Monte Carlo methods in proton beam radiation therapy

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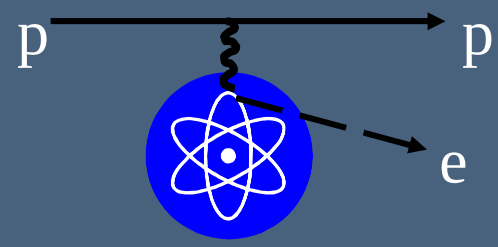
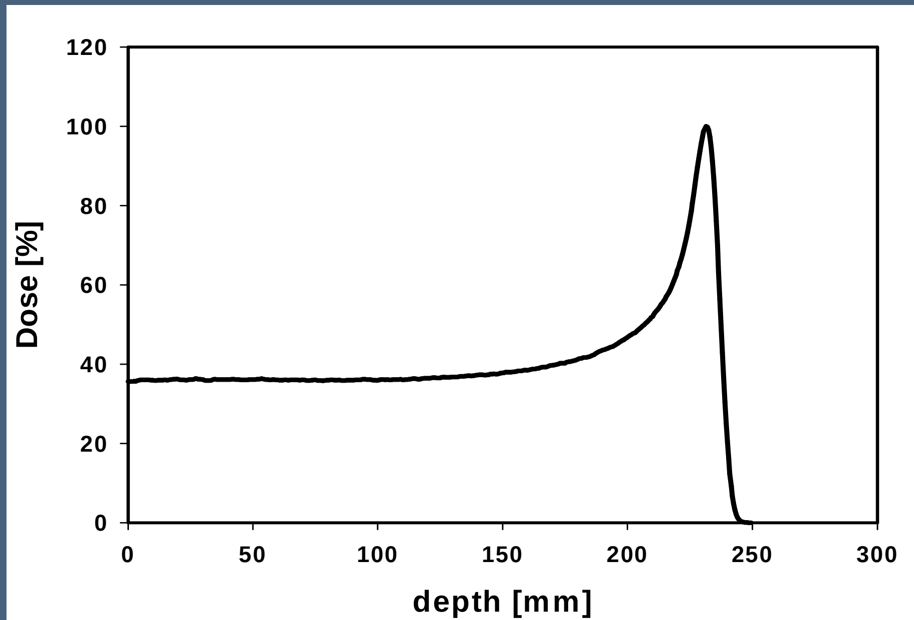
Electromagnetic energy loss of protons



–Ionization

–Excitation

- Distal distribution

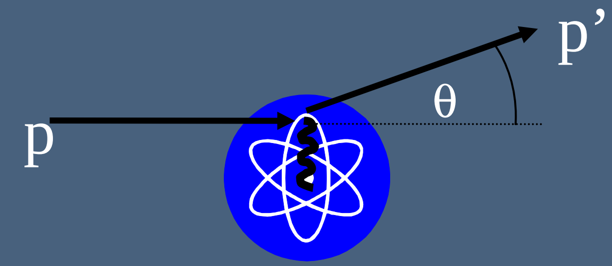


Interaction probability is proportional to proton energy

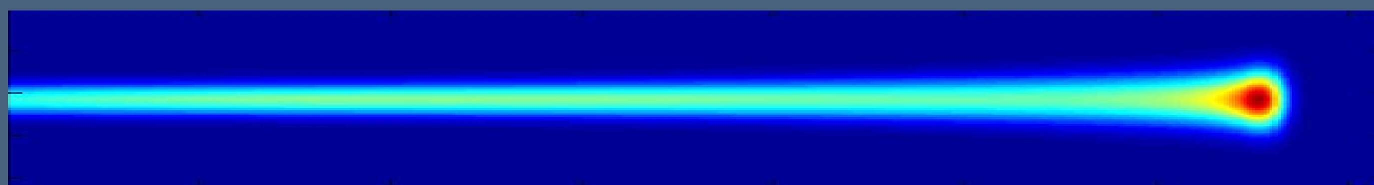
Peak broadening due to range straggling

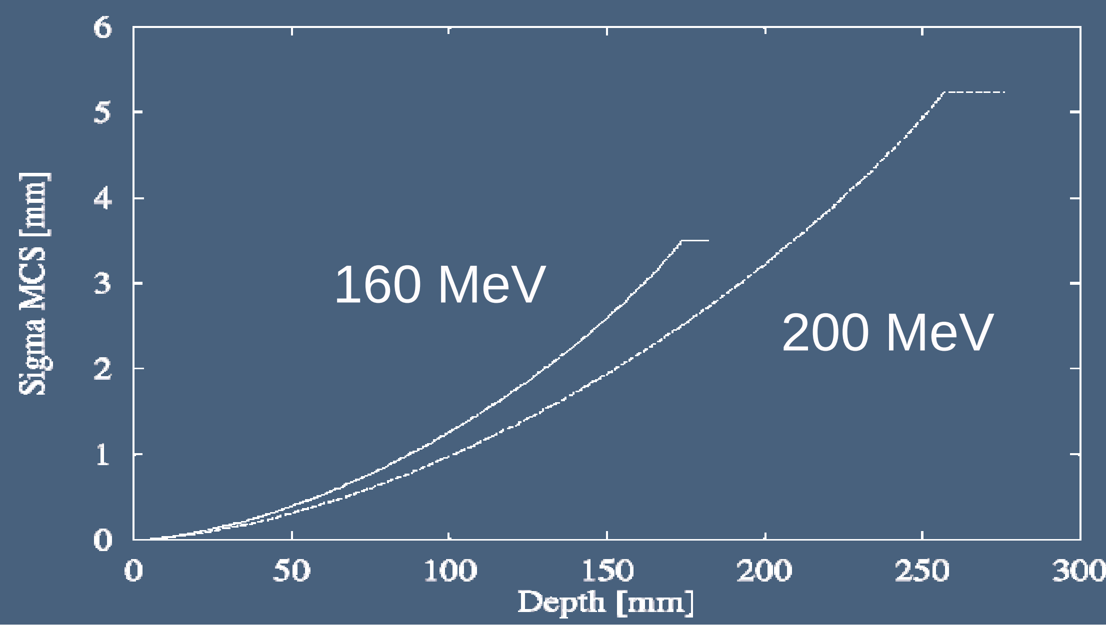
Electromagnetic energy loss of protons

- Lateral distribution

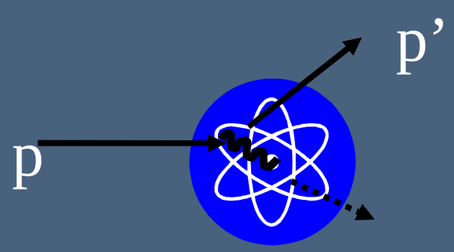


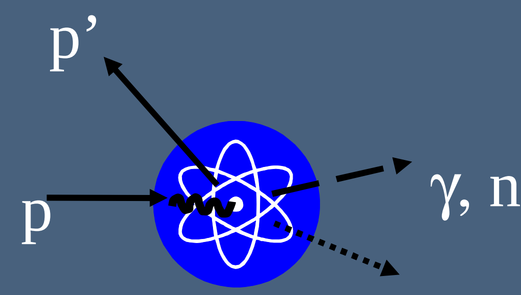
Multiple Coulomb scattering (small angles)



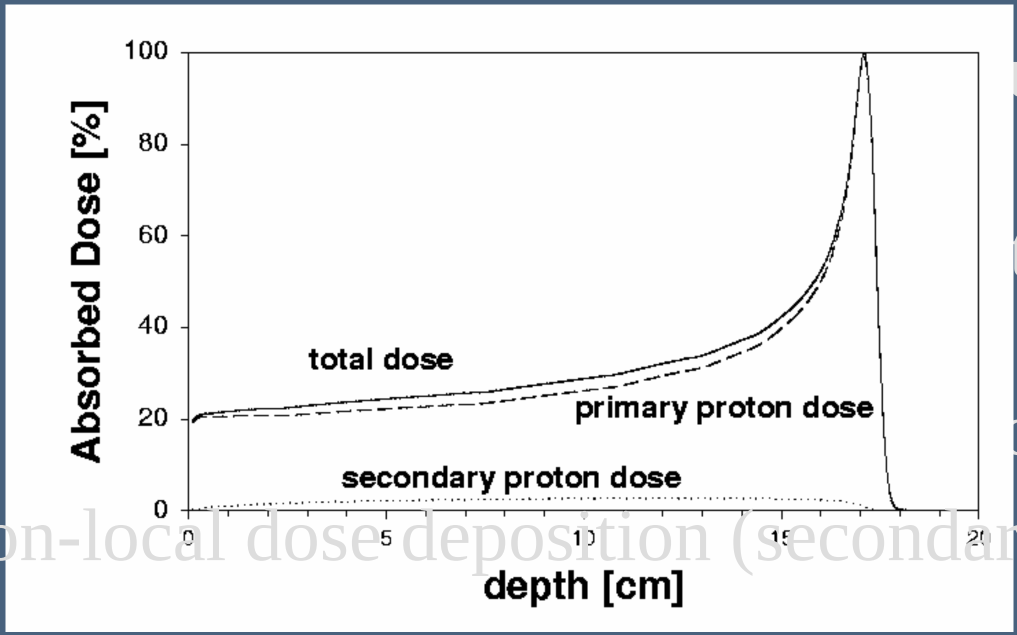


Nuclear interactions of protons





Elastic nuclear collision (large θ) Inelastic int.



