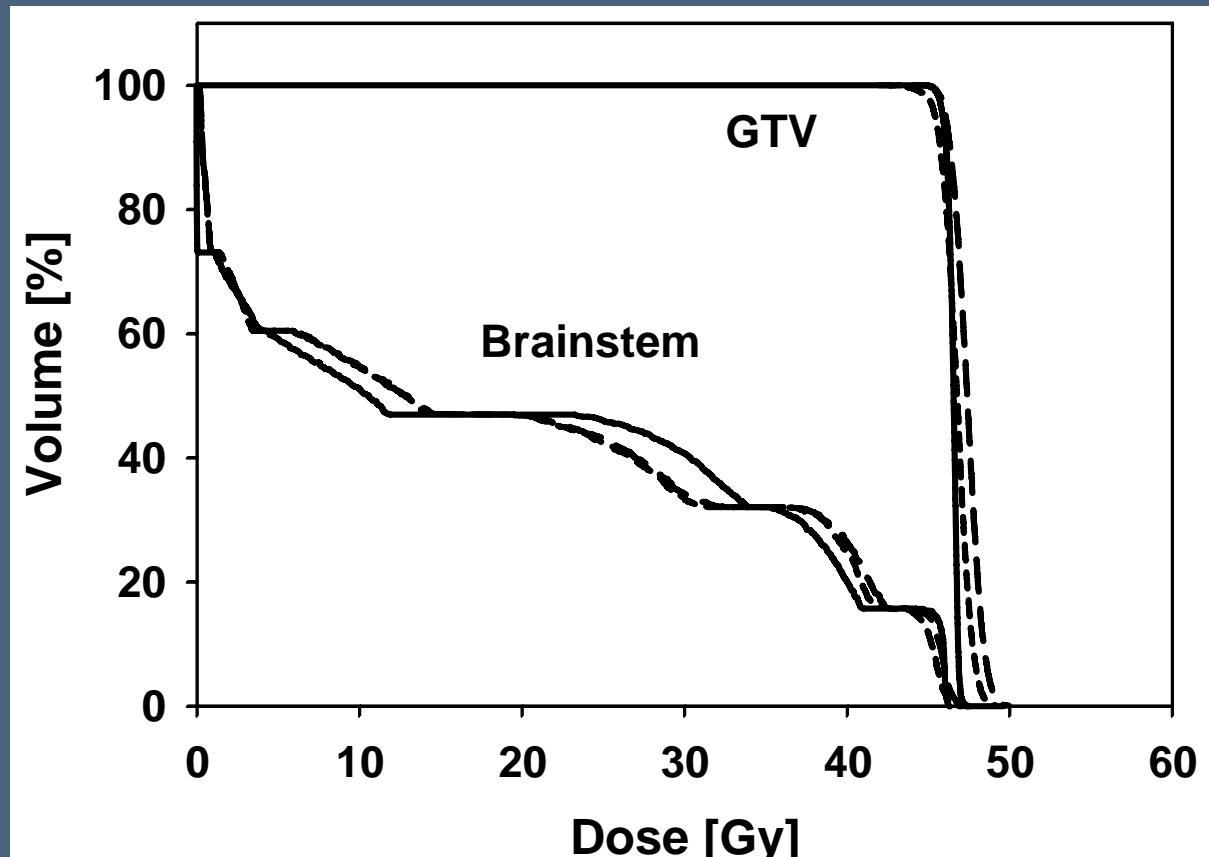




- █ 10 Gy
- █ 15 Gy
- █ 20 Gy
- █ 25 Gy
- █ 30 Gy
- █ 35 Gy
- █ 40 Gy
- █ 45 Gy
- █ 46 Gy

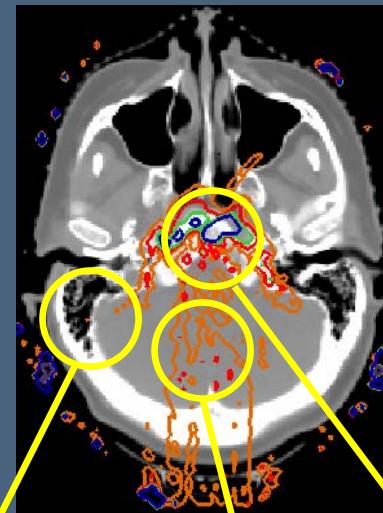
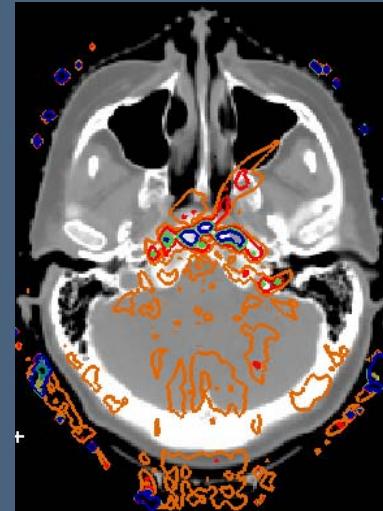
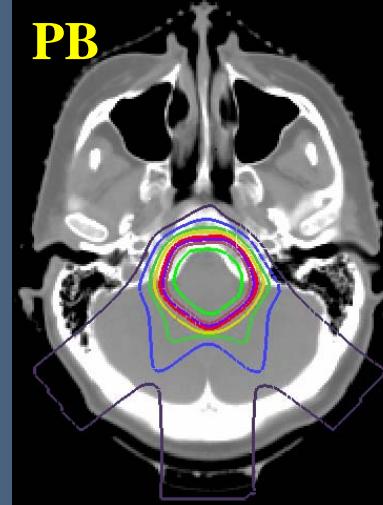
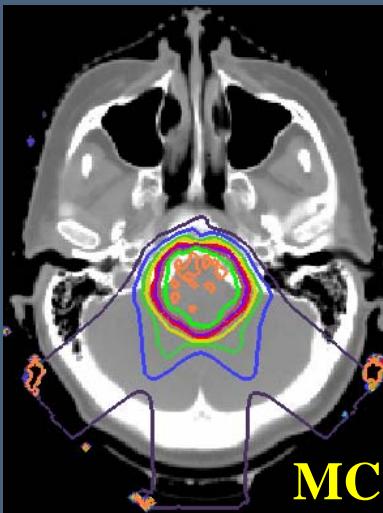
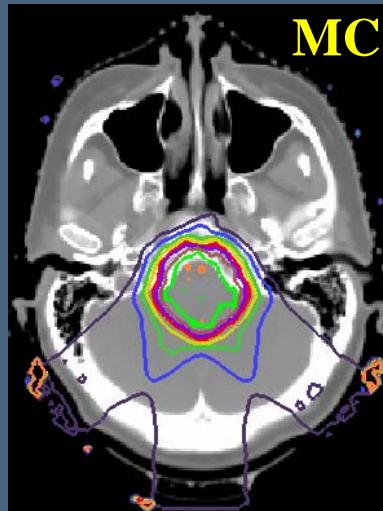


Total DVH



— XiO - - - MC (DTW) - - - - MC (DTT)



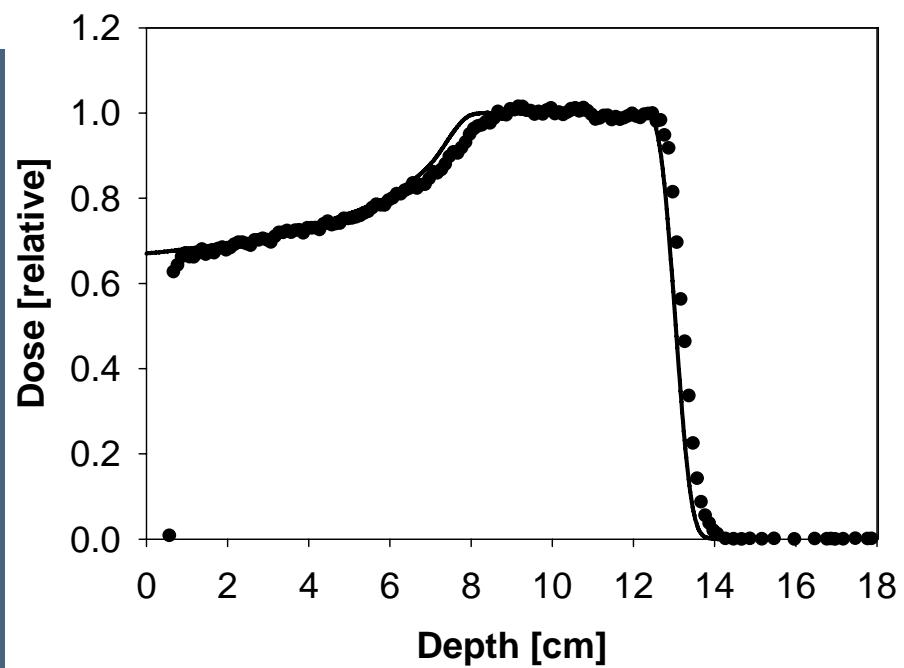
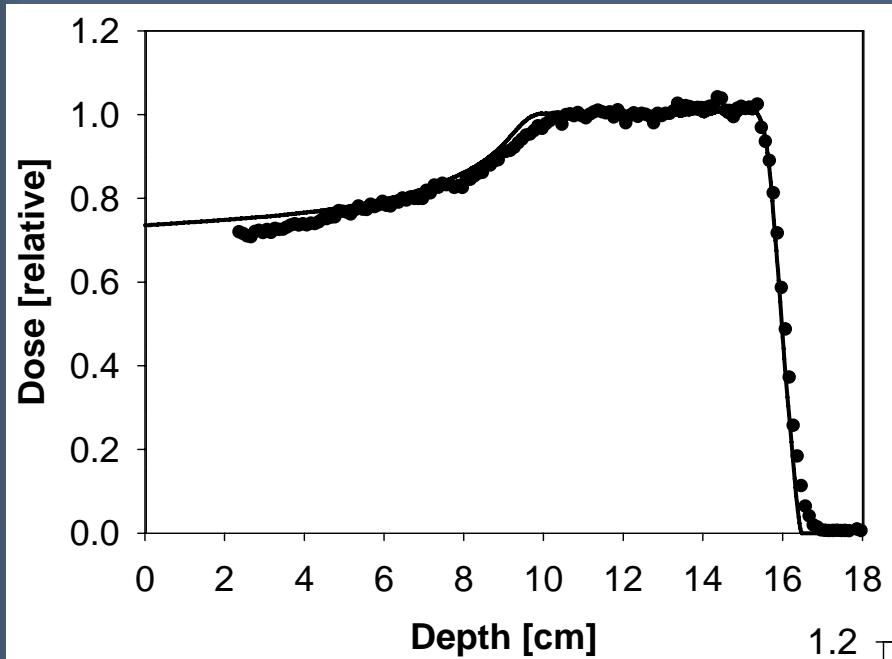


Penumbra

Range

Dose homogeneity

Planned SOBP versus delivered SOBP



Example 2

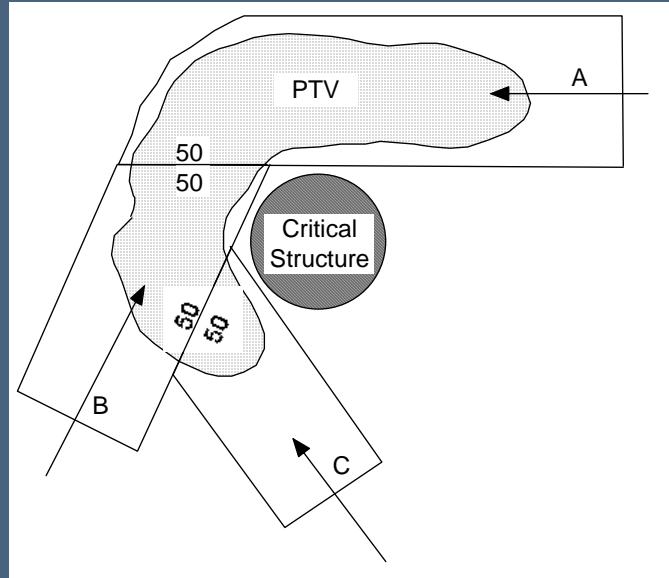
Case 3:

Maxillary sinus

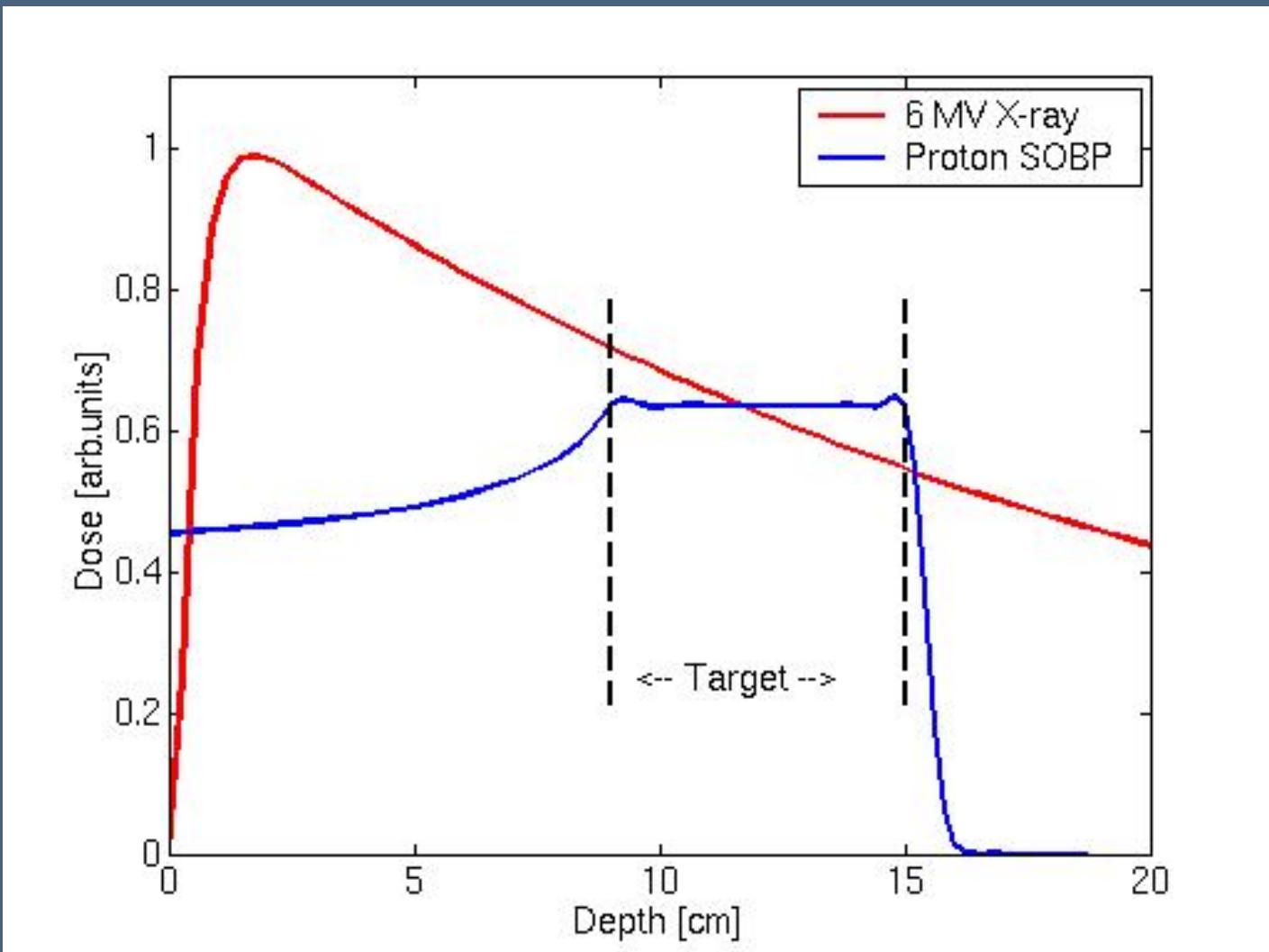
121x121x101 slices

voxels: $0.656 \times 0.656 \times 1.25\text{-}3.75 \text{ mm}^3$

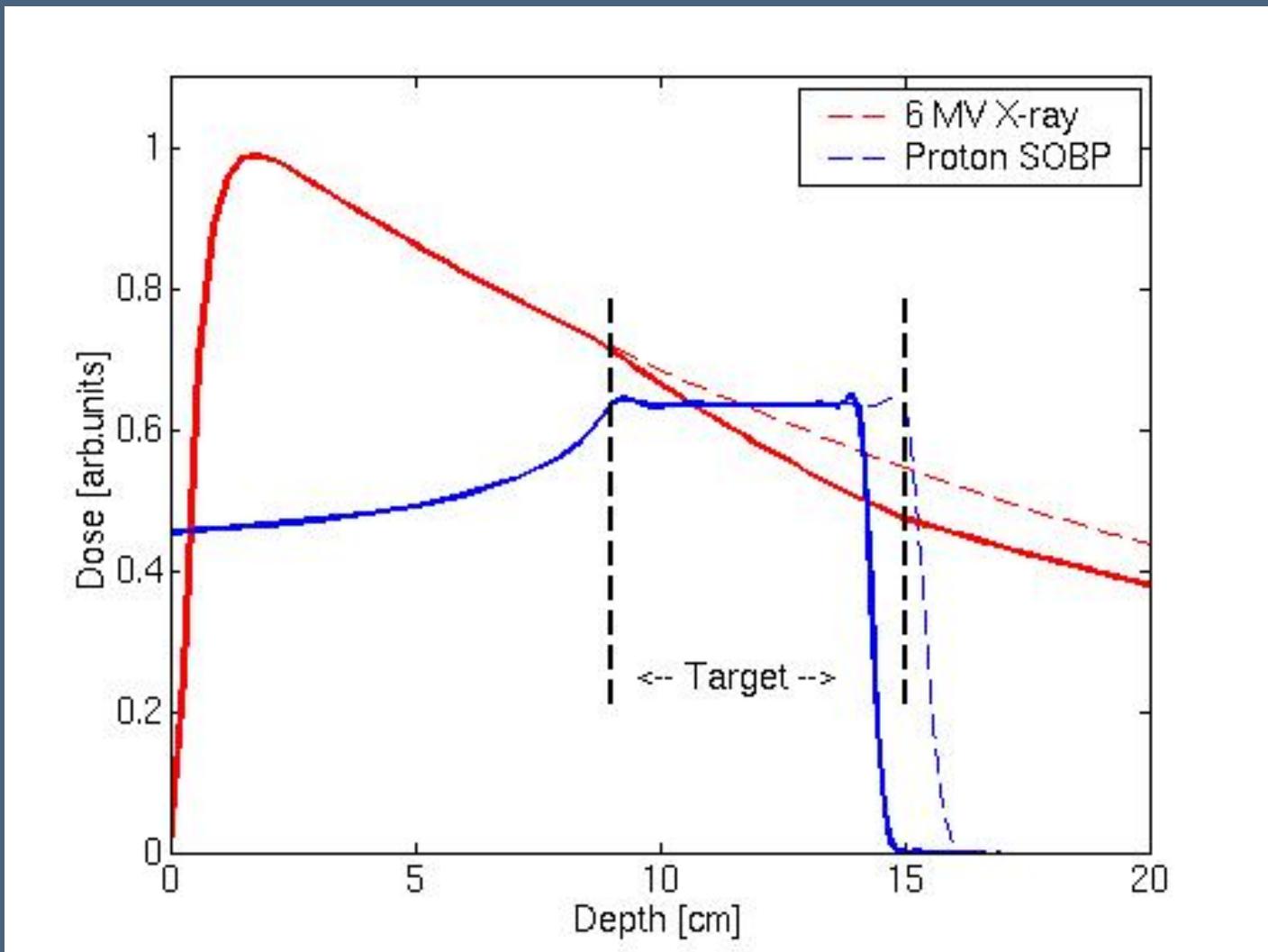
19 fields: 15 protons + 4 photons

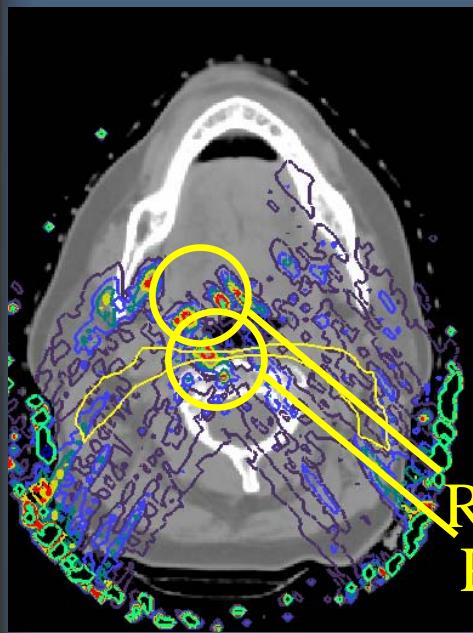
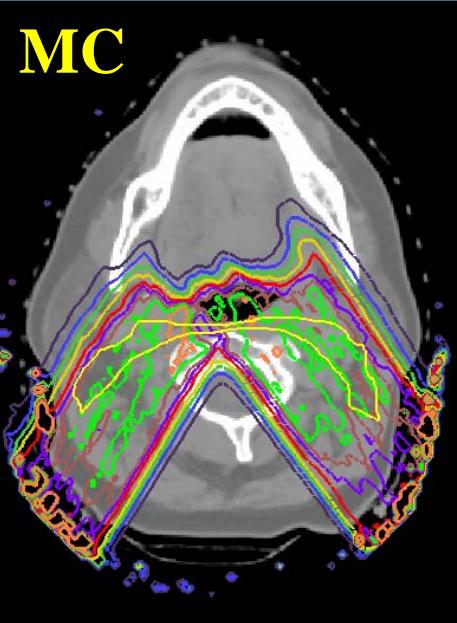
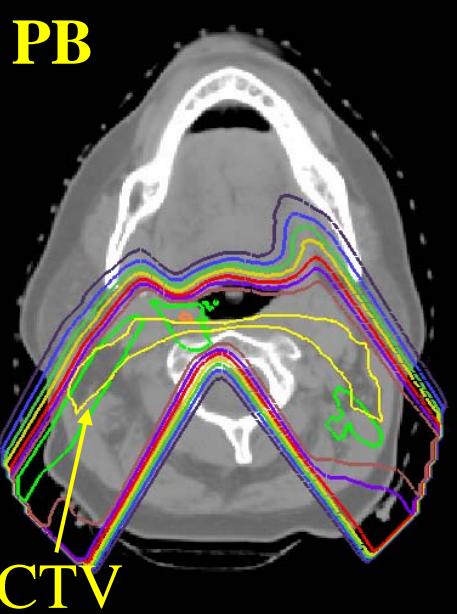


Proton dose in the presence of range uncertainty

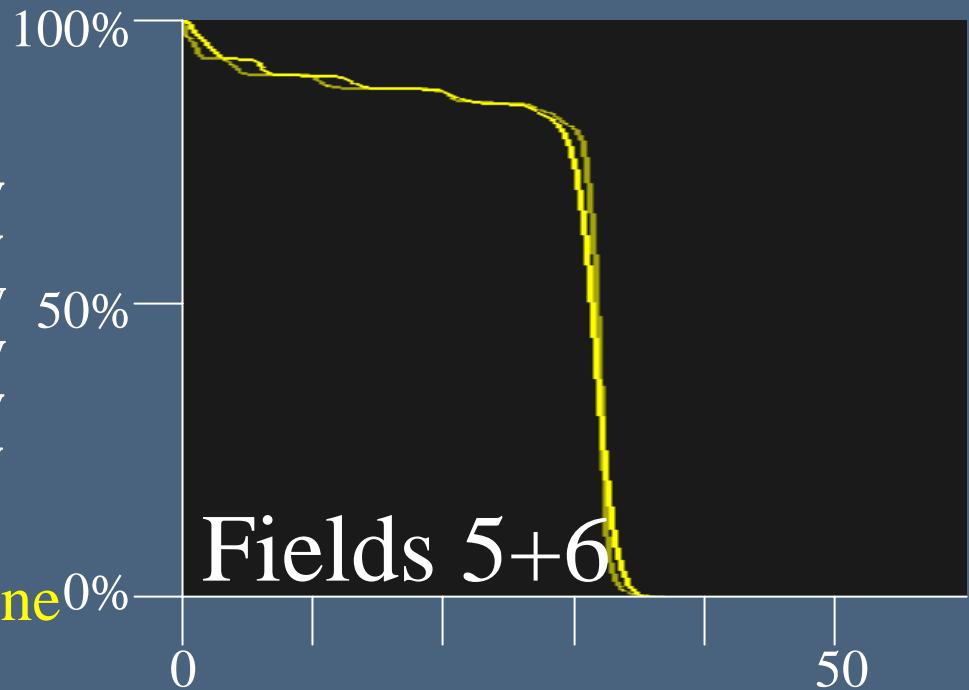


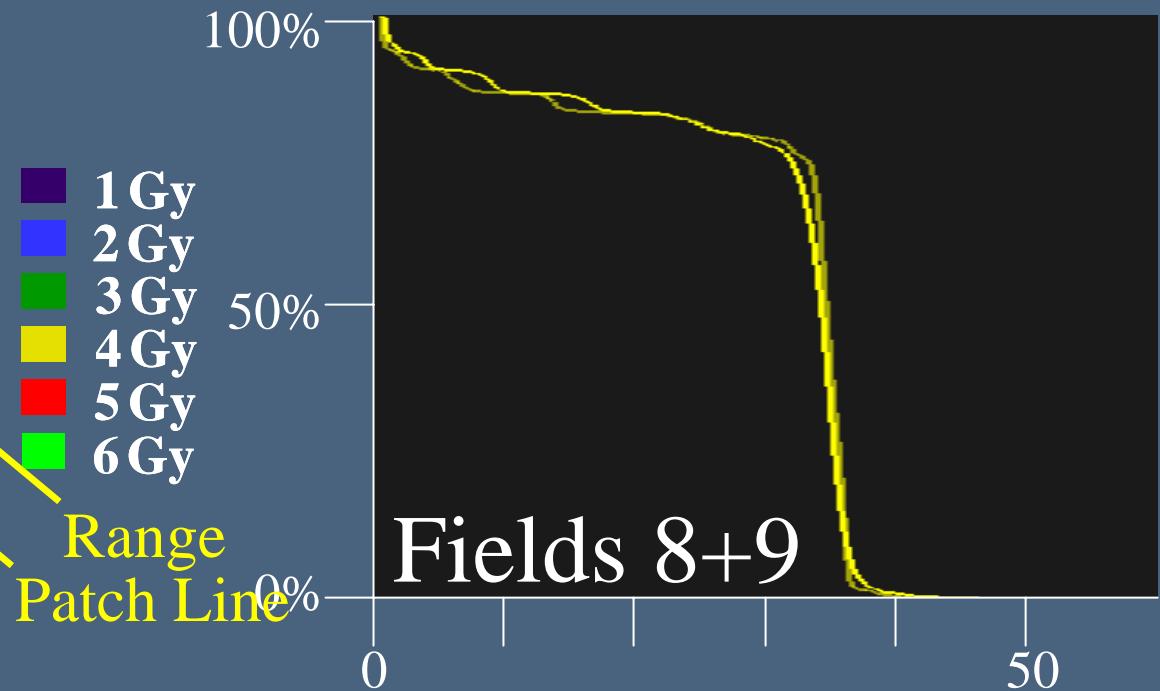
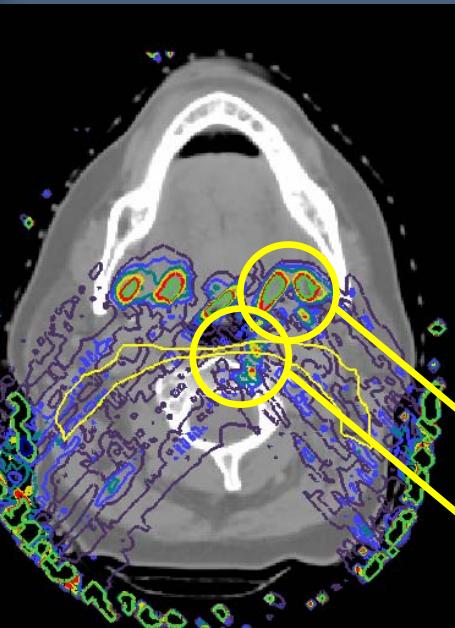
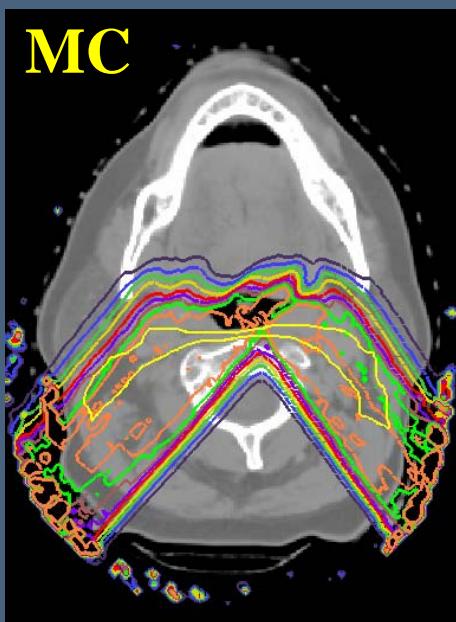
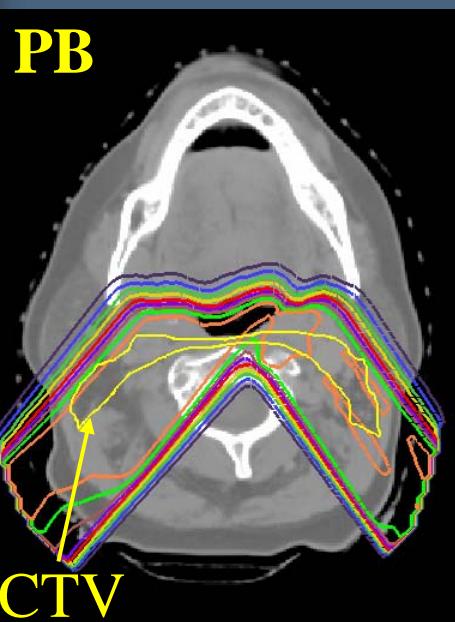
Proton dose in the presence of range uncertainty