Nuclear … uence

Nuclear … ticles and thus to

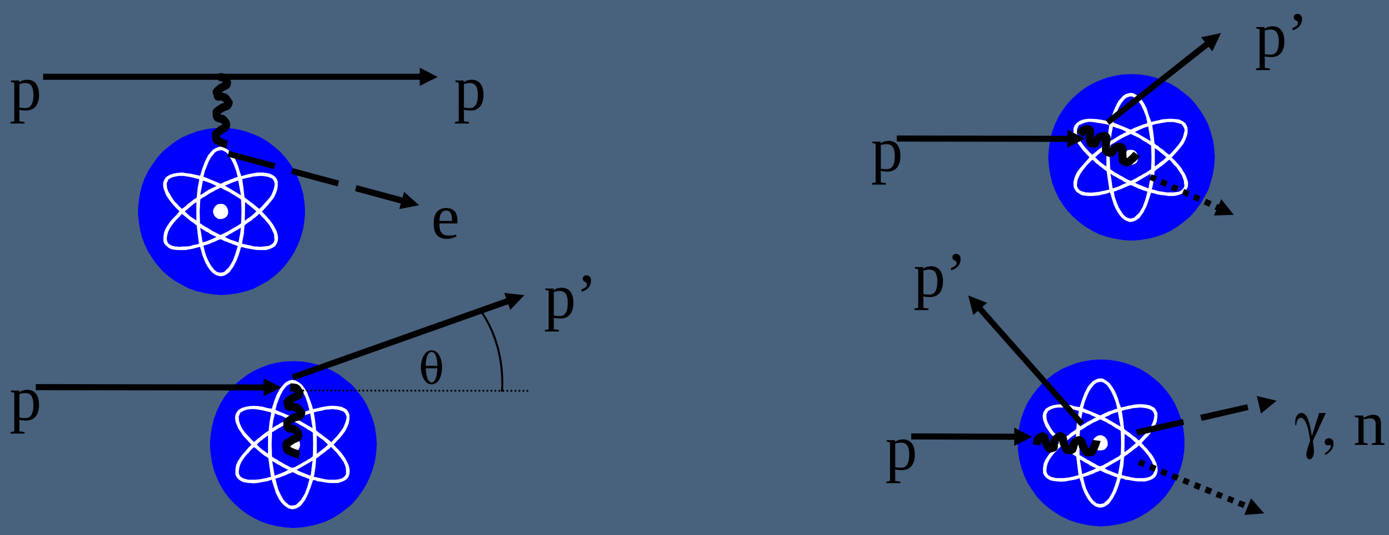
- lo … otons)
- non-local dose deposition (secondary neutrons)

Monte Carlo

Probability Density Function

expresses the relative likelihood that a variable will have a certain value

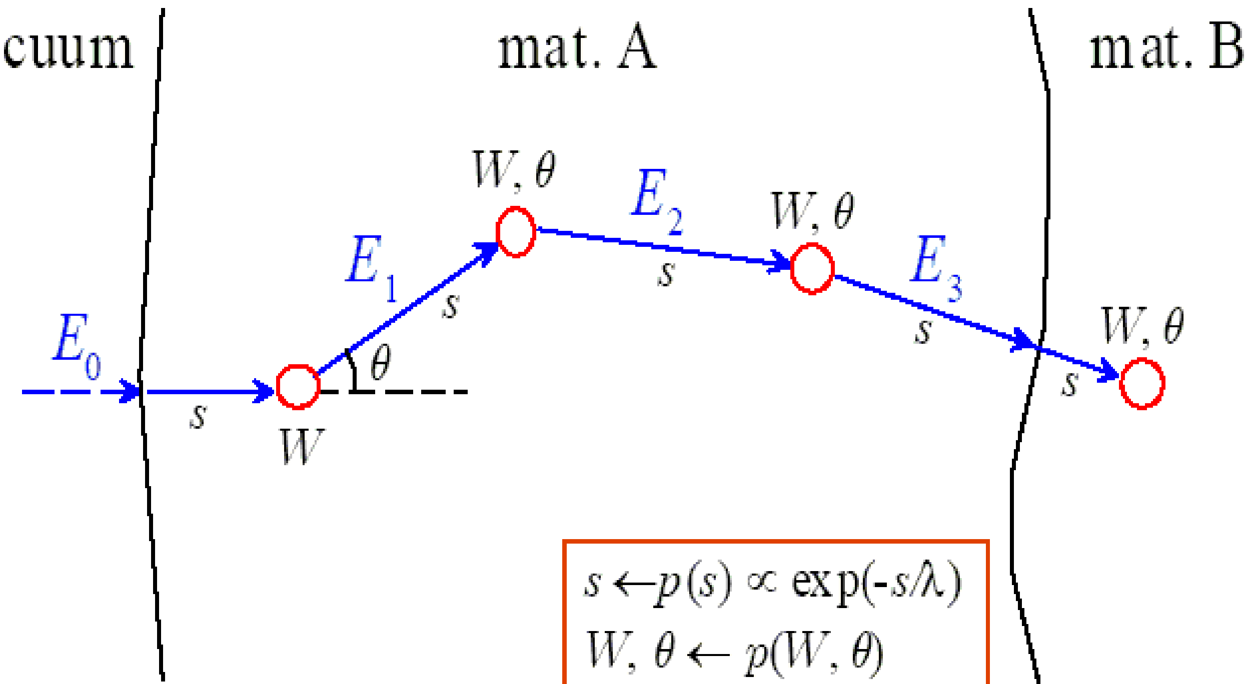
$$f(x) \geq 0 \text{ on } [a,b] \qquad \int_a^b f(x)dx = 1$$



Introduction: Monte Carlo

● Detailed (analogue) simulation

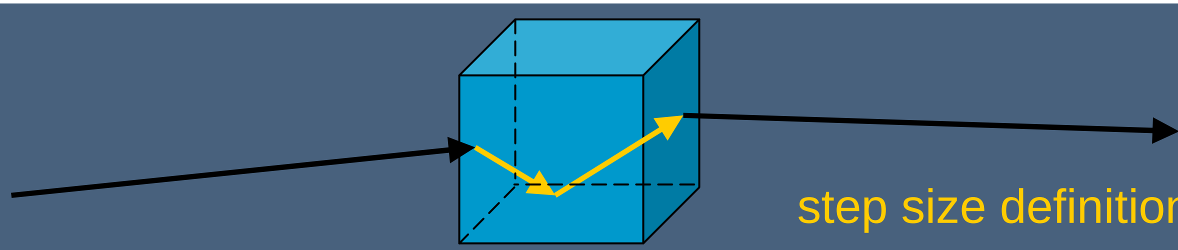
- All interaction events are simulated in chronological succession:



$$s \leftarrow p(s) \propto \exp(-s/\lambda)$$
$$W, \theta \leftarrow p(W, \theta)$$

- The method is nominally exact (for energies higher than ~ 1 keV)
- Feasible only for **photons** and **low-energy electrons and positrons**
- High-energy electrons and positrons are more difficult...

CERN 27/06/2006



step size definition

Condensed history algorithms

group many charged particles track segments into one single ‘condensed’ step

grouped interactions

- elastic scattering on nucleus
  - multiple Coulomb scattering
- soft inelastic collisions
  - collision stopping power
- etc

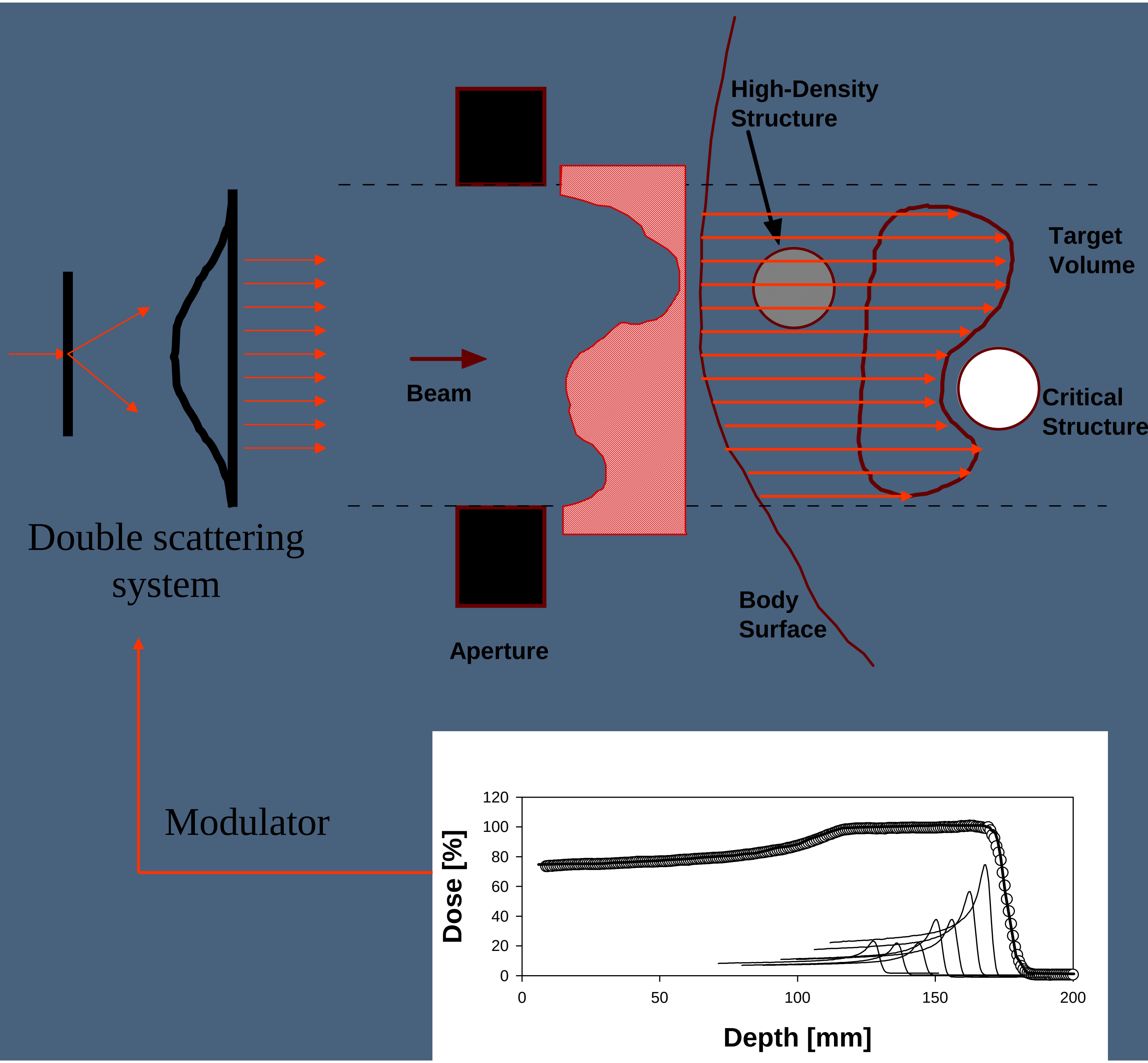
discrete interactions

- ‘hard’ d-ray production
  - energy > cut
- ‘hard’ bremstrahlung emission
  - energy > cut
- etc

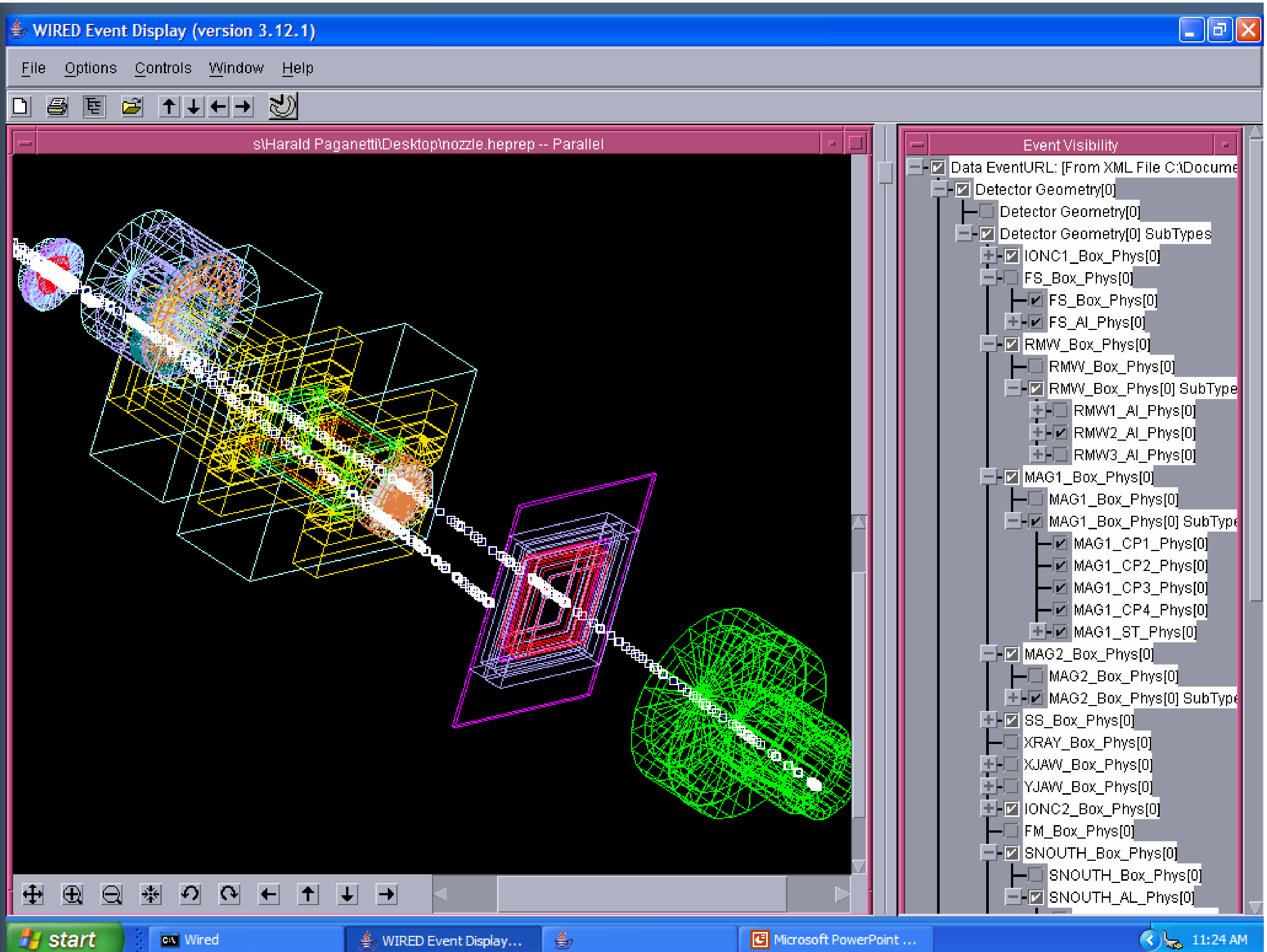
Monte Carlo applications to proton radiation therapy

- **Quality assurance**
  - **Treatment head simulation**
- **Patient dose calculations**
  - **Treatment head simulation**
  - **Phase space calculations**
  - **Patient (CT) simulations**
  - **Clinical implementation**
- **Neutron dose calculations**
  - **Treatment head simulation**
  - **Patient simulations**

Treatment Head Simulation



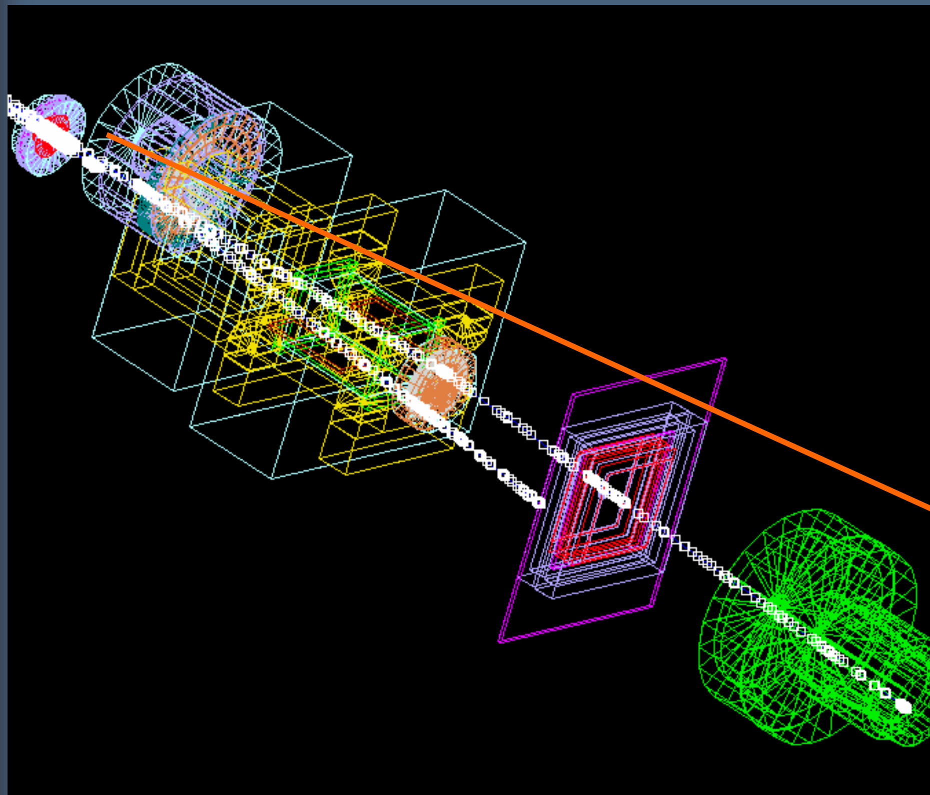
Treatment Head Simulation

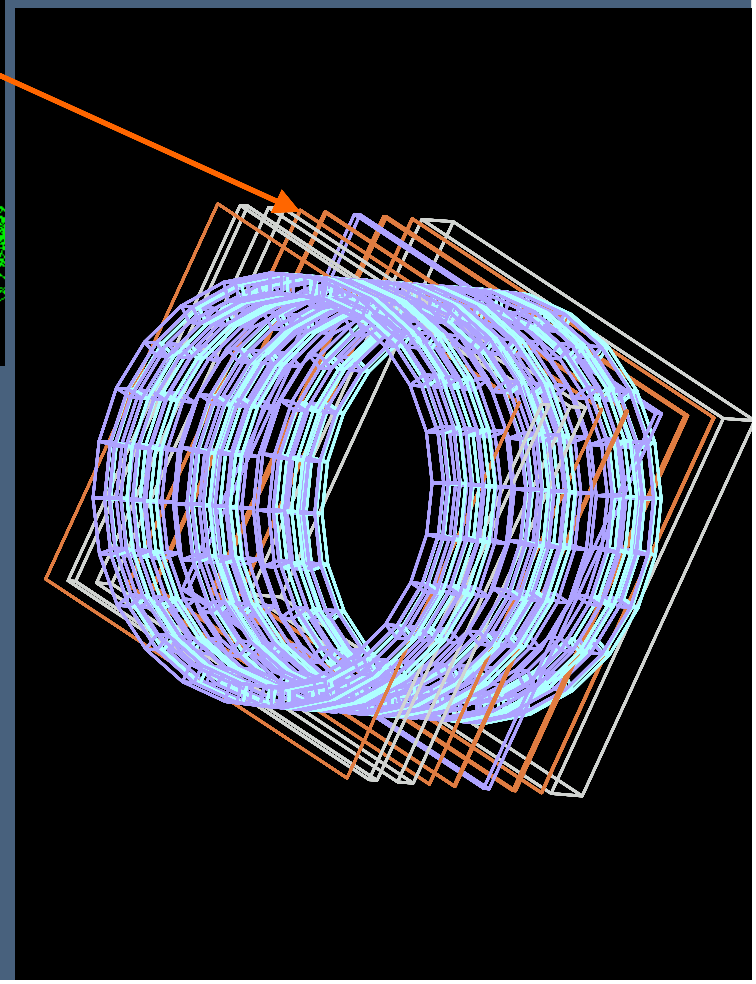


Monte Carlo model of the nozzle (~1000 objects)