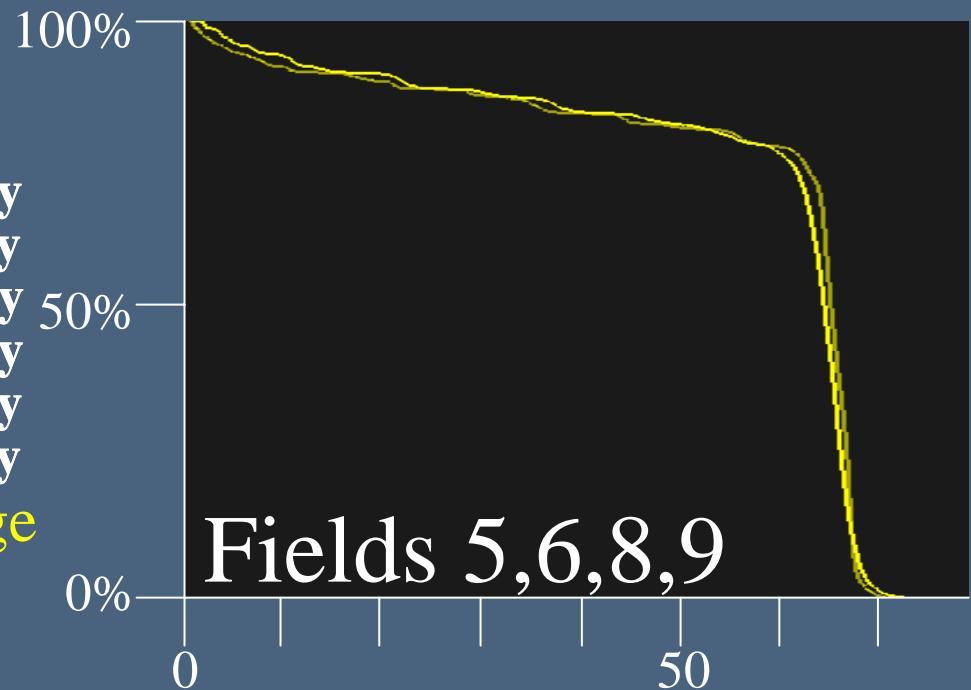
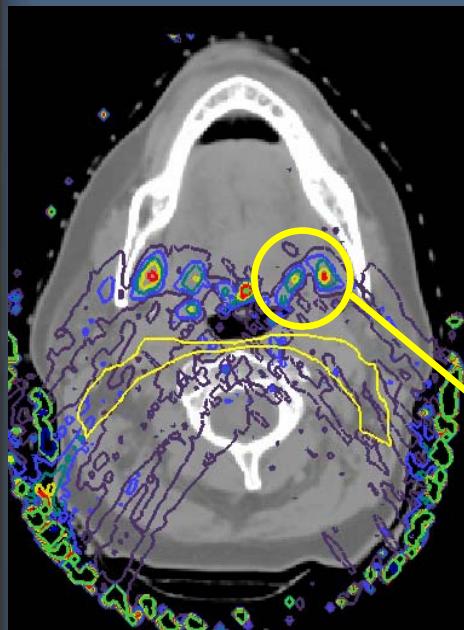
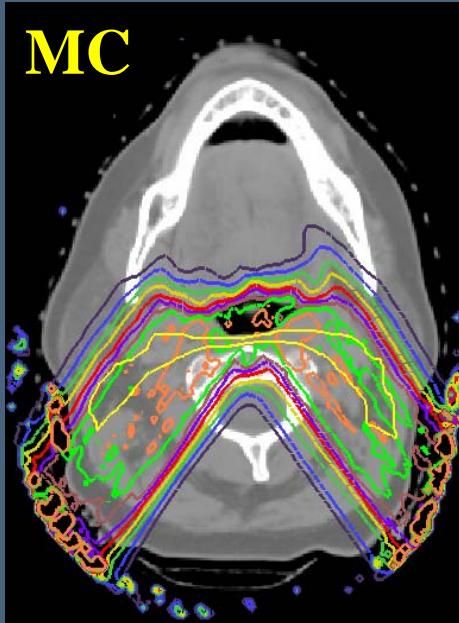
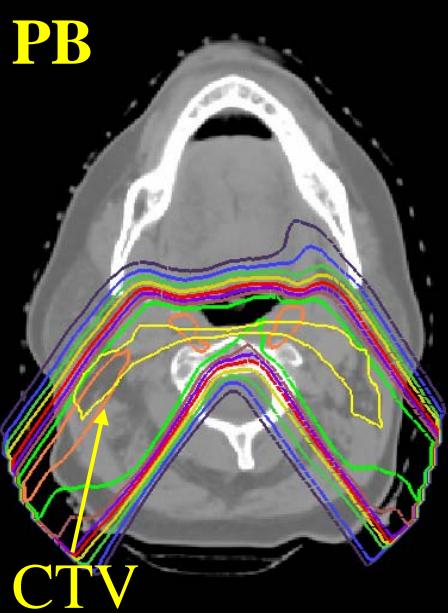




Range
Patch Line







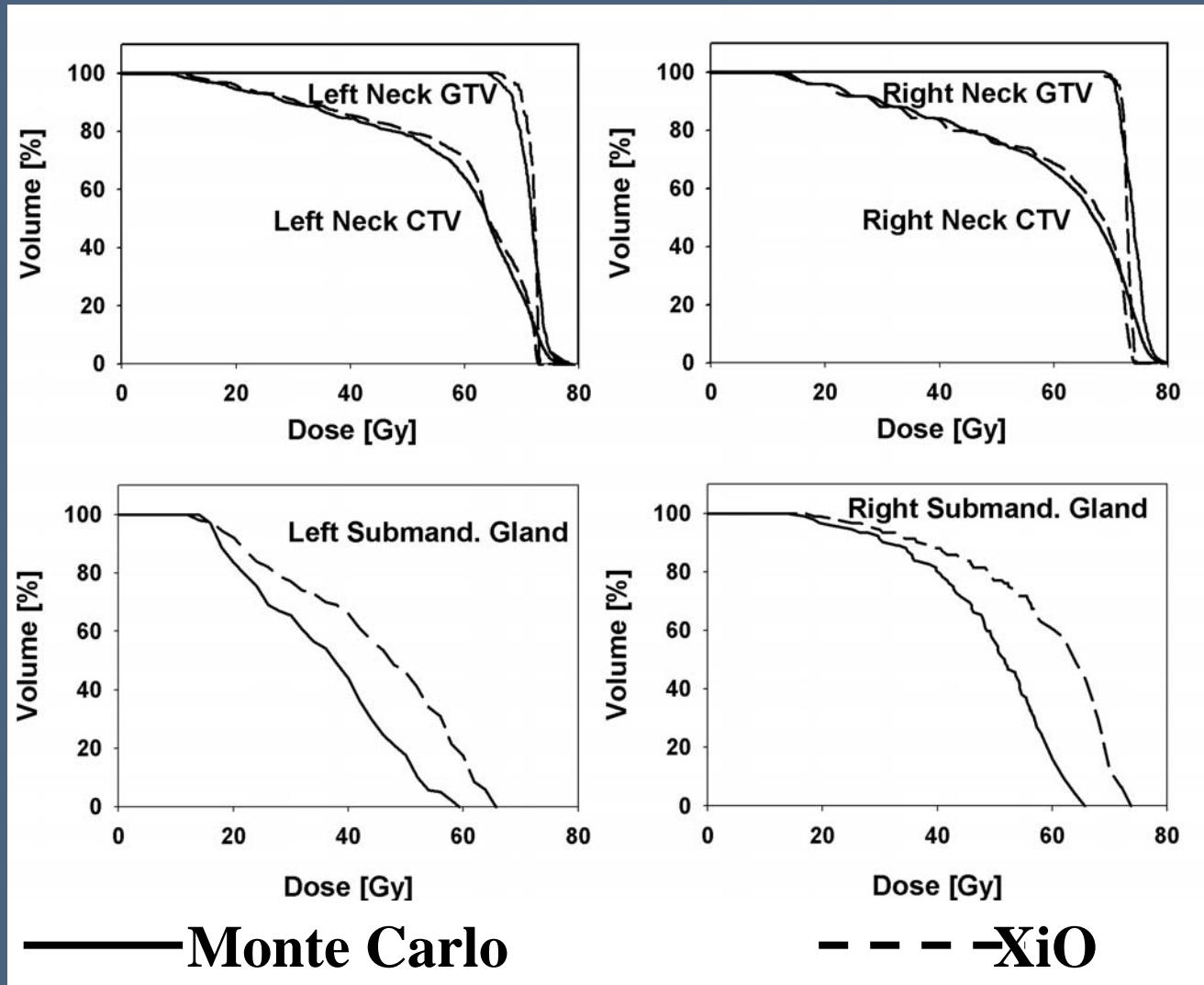
Case 2:

Nasopharynx & both necks

169 x 155 x 125 slices

voxels: 0.656 x 0.656 x 1.25-3.75 mm³

8 fields: 7 protons + 1 IMRT



Example 3

Case 2:

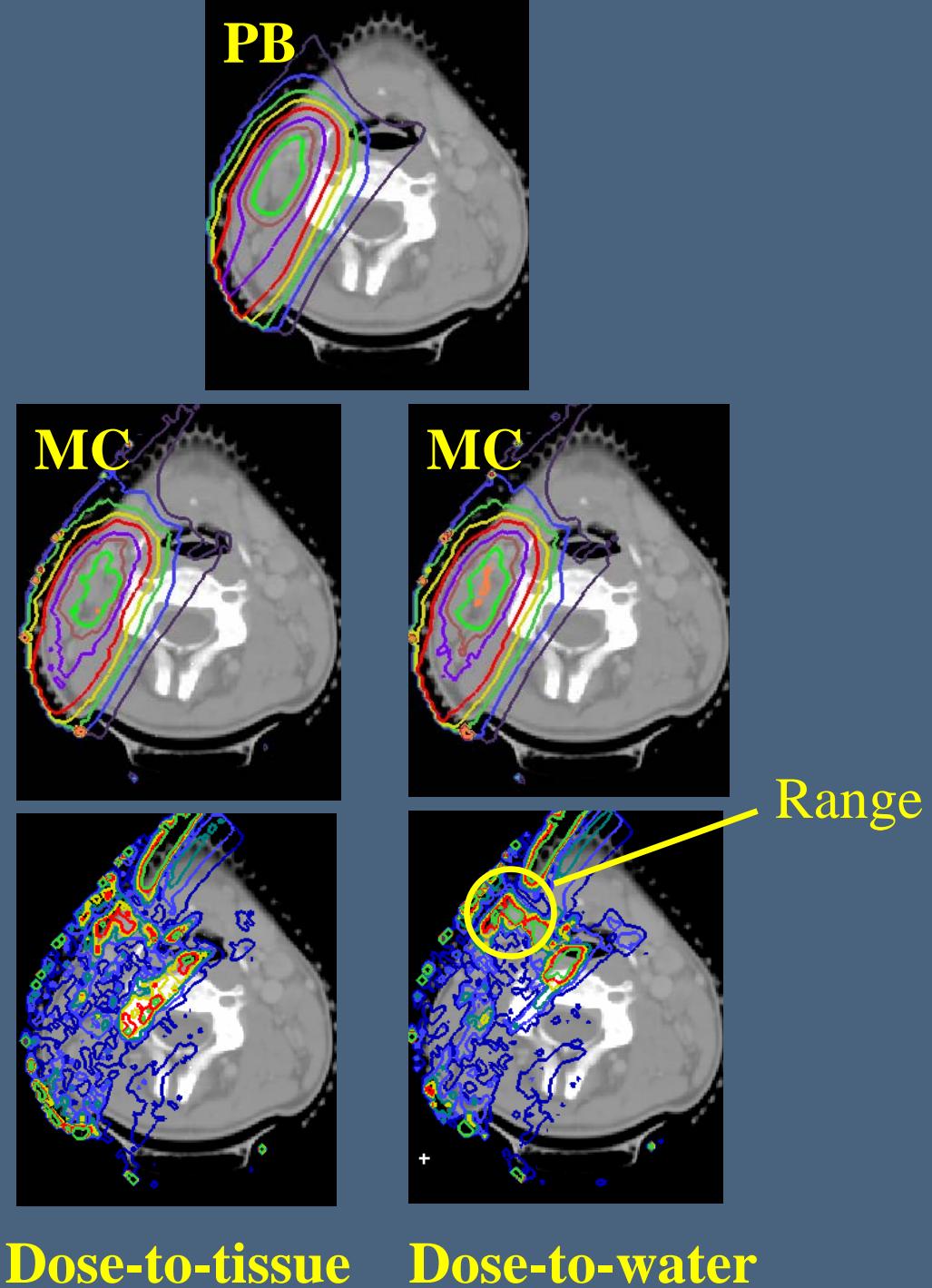
Nasopharynx & both necks

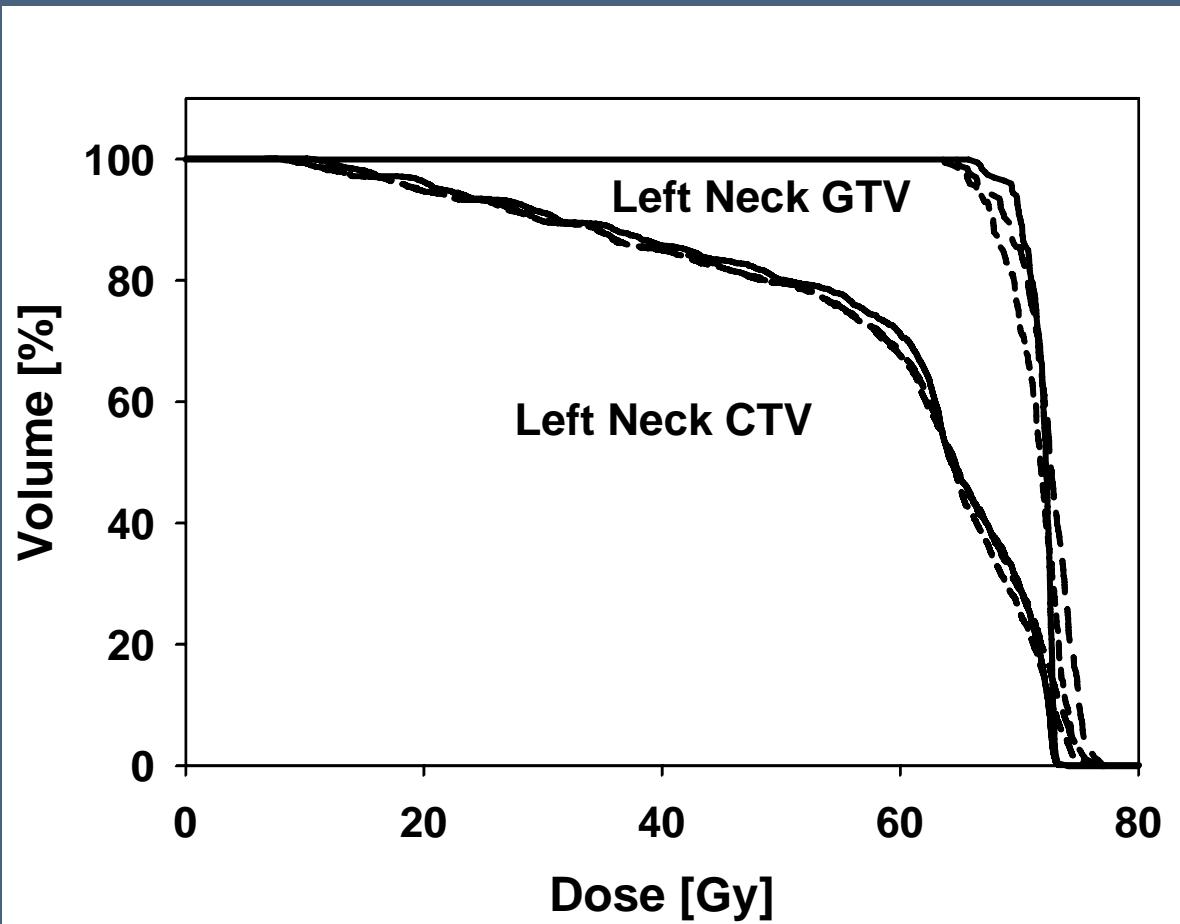
169 x 155 x 125 slices

voxels: 0.656 x 0.656 x 1.25-3.75 mm³

8 fields: 7 protons + 1 photons





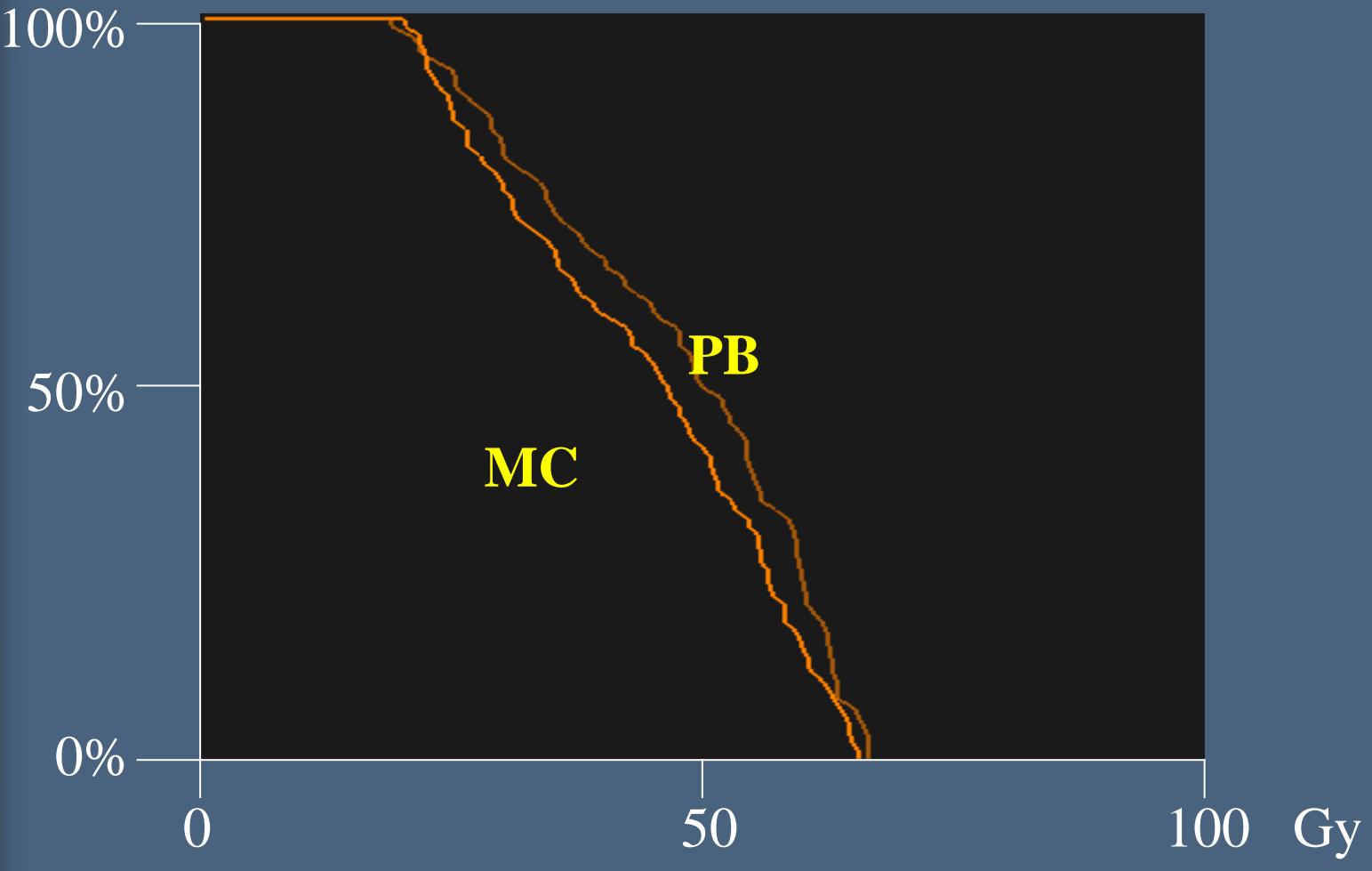


— XiO

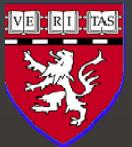
— — — MC (DTW)

— · — · MC (DTT)





DVH for left submandibular gland



Geant4 application to proton radiation therapy

- Time dependent patient geometries



Dynamic Systems in Radiation Therapy

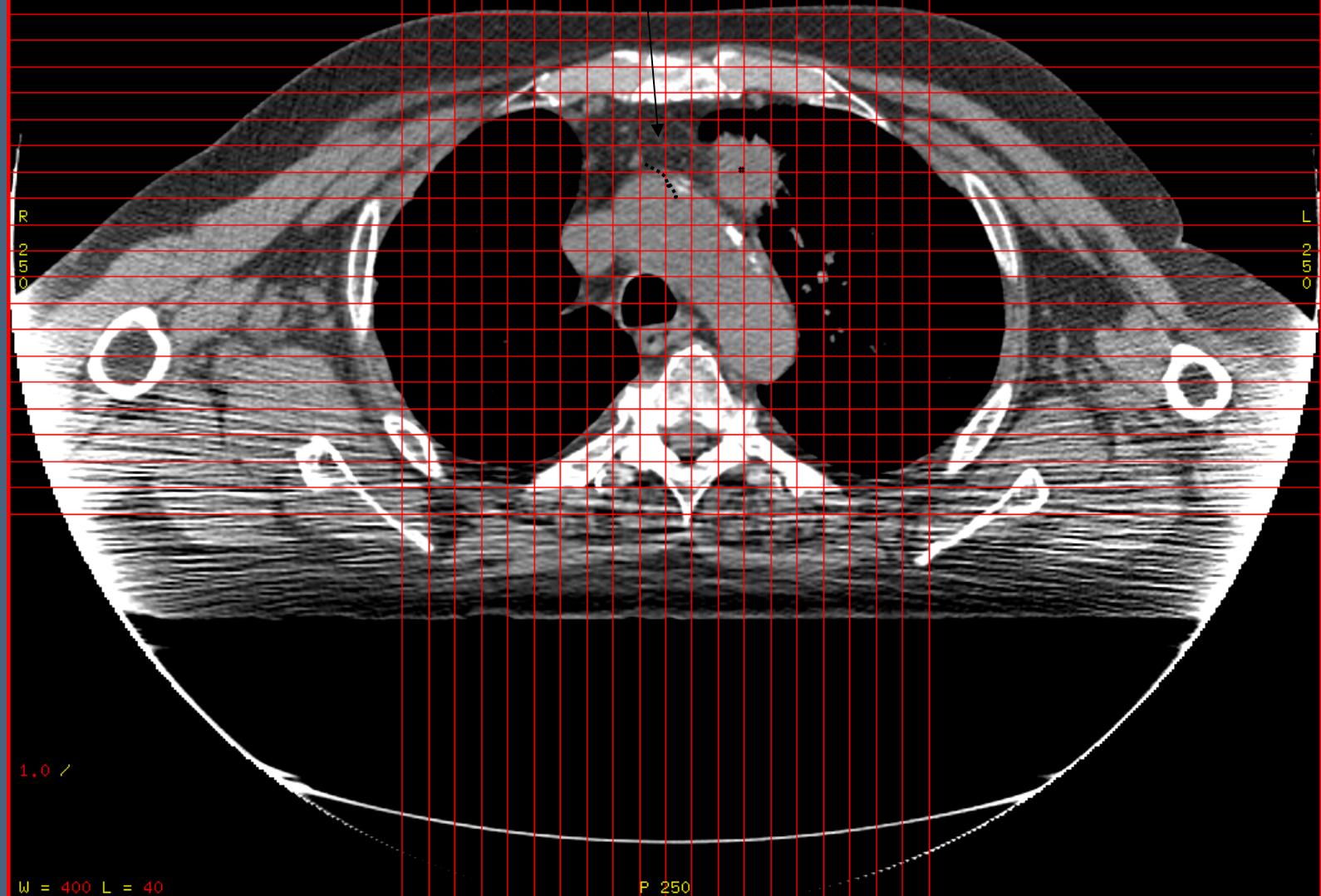
- Patient -

Tumor motion is of particular interest for intra-thoracic tumors

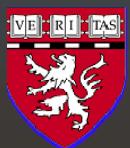
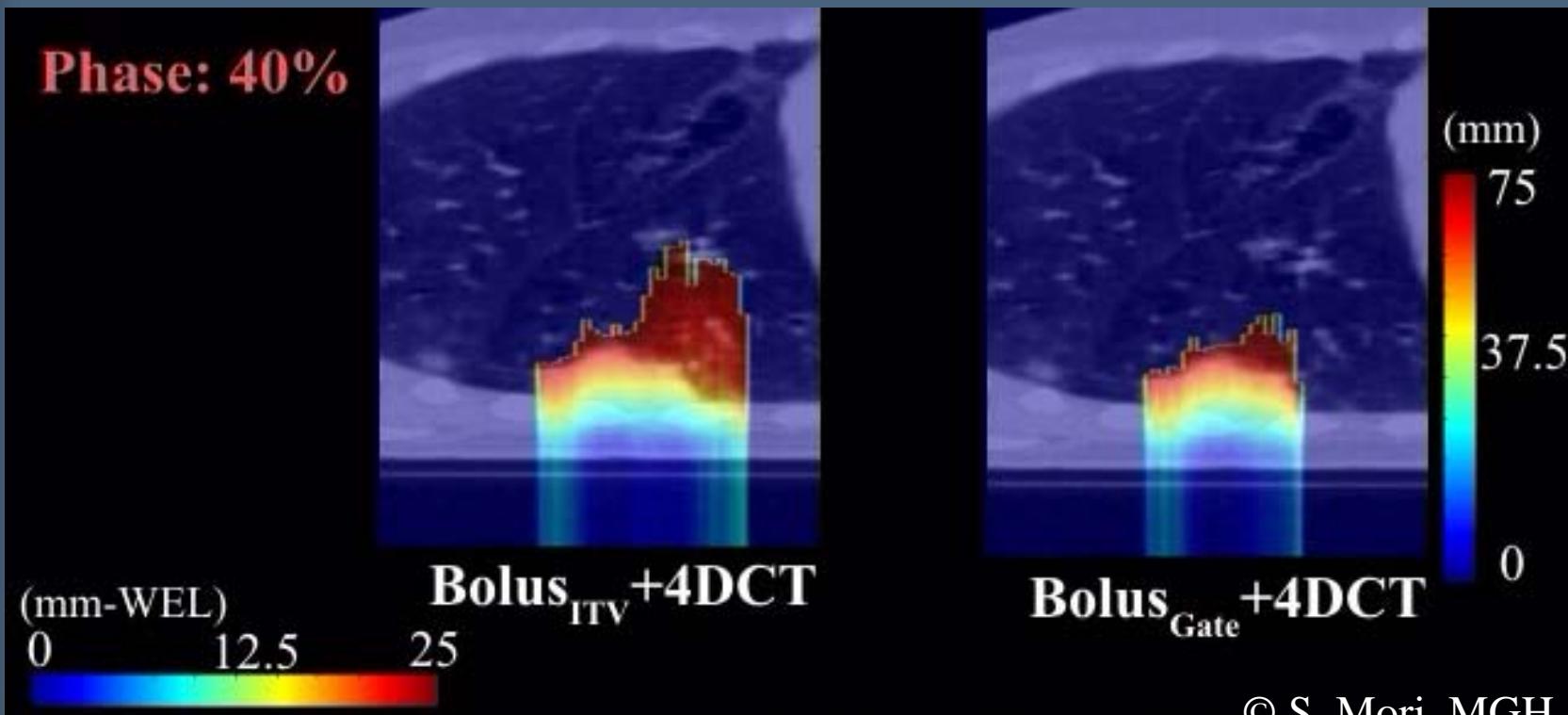
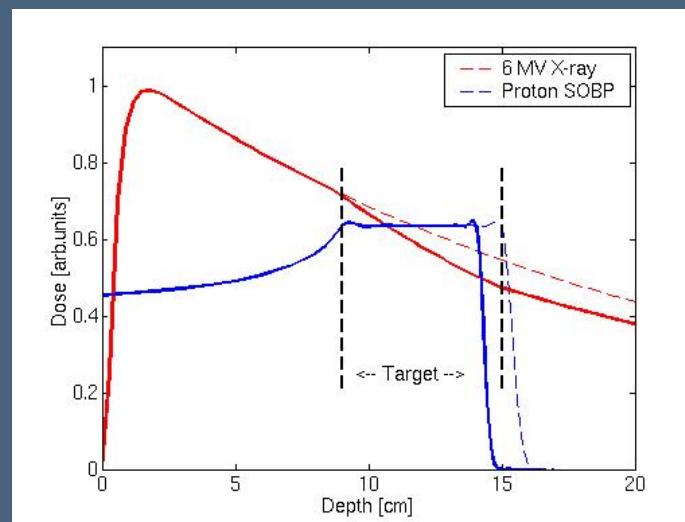
- Inter-patient variations due to tumor position in the lung, patient breathing pattern, lung capacity, etc.
- Organs in the thorax and abdomen move approximately periodically along the cranio-caudal and anterior-posterior axes with a period of about 4 seconds.
- Tumor motion in the lung can be up to 4 cm and is on average in the order of 3 – 7 mm.