Treatment Head Simulation

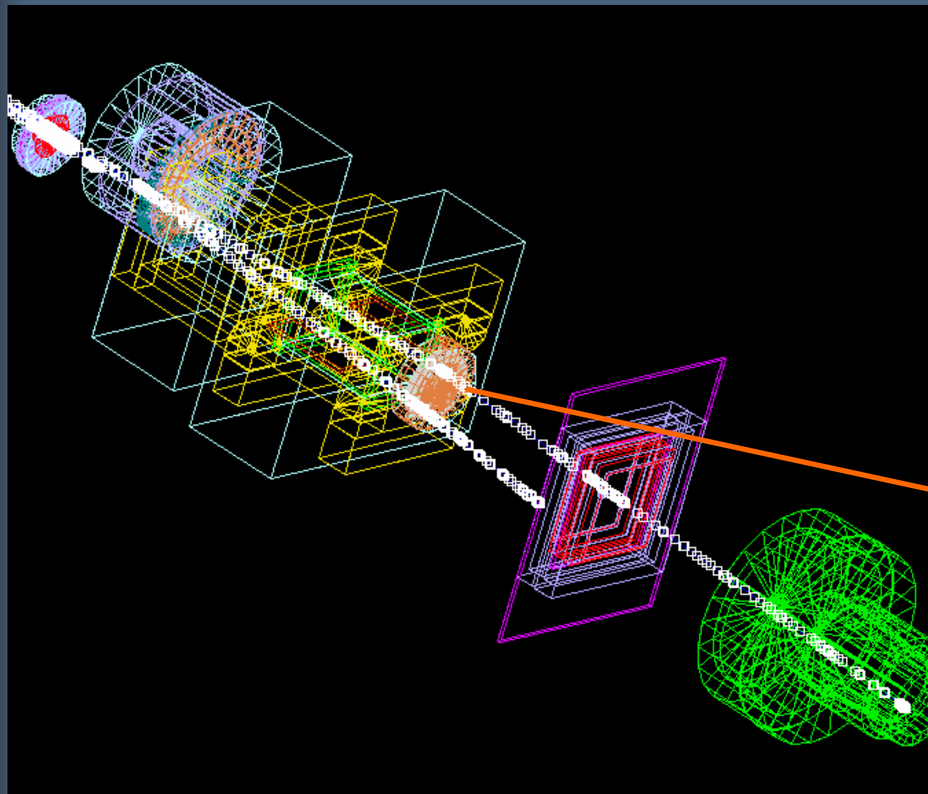
Monte Carlo model of the nozzle at the FHBPTC

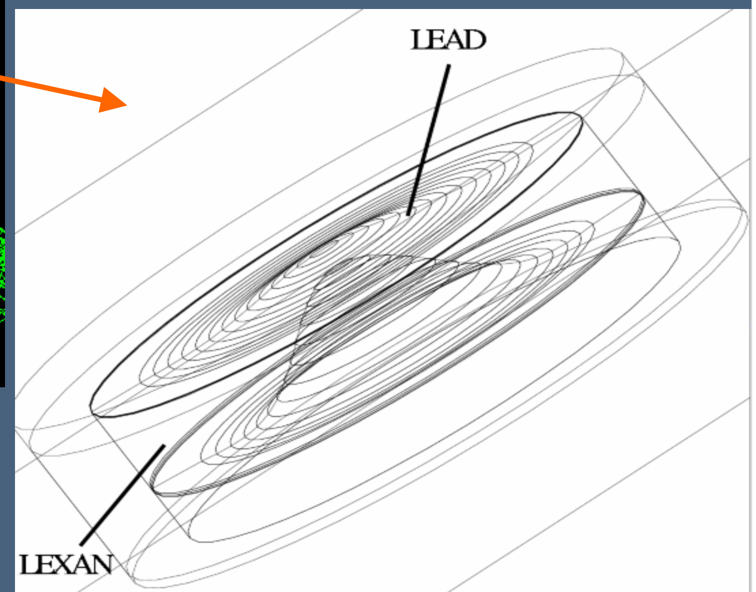


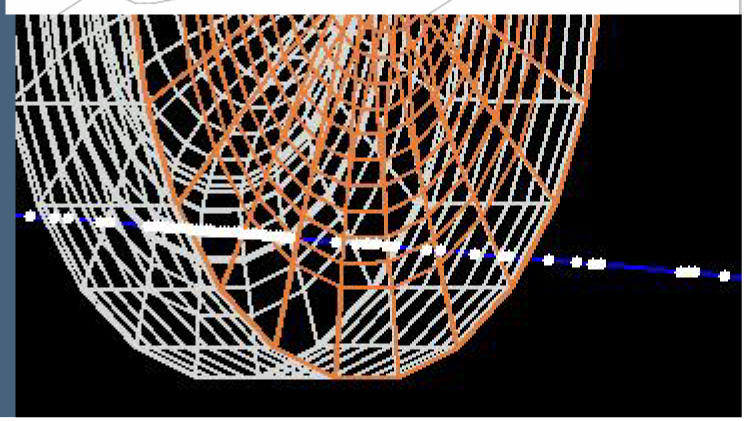


Treatment Head Simulation

Monte Carlo model of the nozzle at the FHBPTC

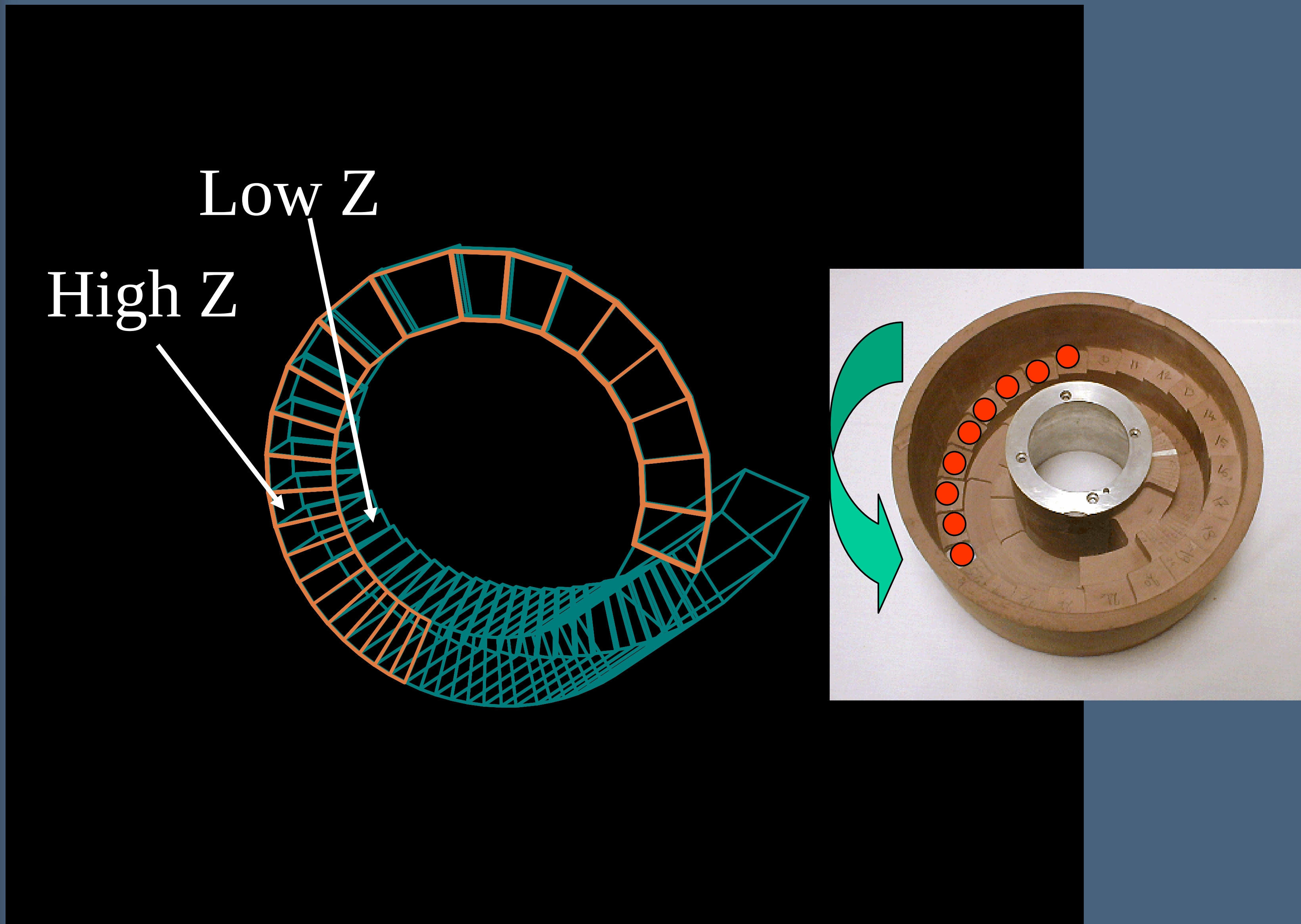






Treatment Head Simulation

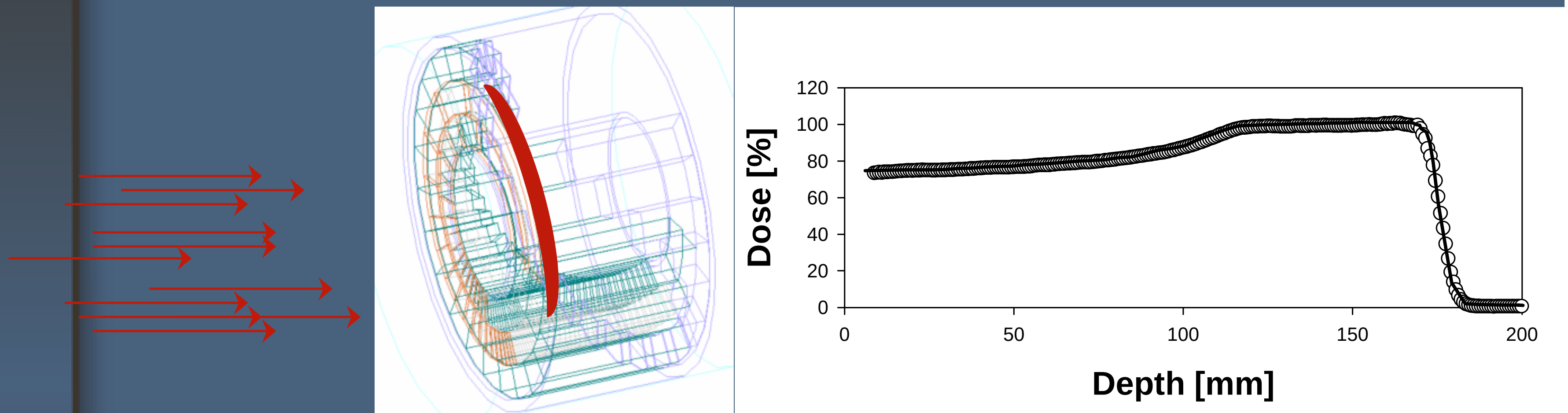
4D Monte Carlo: Geometry changes during the simulation via C++ class architecture



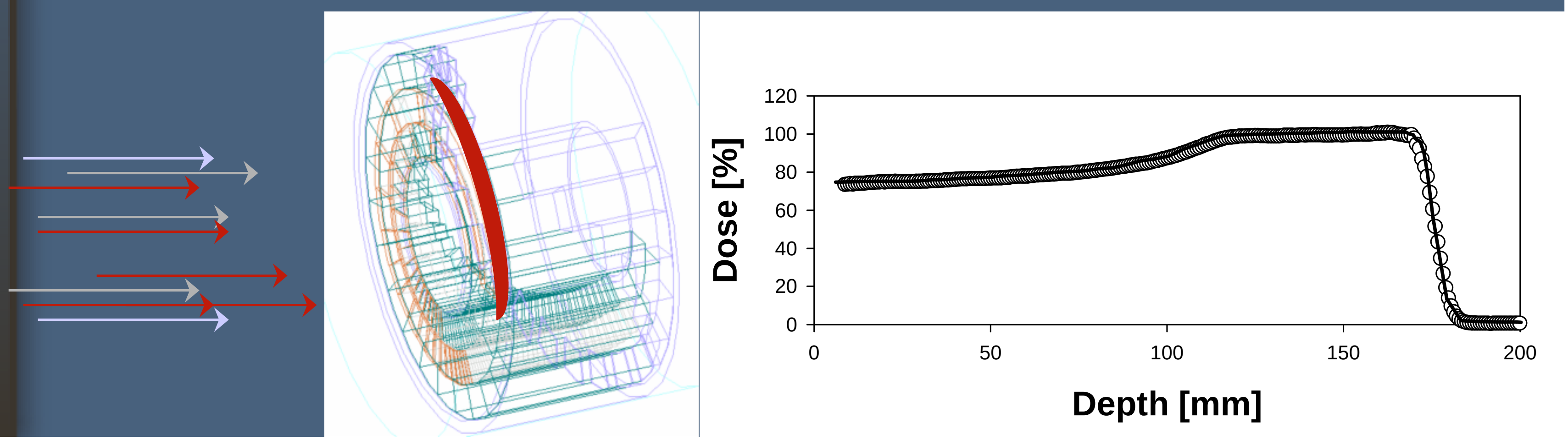
Treatment Head Simulation

Range Modulator Wheel Issues

1. Beam Gating

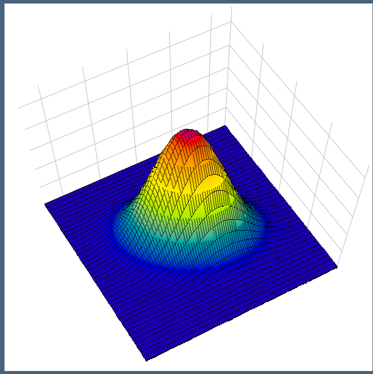


2. Beam Current Modulation



Parameters to characterize the beam at nozzle entrance

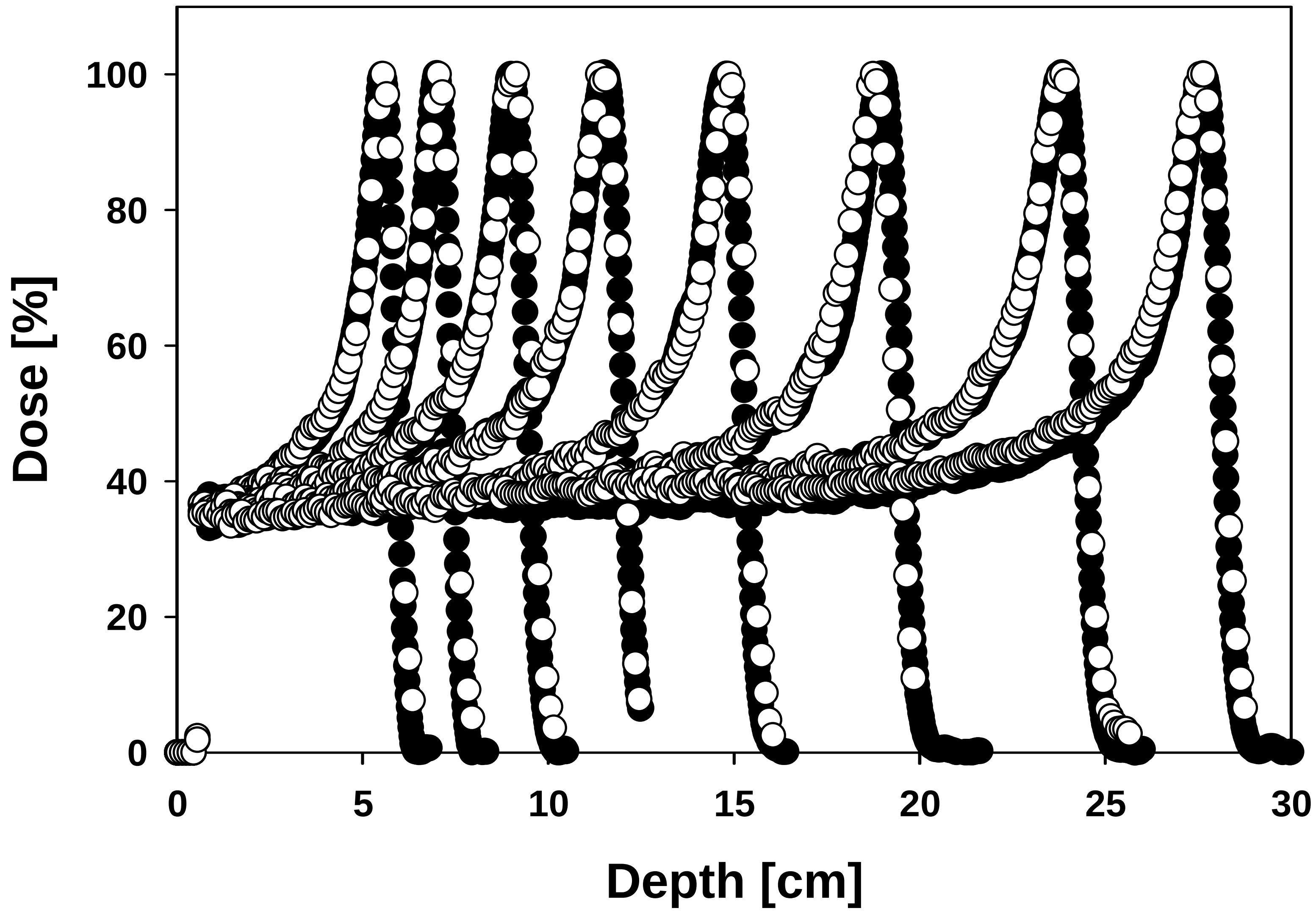
1. Beam size and spread	(IC measurement)
2. Beam angular spread	(manufacturer info)
3. Beam energy (range!)	(control system)
4. Beam energy spread	(manufacturer info, measured)



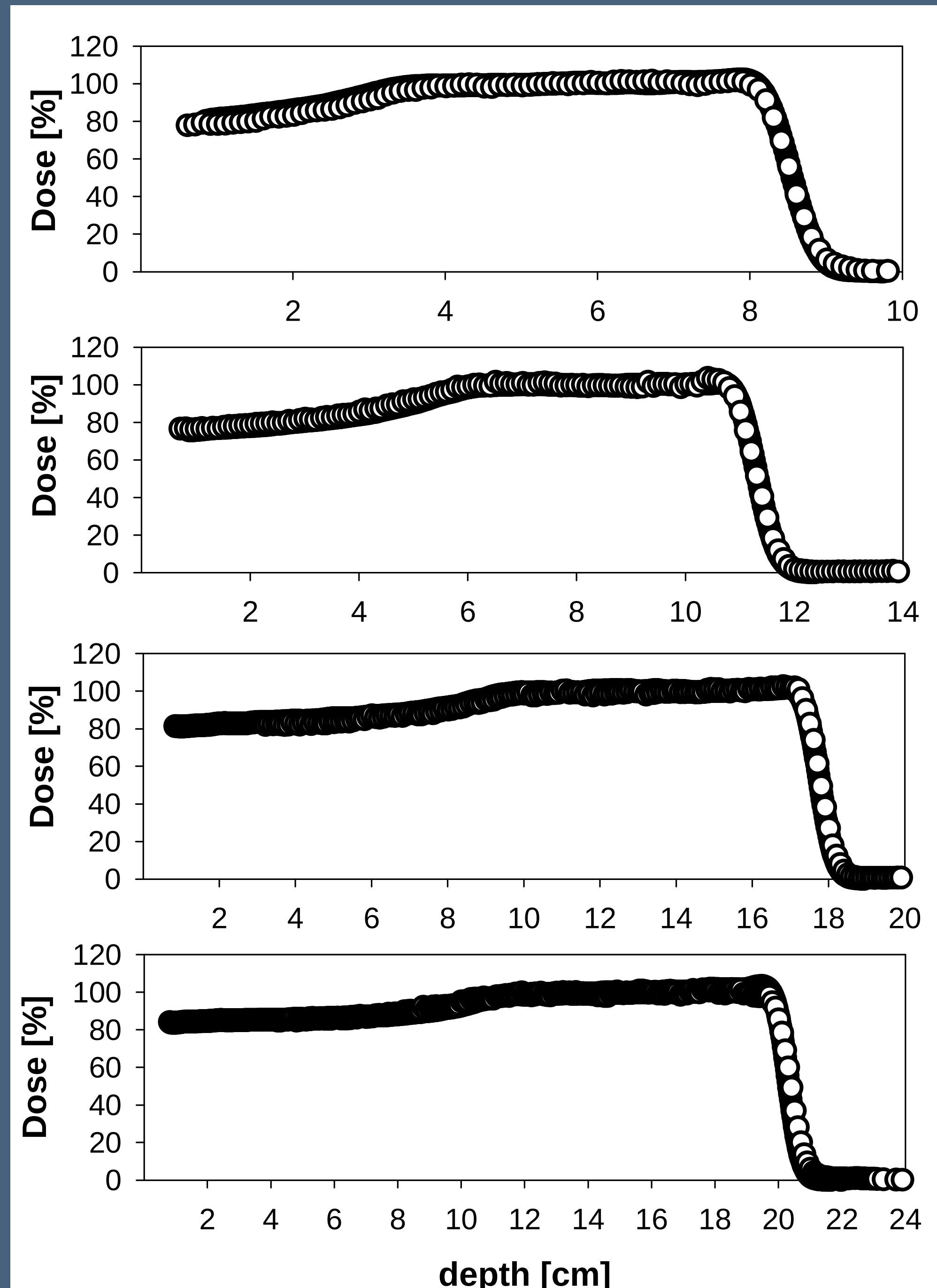
Are these parameters correlated ?