Lateral Motion of Lung Tumor

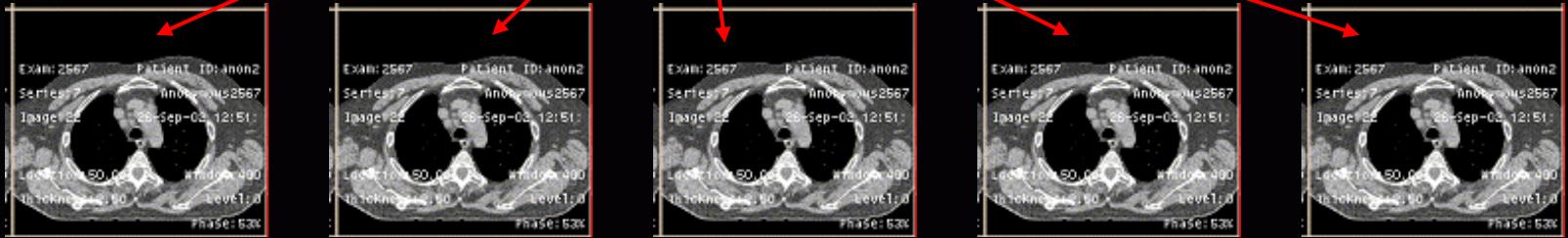
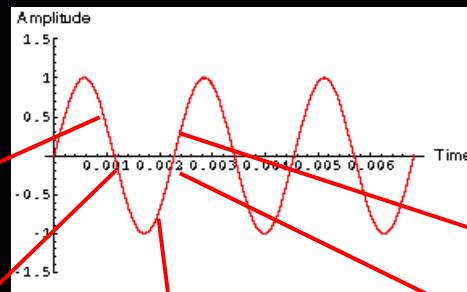
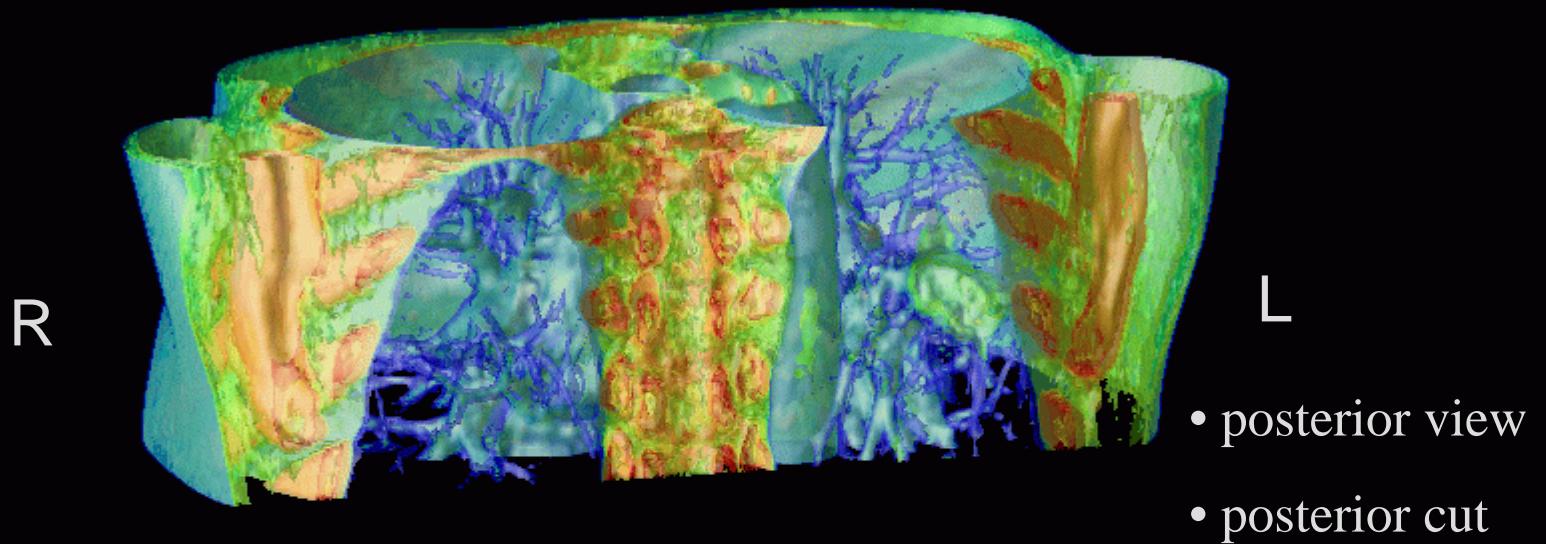


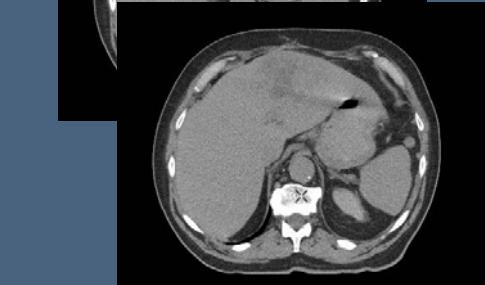
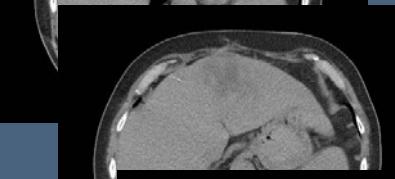
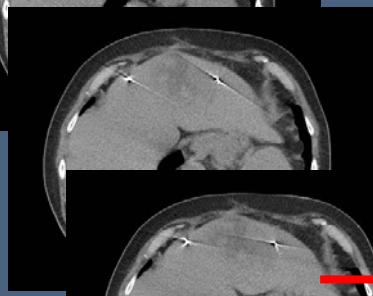
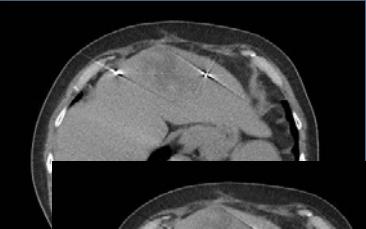
Dosimetric effects due to motion in proton therapy



- Breathing Patient -

© Eike Rietzel

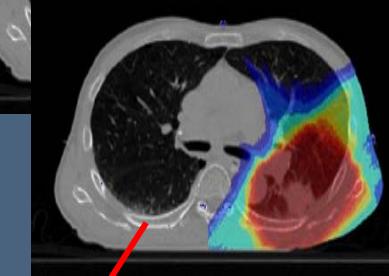
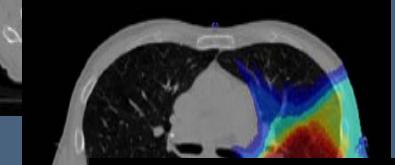
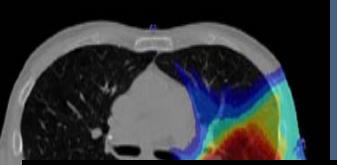
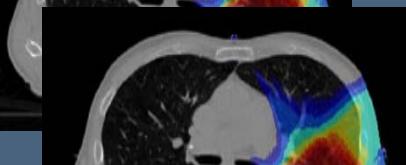
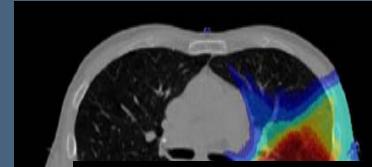




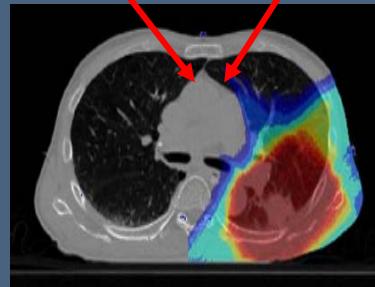
10 x CT



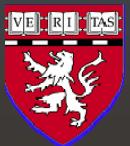
10 x VDM

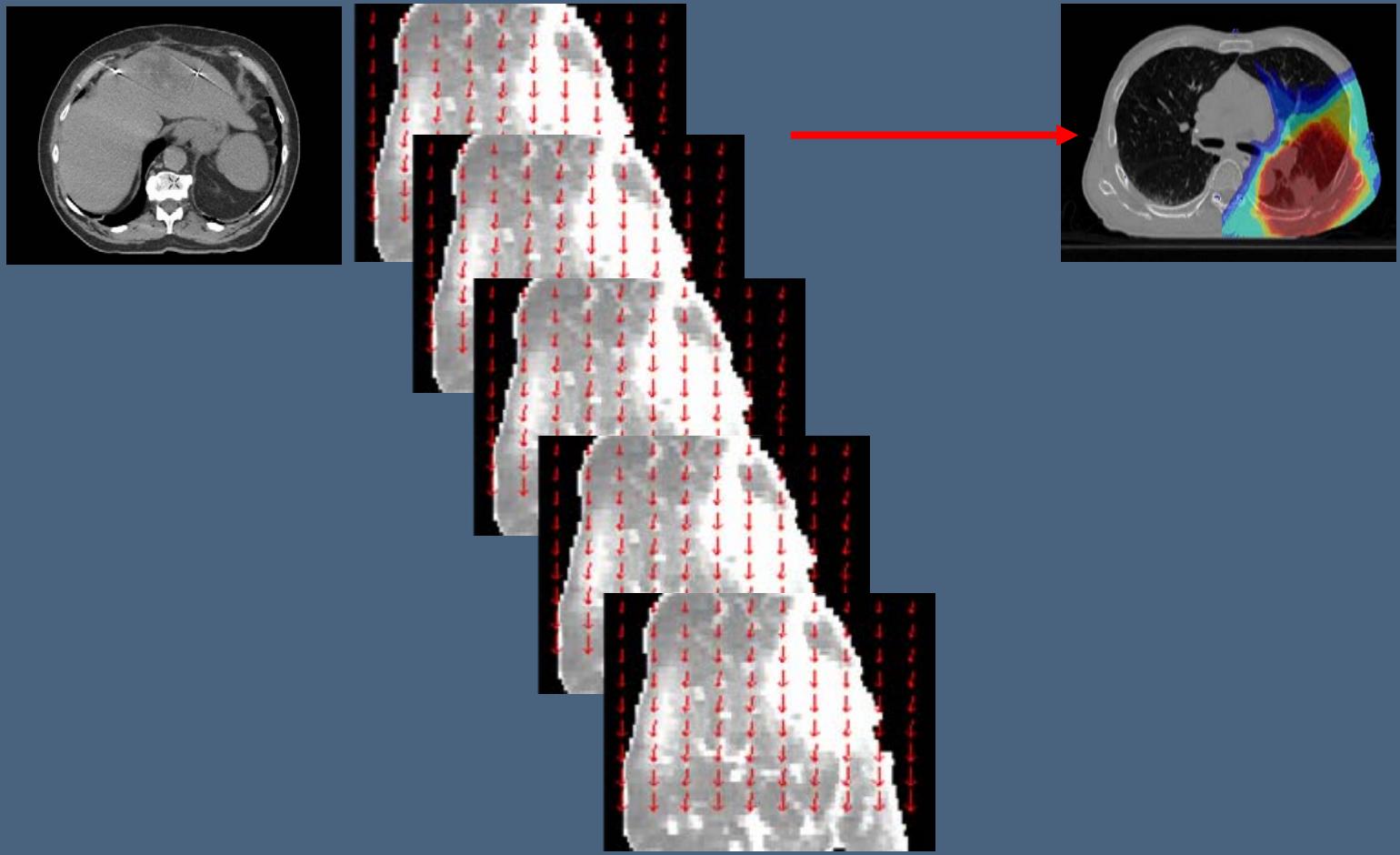


10 x Dose

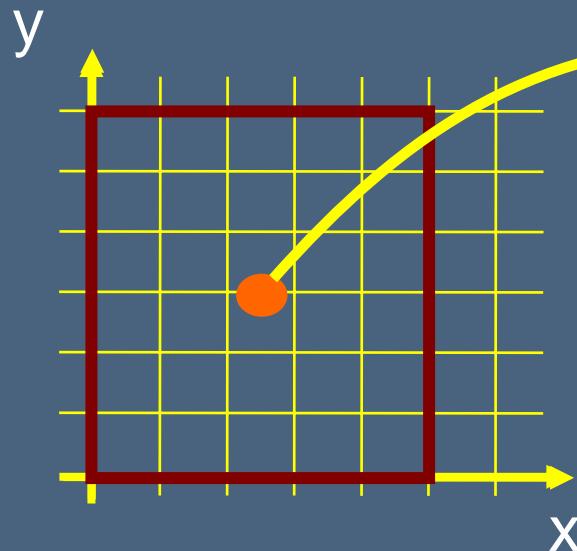


Dose at a reference phase

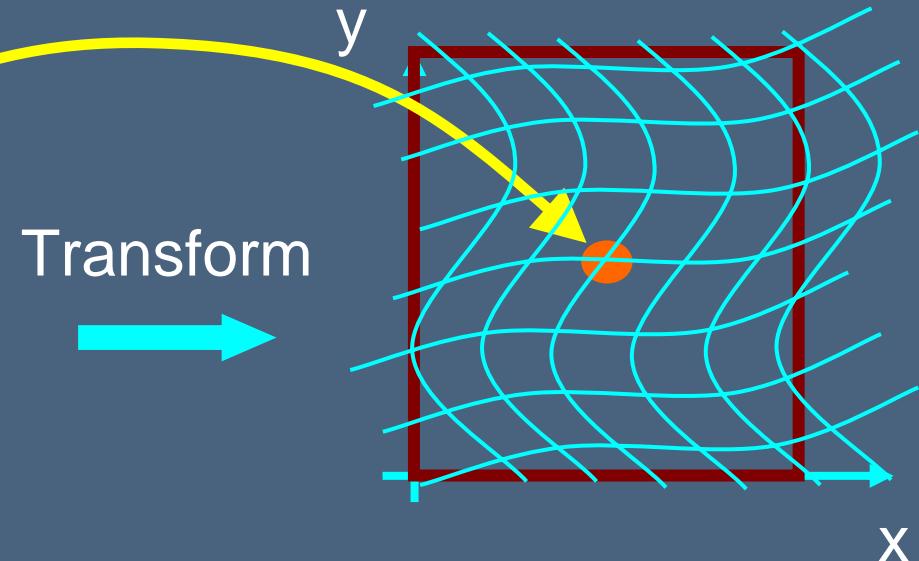




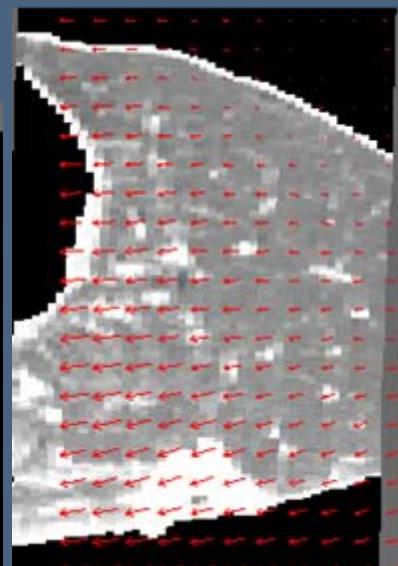
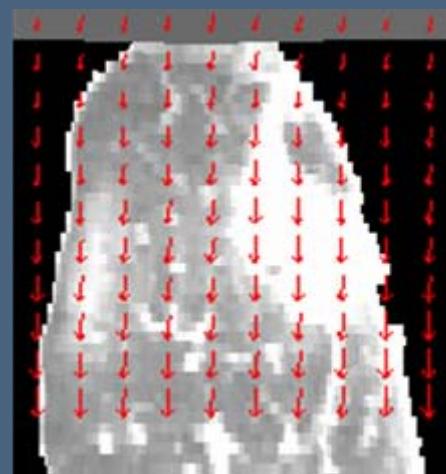
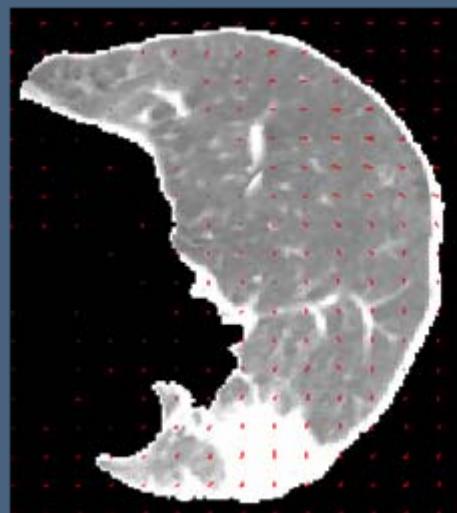
Deformable Registration Methods