“Commissioning” of the Monte Carlo

Treatment Head Simulation

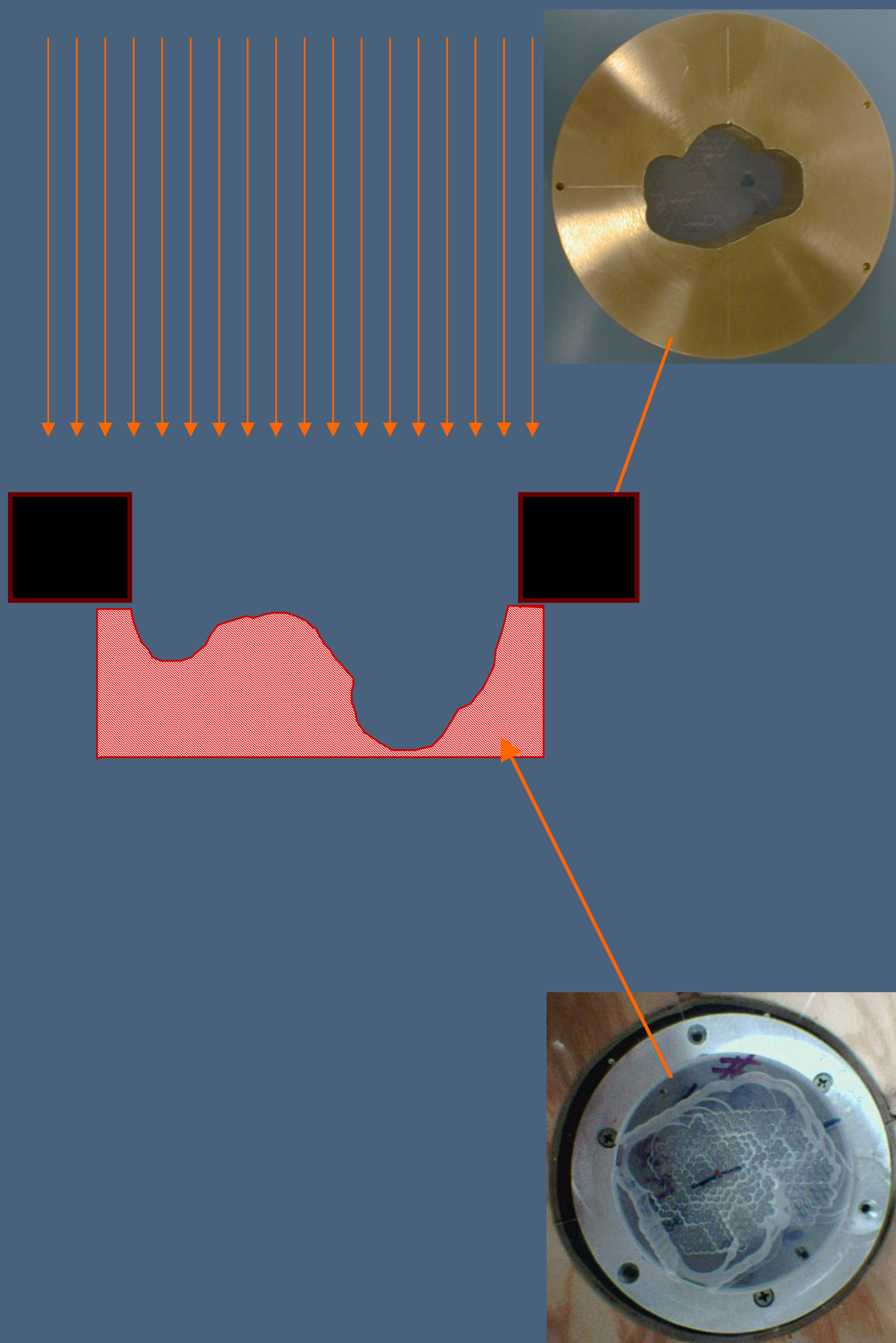


Treatment Head Simulation



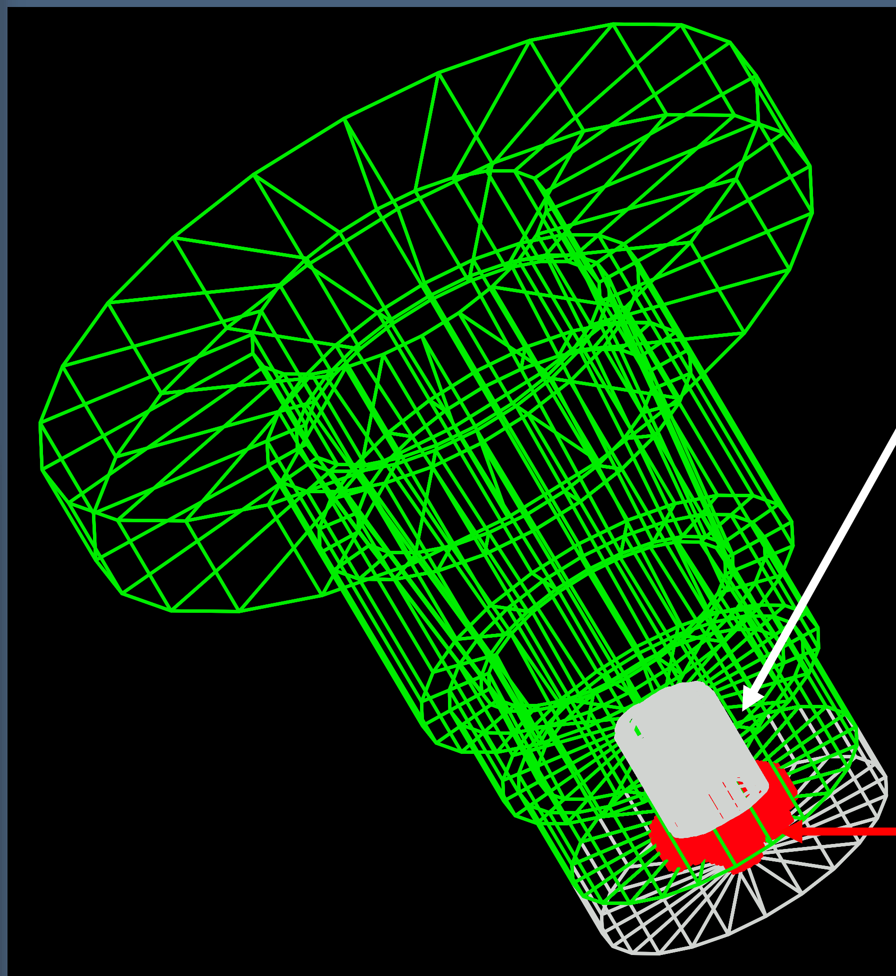
Treatment Head Simulation

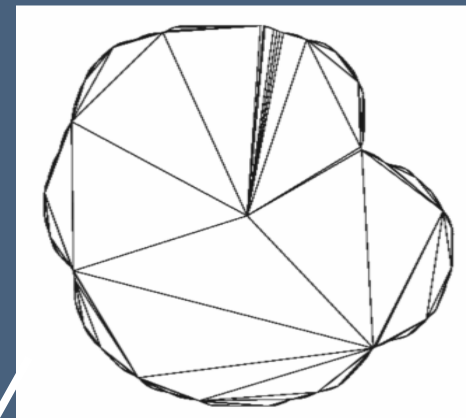
Aperture and Compensator

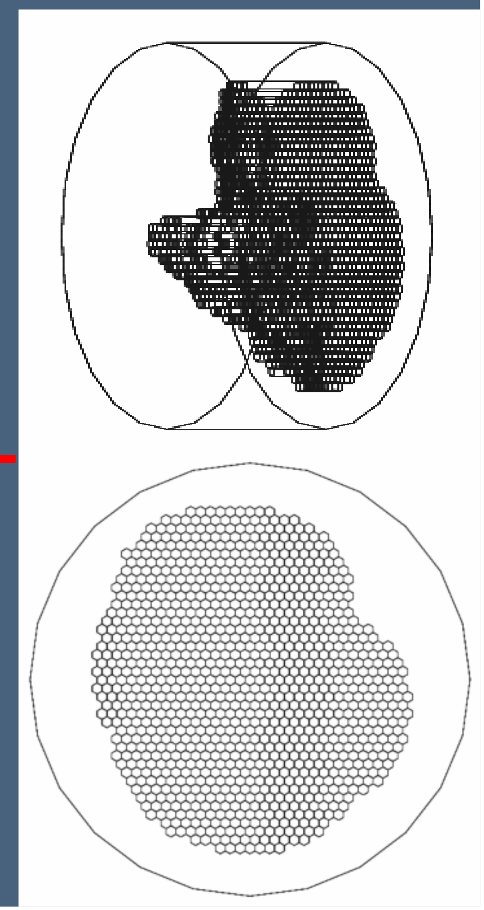


Treatment Head Simulation

Aperture and Compensator



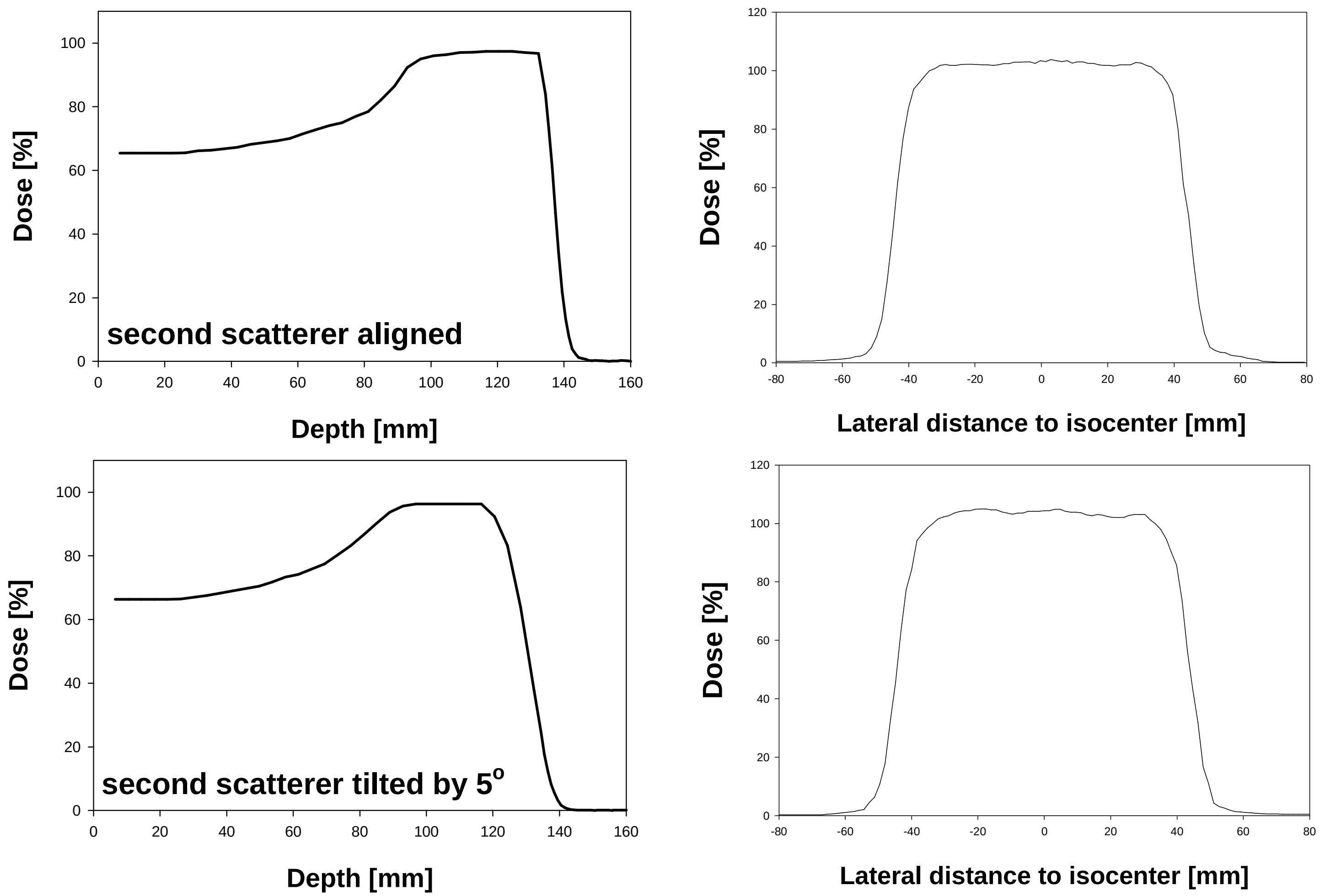




Monte Carlo simulation based on milling machine files

Example: Quality Assurance / Tolerance Studies

Alignment of second scatterer



Quality Assurance

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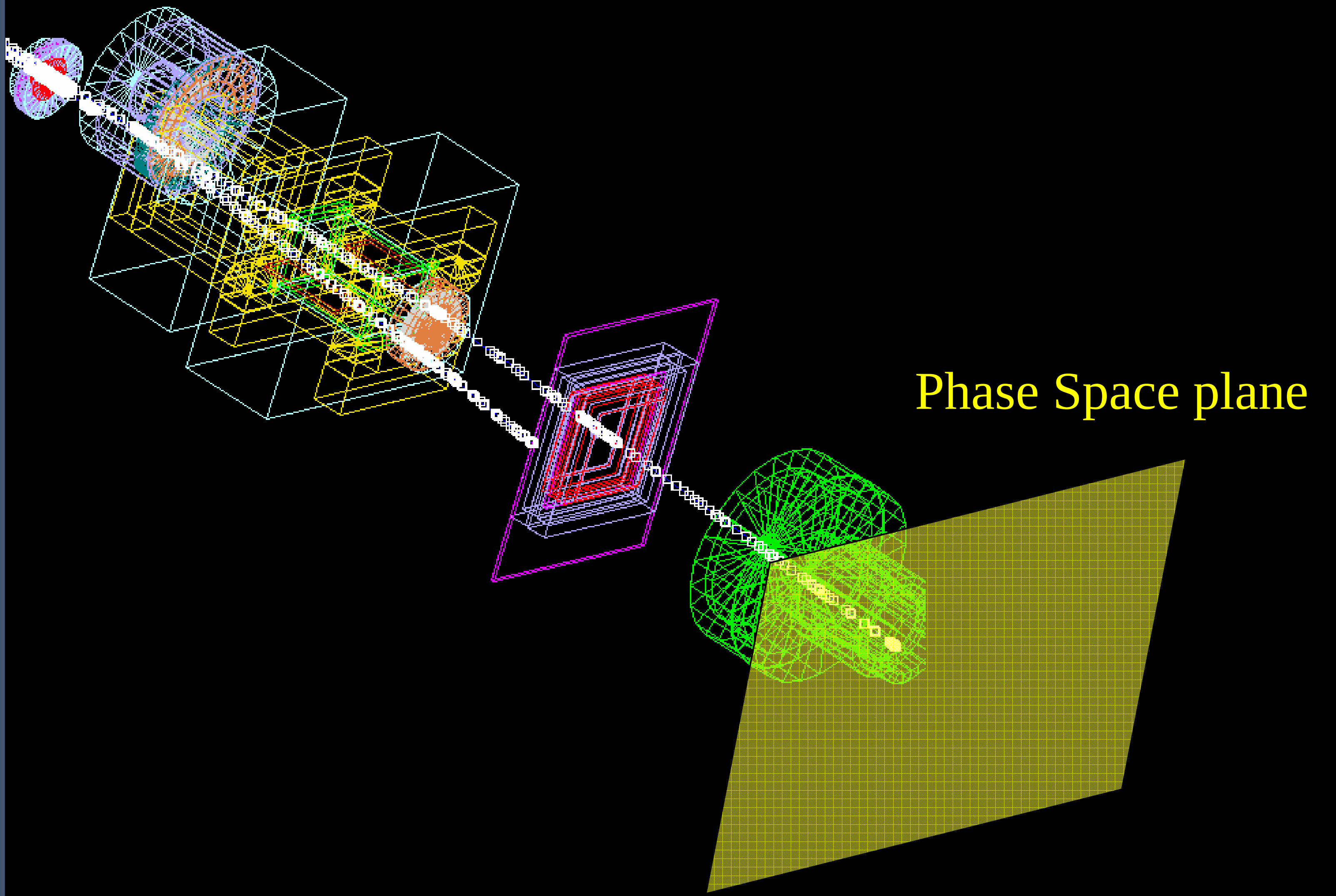
Treatment Head Simulation

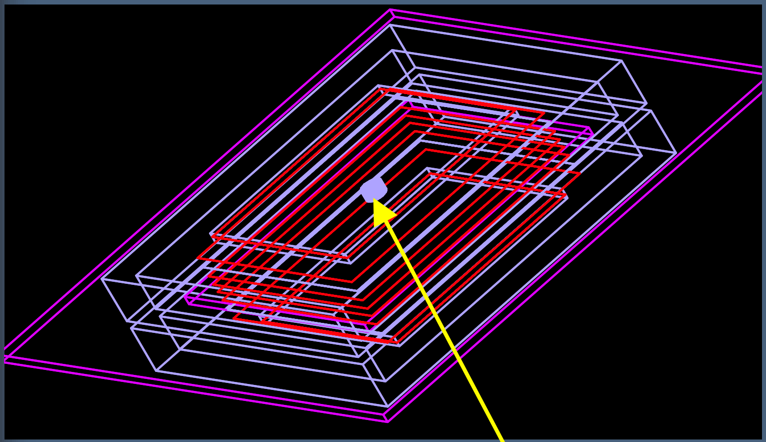


Phase Space Format Example: (part, x, y, p_x, p_y, p_z, flags …)

Treatment Head Simulation

Absolute dosimetry (output factor prediction)

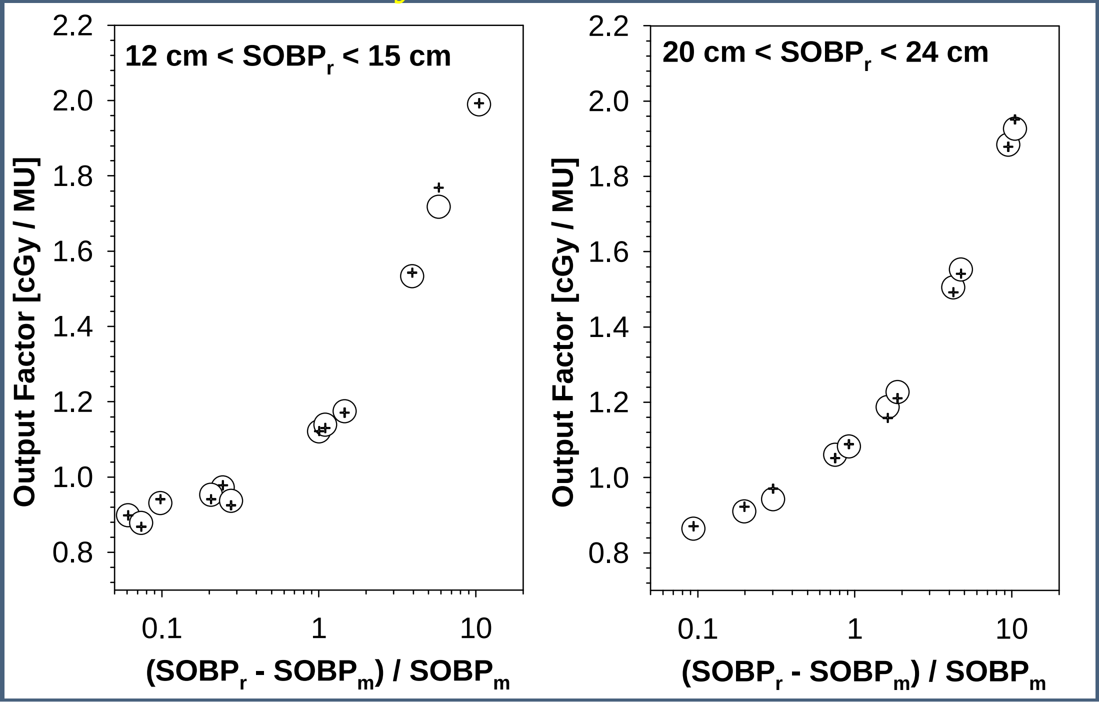
by simulating the ionization chamber output charge