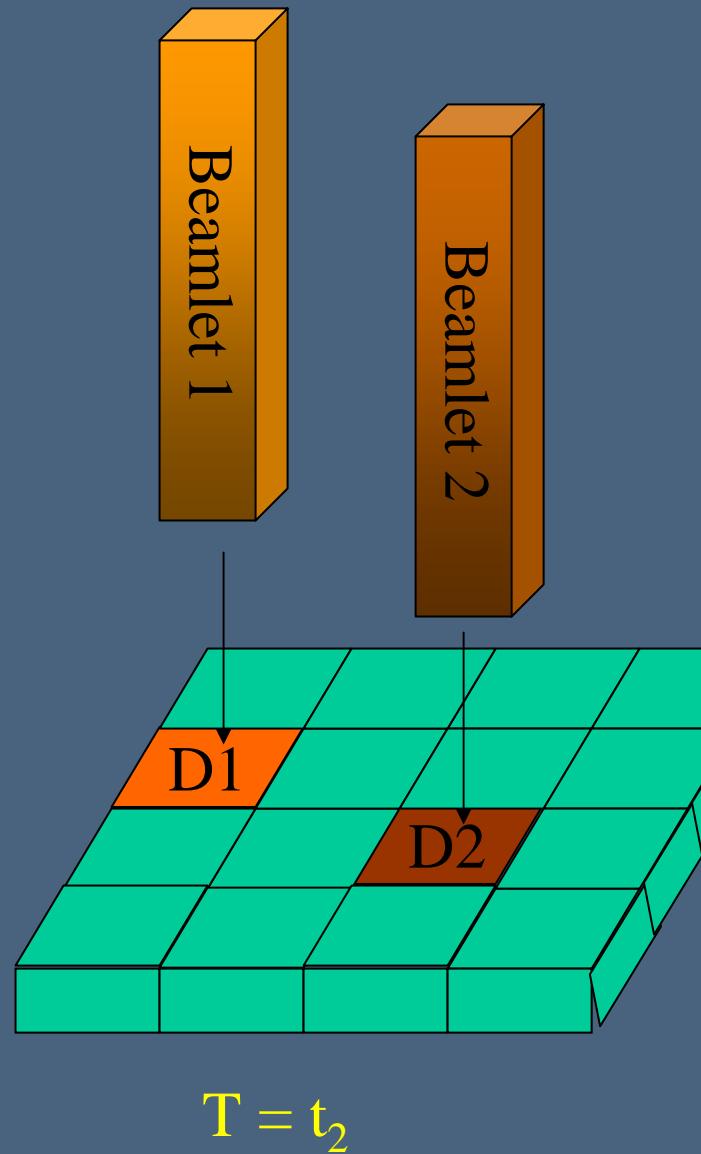
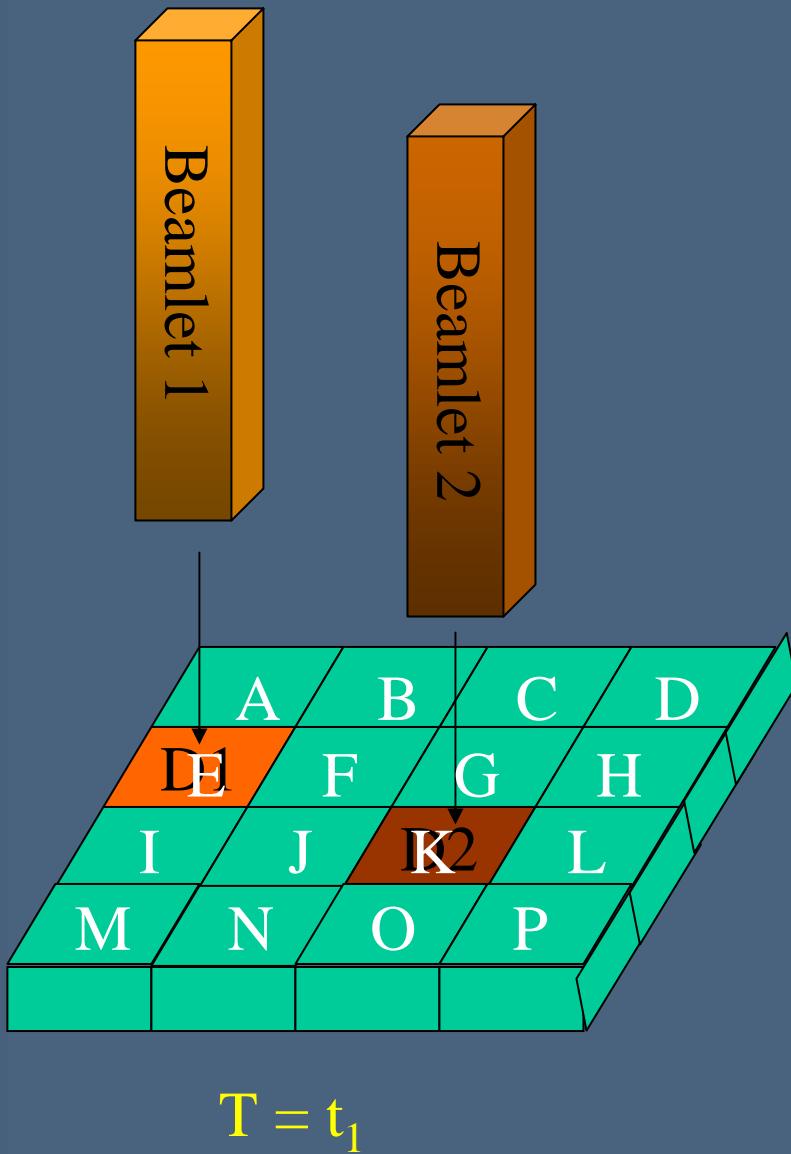
Fixed Image



Moving Image

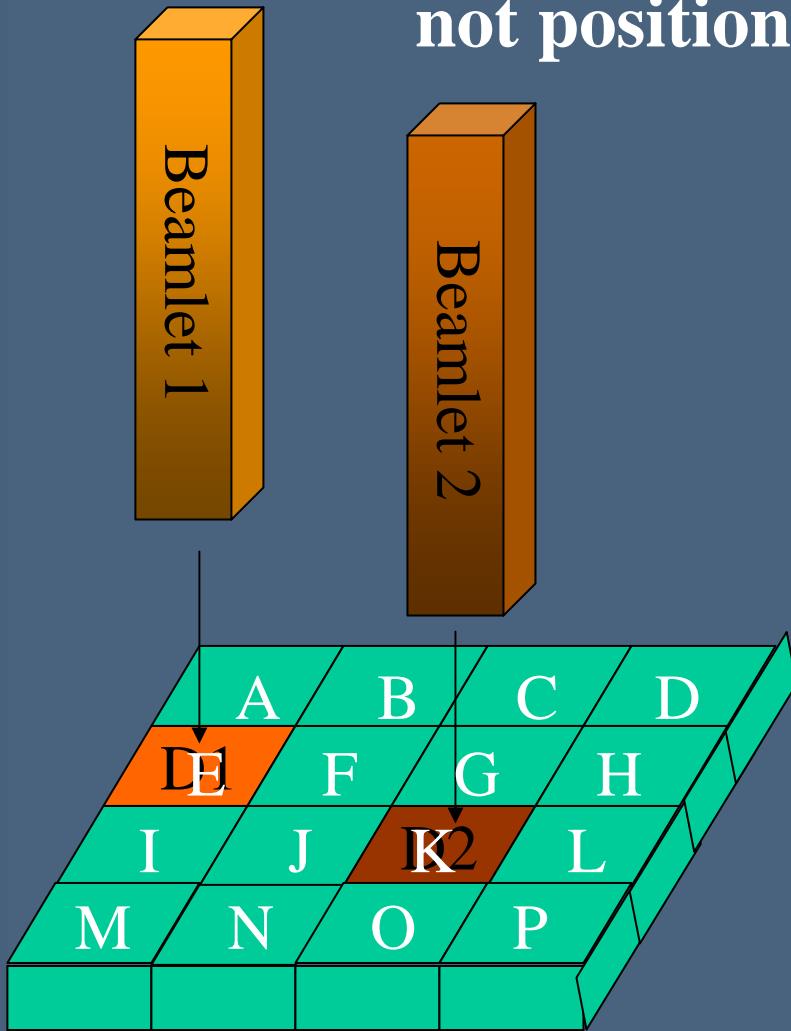


4D Dose Deposition

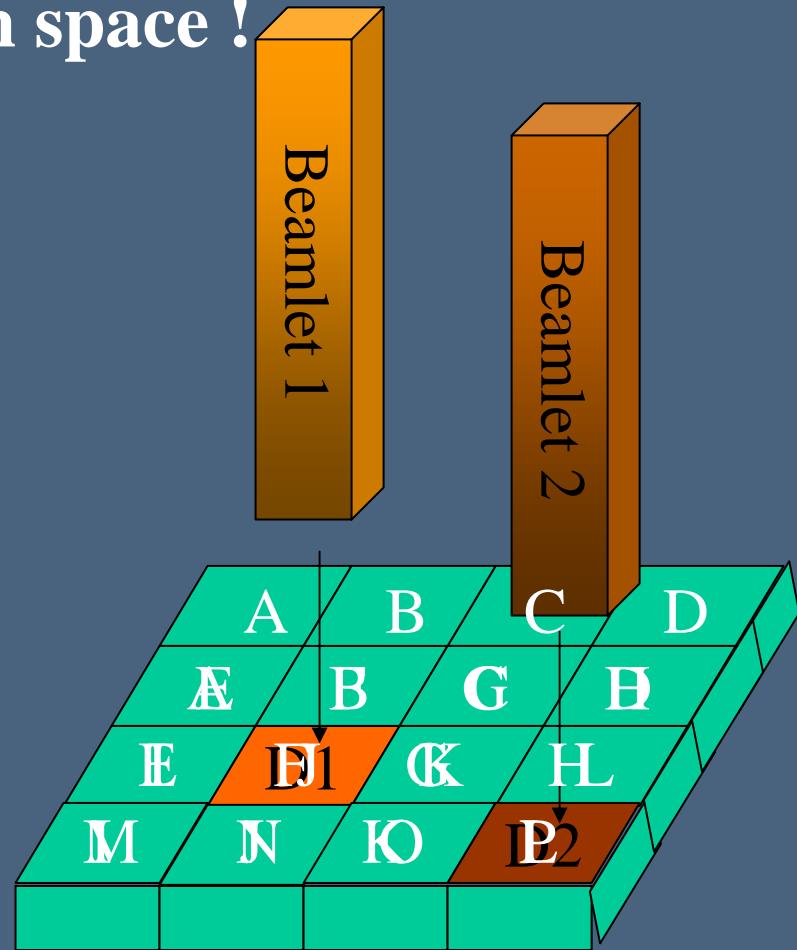


4D Dose Deposition

Dose deposition defined via voxel identifiers,
not position in space !

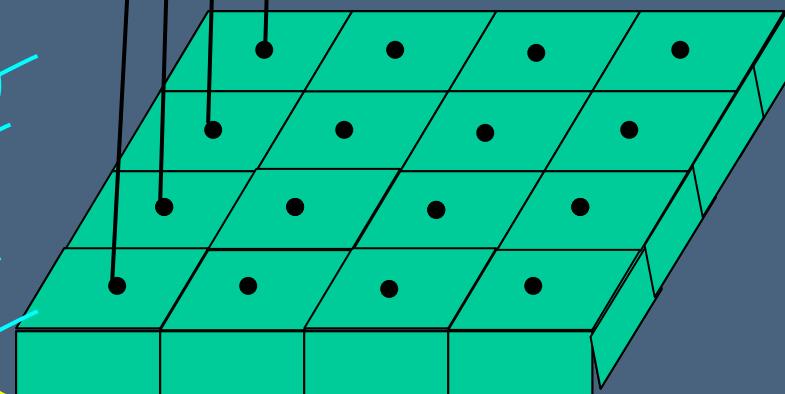
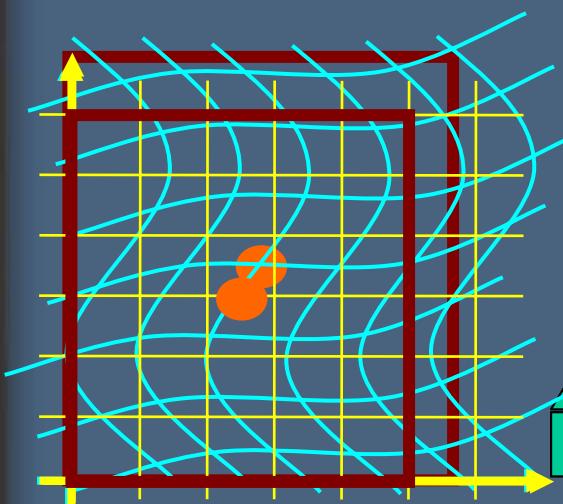
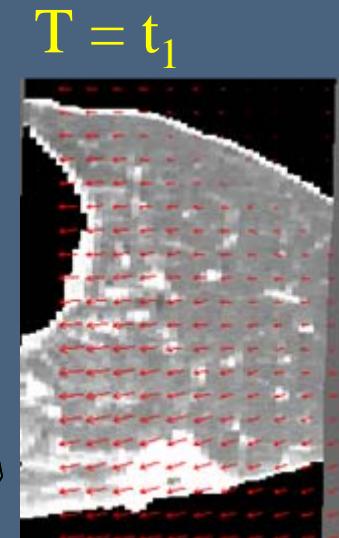
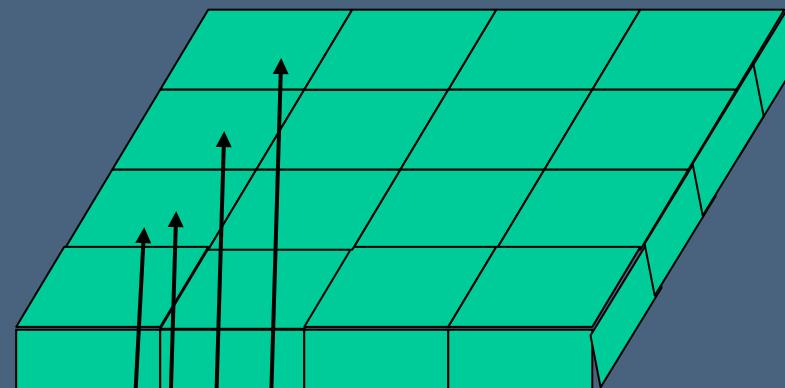
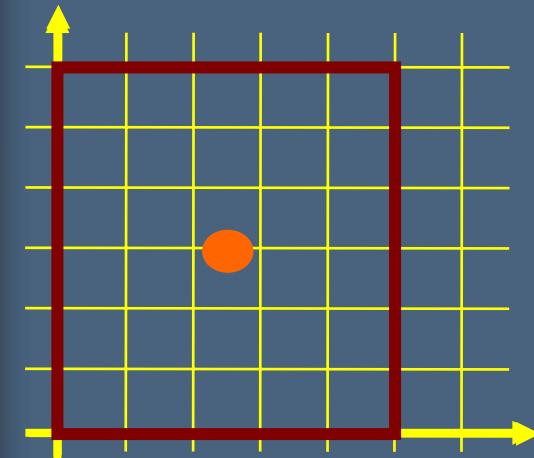


$$T = t_1$$

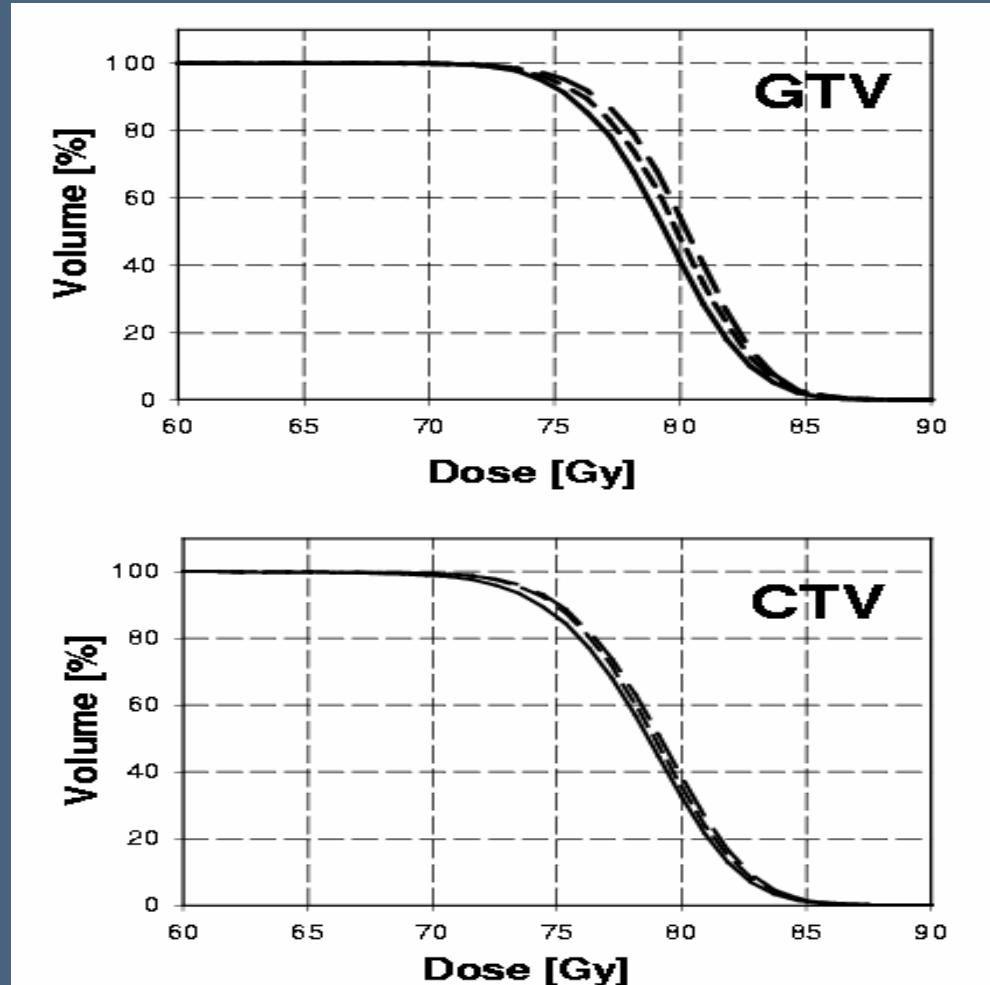
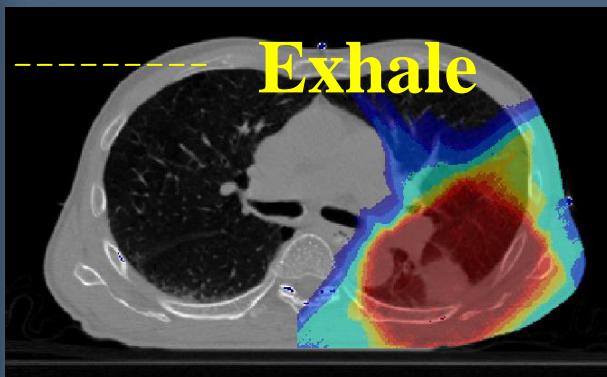
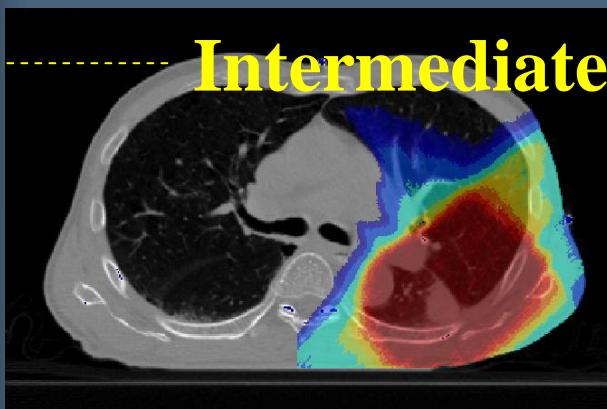
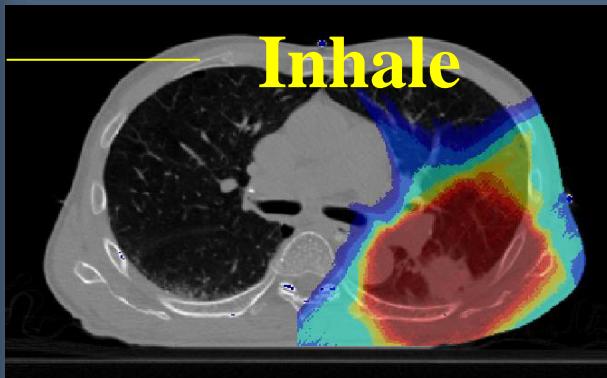


$$T = t_2$$

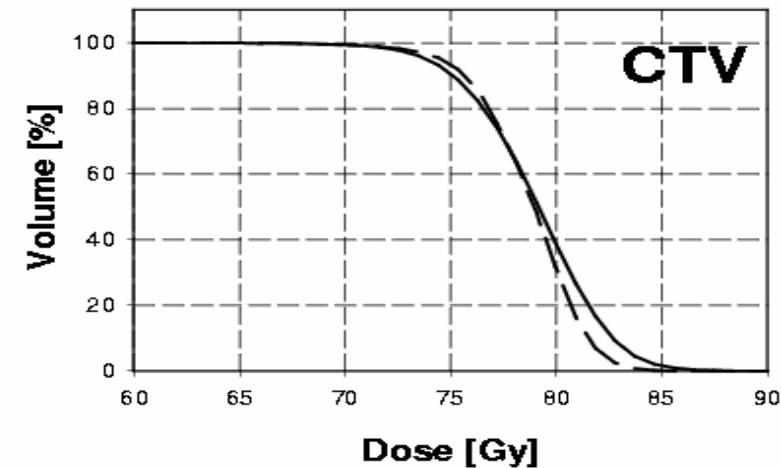
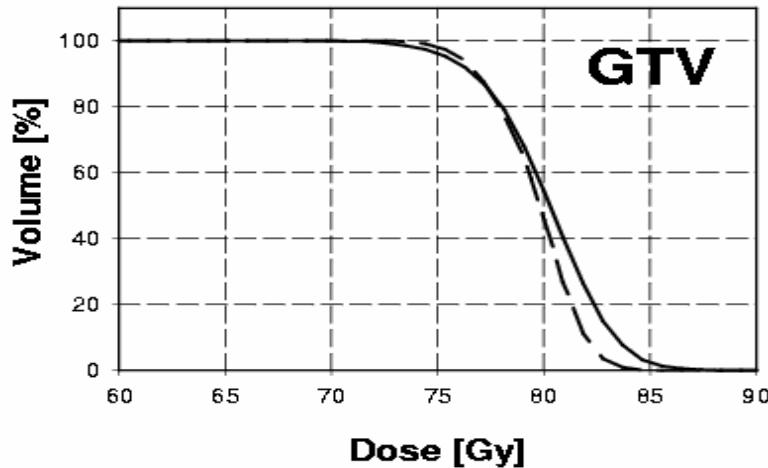
Dose calculation during non-rigid motion



Four-dimensional Monte Carlo simulation based on 4D CT



Four-dimensional Monte Carlo simulation based on 4D CT



Solid lines:

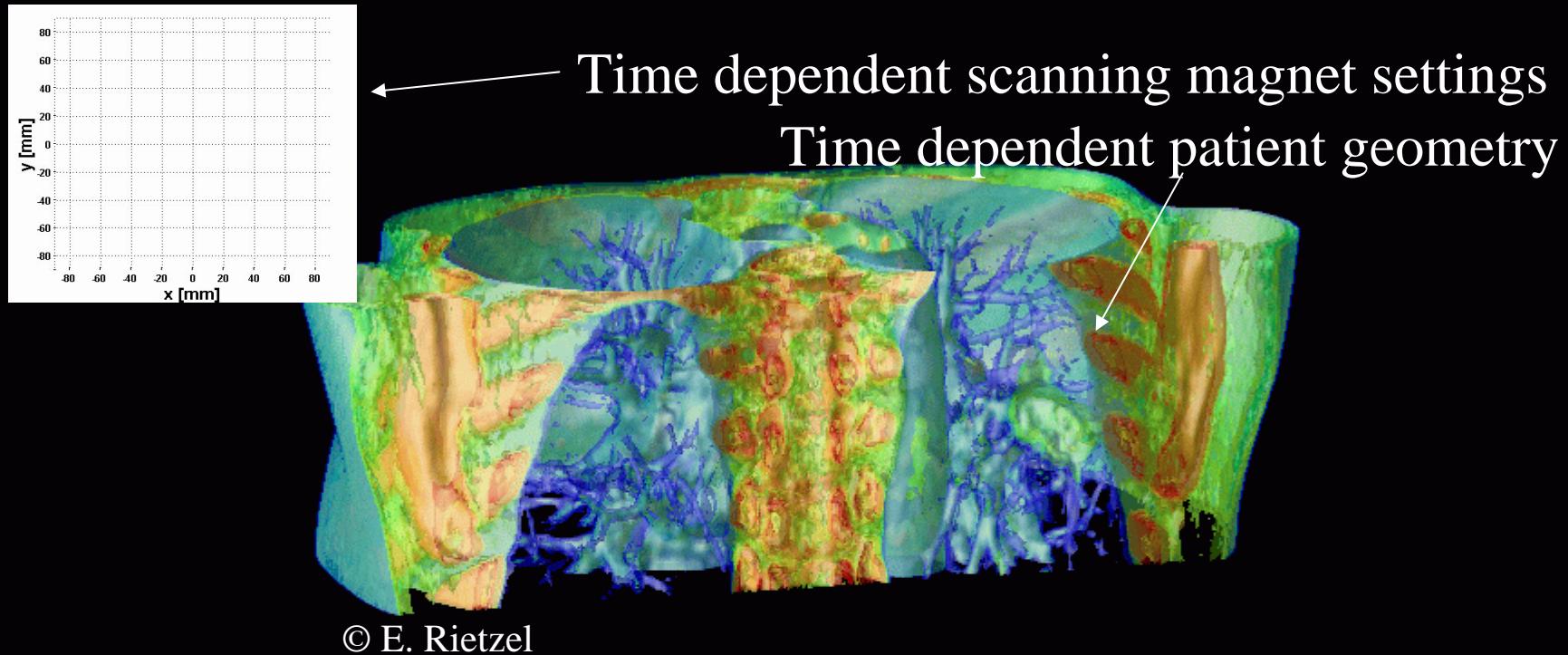
Patient in inhale

Dashed lines:

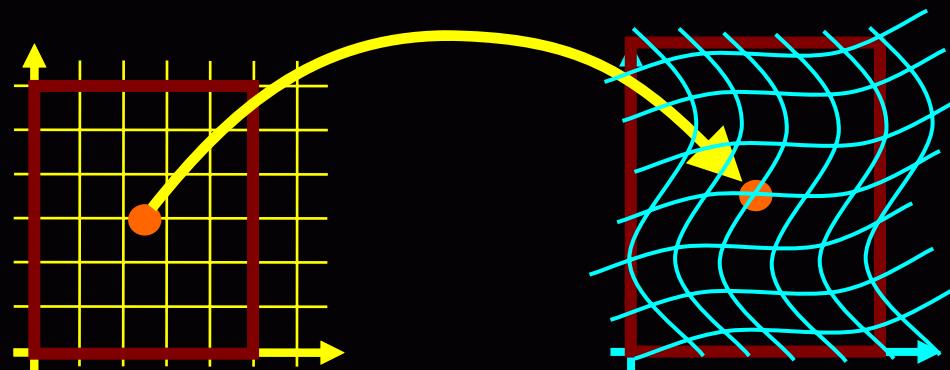
Considering the entire breathing phase



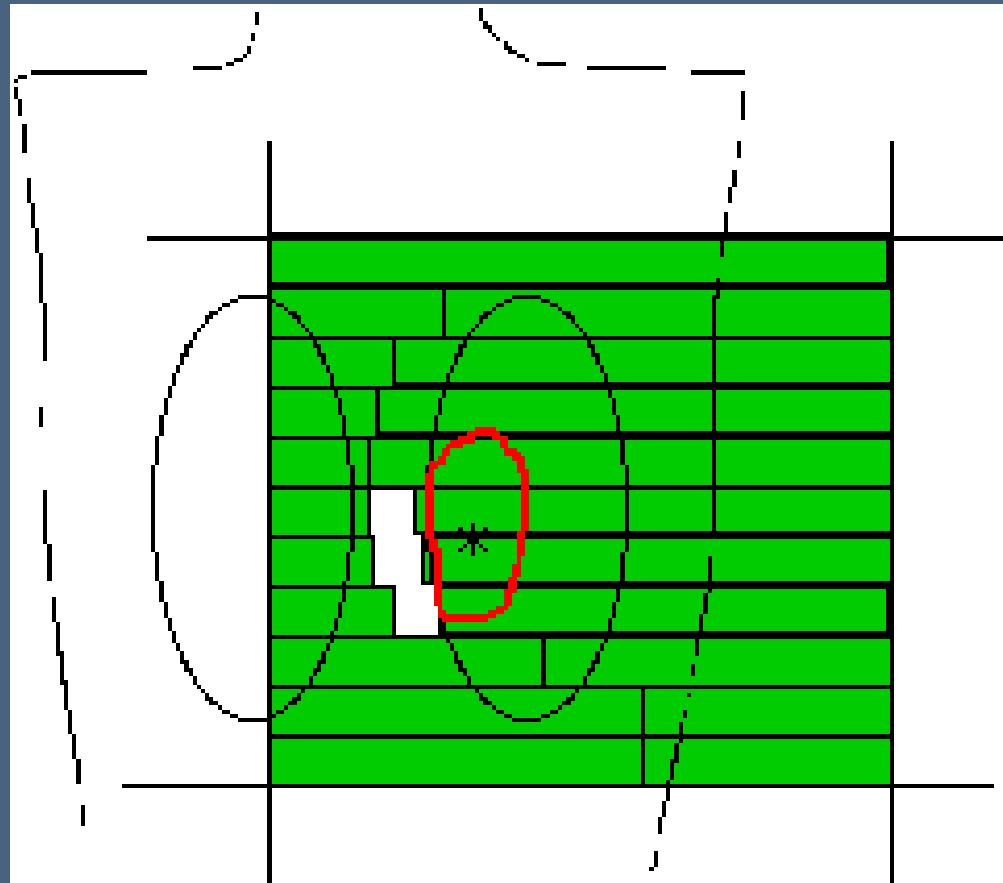
Interplay effects of motion (4D Monte Carlo)



© E. Rietzel



Interplay effects between organ motion and MLC movement

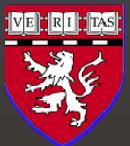
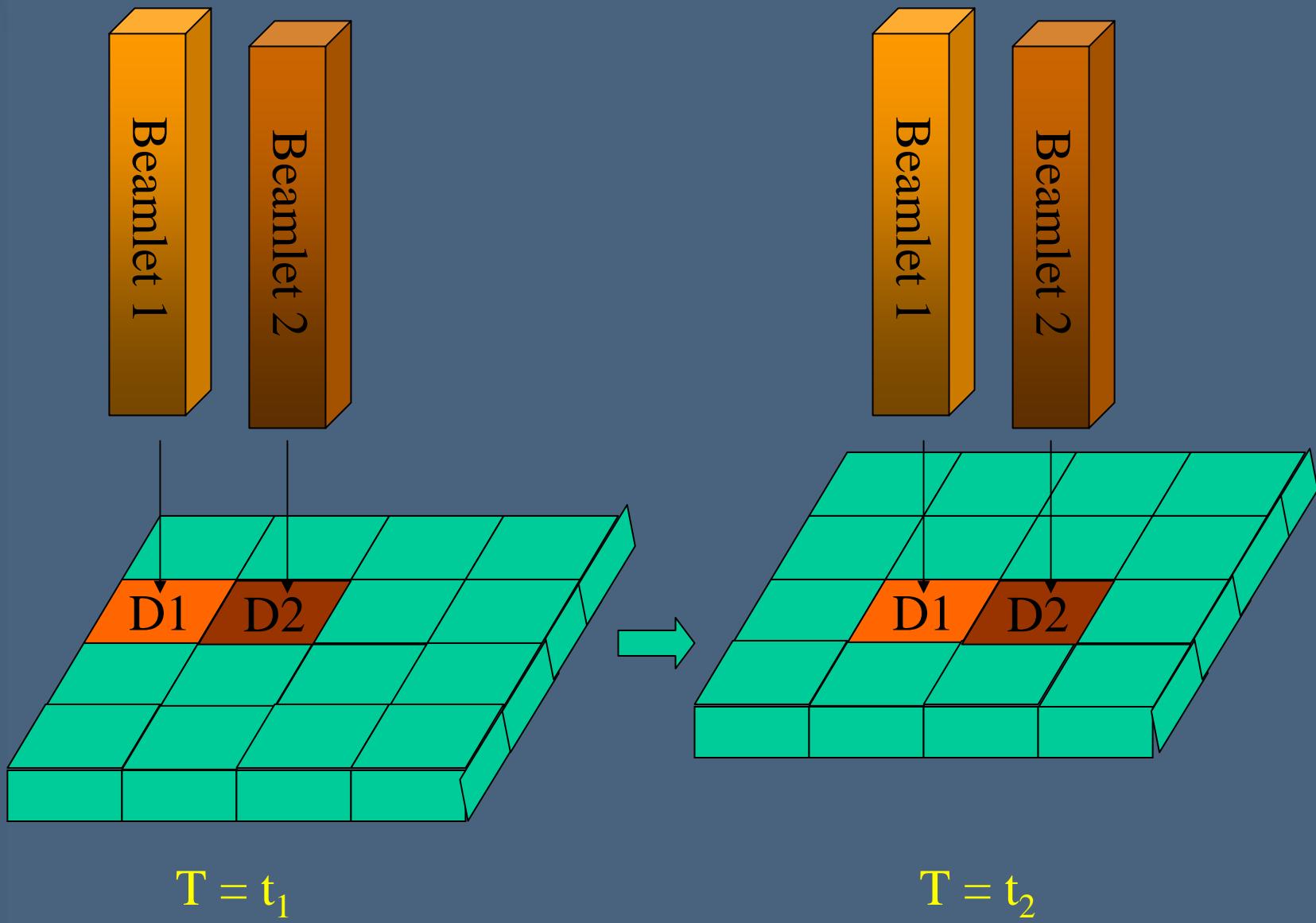


JH Kung and P Zygmanski

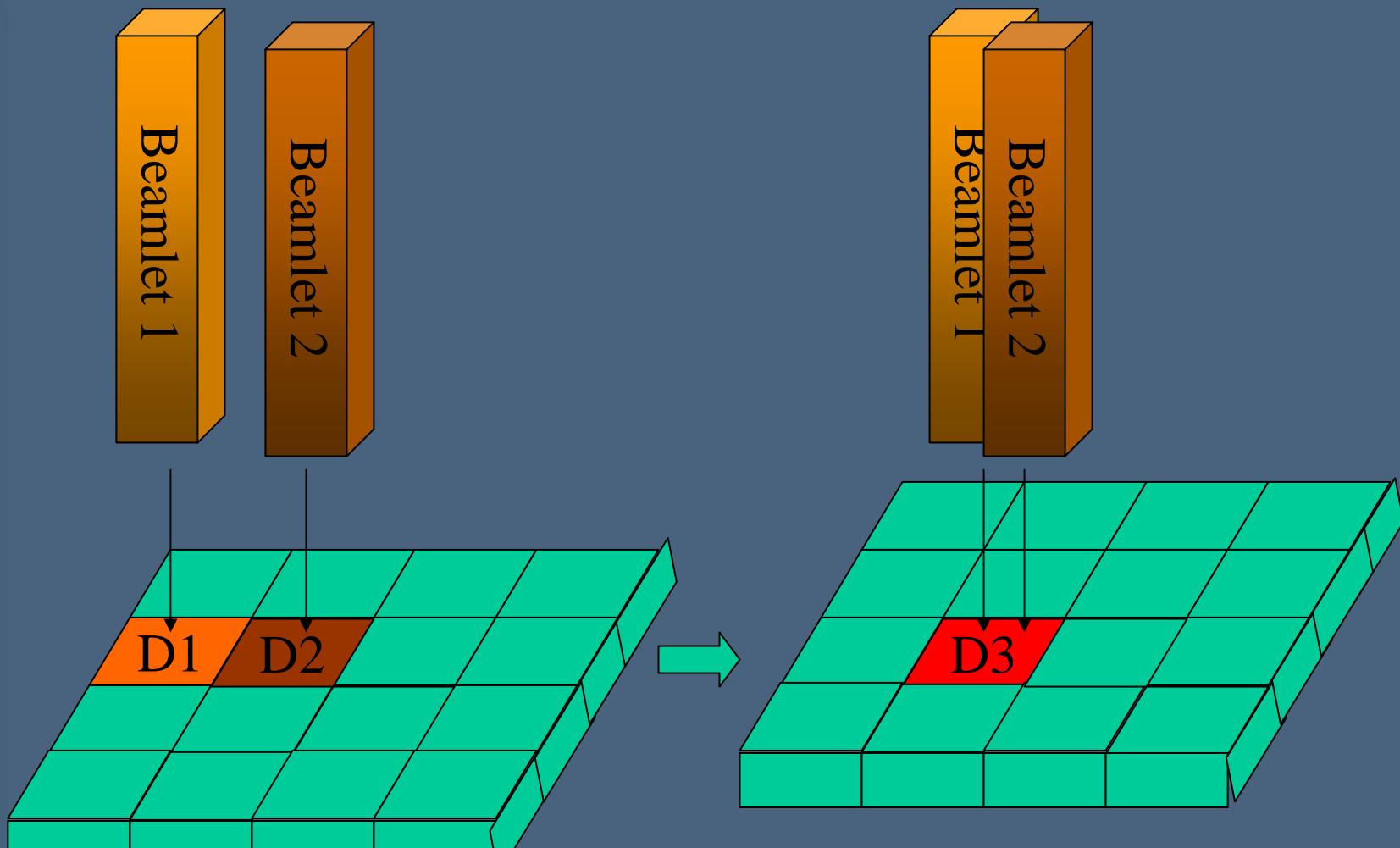


Single-dynamic (patient movement ; static beam delivery)

Implementation



Double-dynamic (patient movement; dynamic beam delivery)



$$T = t_1$$

$$T = t_2$$

Effect can be reduced by ‘repaiting’



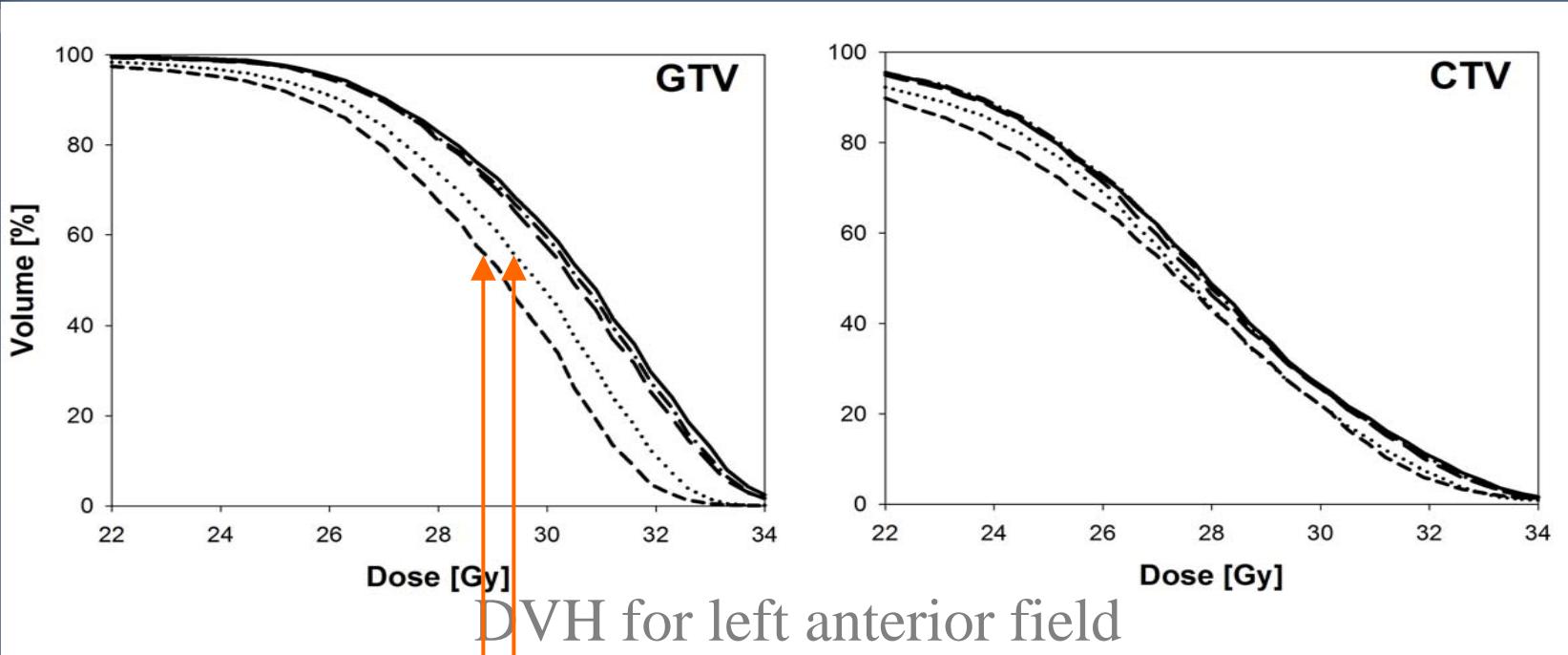
4D Monte Carlo of IMPT

- Beamlets and patient are moved continuously (rigid)
- Assumptions:
 - Irradiation time per slice is 0.4 seconds (on average)
 - Changing the cyclotron beam energy with a degrader takes a few seconds
 - Breathing cycle is 4 seconds
- Choose a specific scanning pattern
- Choose a specific number of protons per second
- Update the beam delivery setup and the patient setup every 0.1 virtual seconds



4D Monte Carlo

4D Monte Carlo of IMPT



- Static
- - Patient moves ± 0.5 cm
- - - Patient moves ± 1.5 cm
- - . Patient moves ± 0.5 cm; repainting
- Patient moves ± 1.5 cm; repainting



Geant4 application to proton radiation therapy

SUMMARY / TAKE-HOME MESSAGES

- Proton therapy techniques in a nutshell
- Treatment head developments
- Quality assurance
- Phase space calculations
- Patient simulations
- Clinical use
- Time dependent patient geometries
- Neutron dose in proton beam therapy
- PET imaging for quality assurance



Acknowledgements

NIH support: *P01 CA21239*
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RO1 CA116743

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Hongyu Jiang
Hanne Kooy
Greg Sharp
Ziji Wu**