Volume for absolute dosimetry

$$Output-Factor \cong \frac{D_{cal}}{i_{ic}}\left[{cGy}/{MU}\right]$$

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



Monte Carlo dose calculation

- Simulate a large number of particle histories until all primary and secondary particles are absorbed or have left the calculation grid
- Calculate and store the amount of absorbed energy of each particle in each region (voxel)
- The statistical accuracy of the dose is determined by the number of particle histories

HP1

Patient Simulation

Patient information

Example:

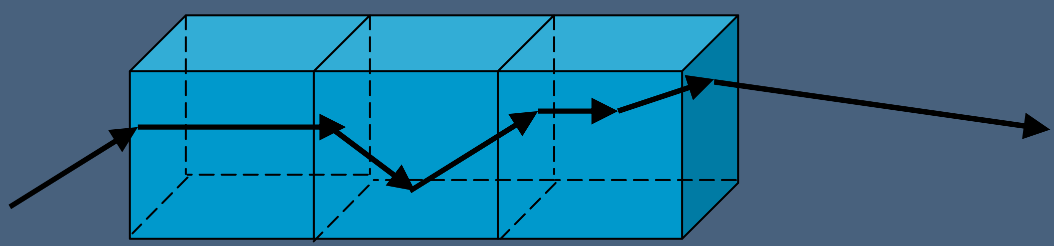
CT scan:

134 CT slices, 512 × 512 voxels/slice

0.488 mm × 0.488 mm × 1.25/2.5 mm

Treatment planning grid:

2.0 mm × 2.0 mm × 2.5 mm



Challenges:

- **Memory Consumption**
- **Many boundary crossings**

Slide 24

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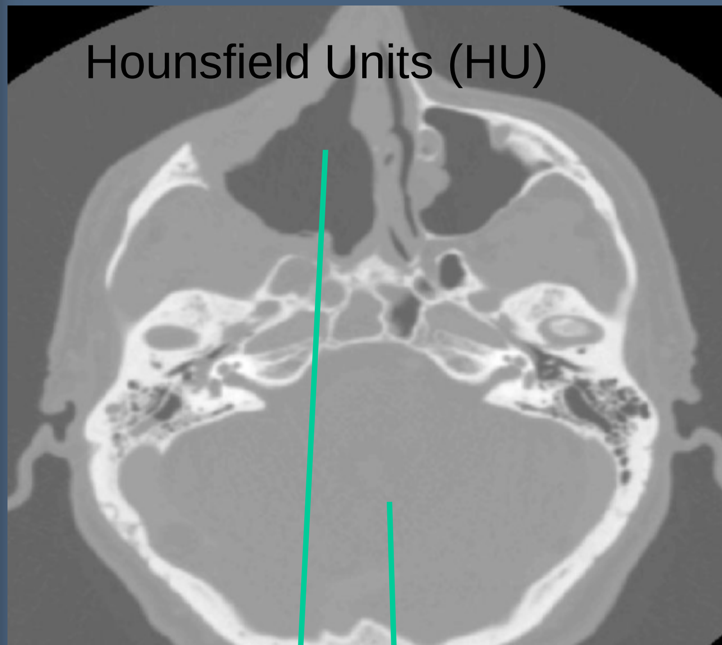
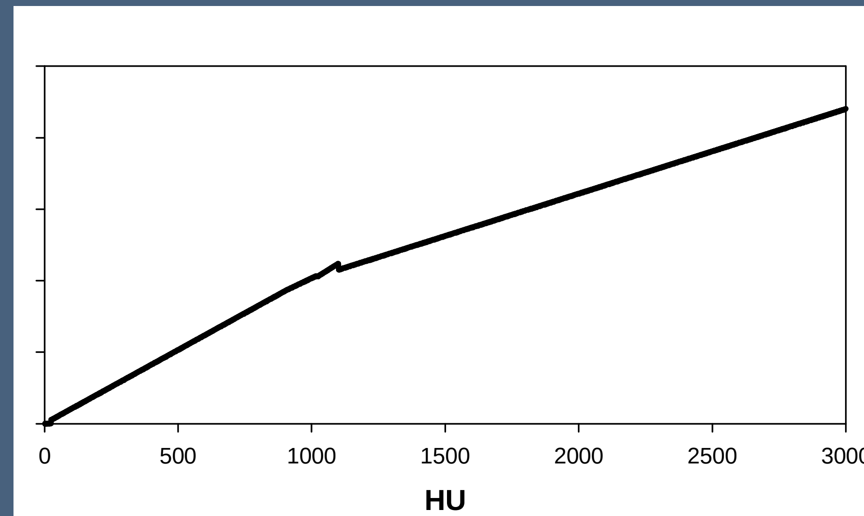
CT conversion

Patient Simulation



Density; Material comp.

Density; Material comp.



Photon Planning System

HU versus electron density

→ Dose-to-water

Proton Planning System

HU versus rel. stopping power

→ Dose-to-water

Monte Carlo

HU versus mass density

HU versus material

→ Dose-to-medium (tissue)

– HU conversion –

Patient Simulation

Group	HU range	Density [g/cm3] (center of HU bin)	Density correction	H	C	N	O	Na	Mg	P	S	Cl	Ar	K	Ca	Ti
				Material composition weights [%]												
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

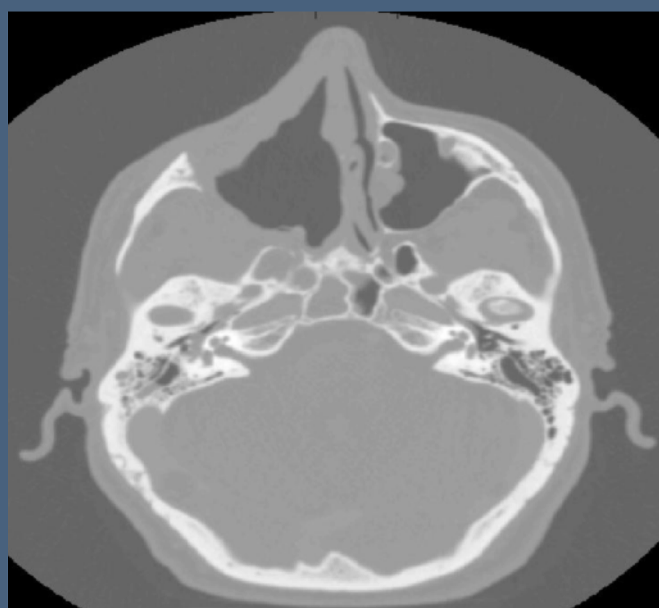
HU space is divided into 27 groups with members of each group sharing the same element composition but differ in mass density (4000 densities)

Patient Simulation

Gantry Angle

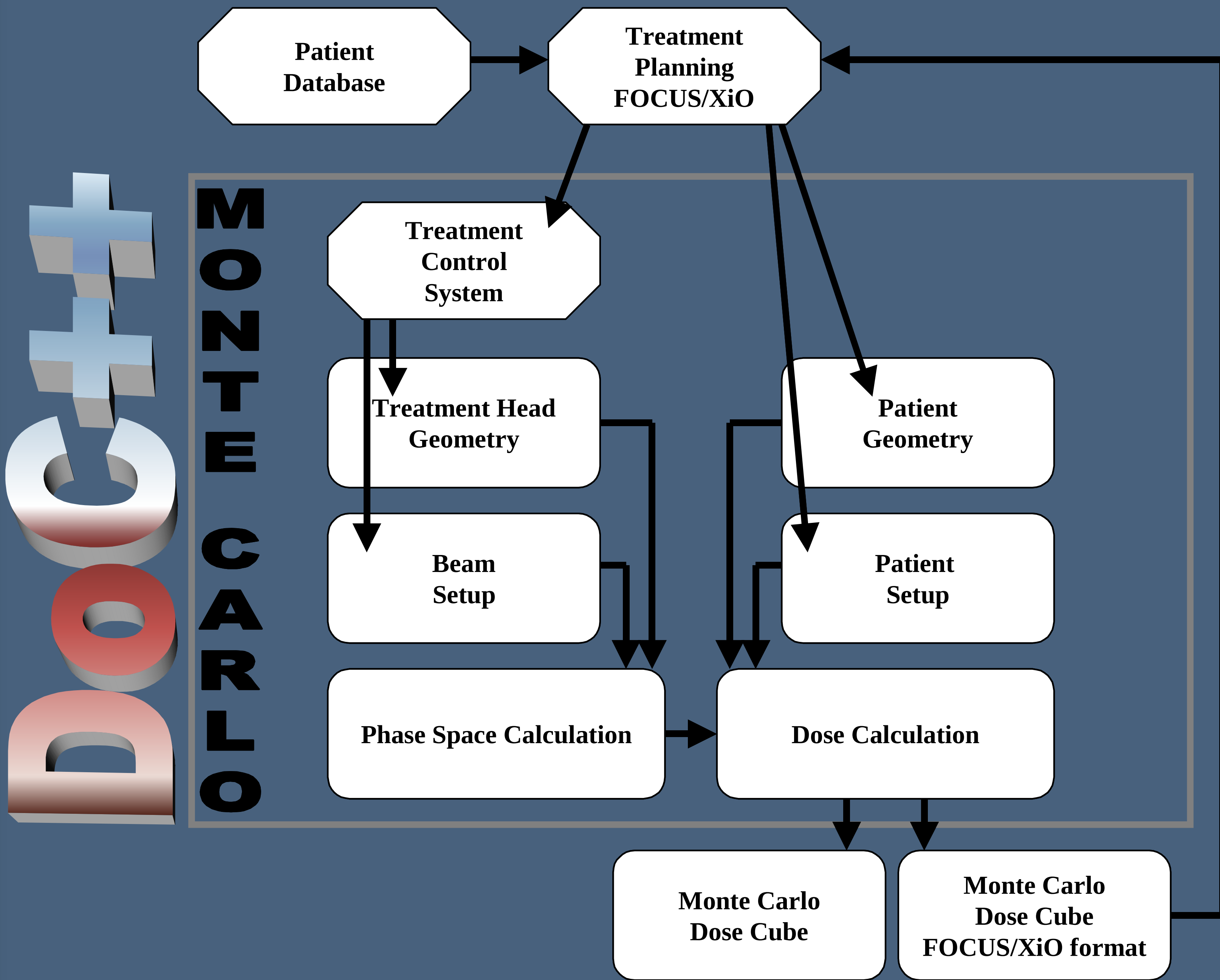
Position XYZ
Rotation
Pitch
Roll

Air Gap



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

Clinical Implementation

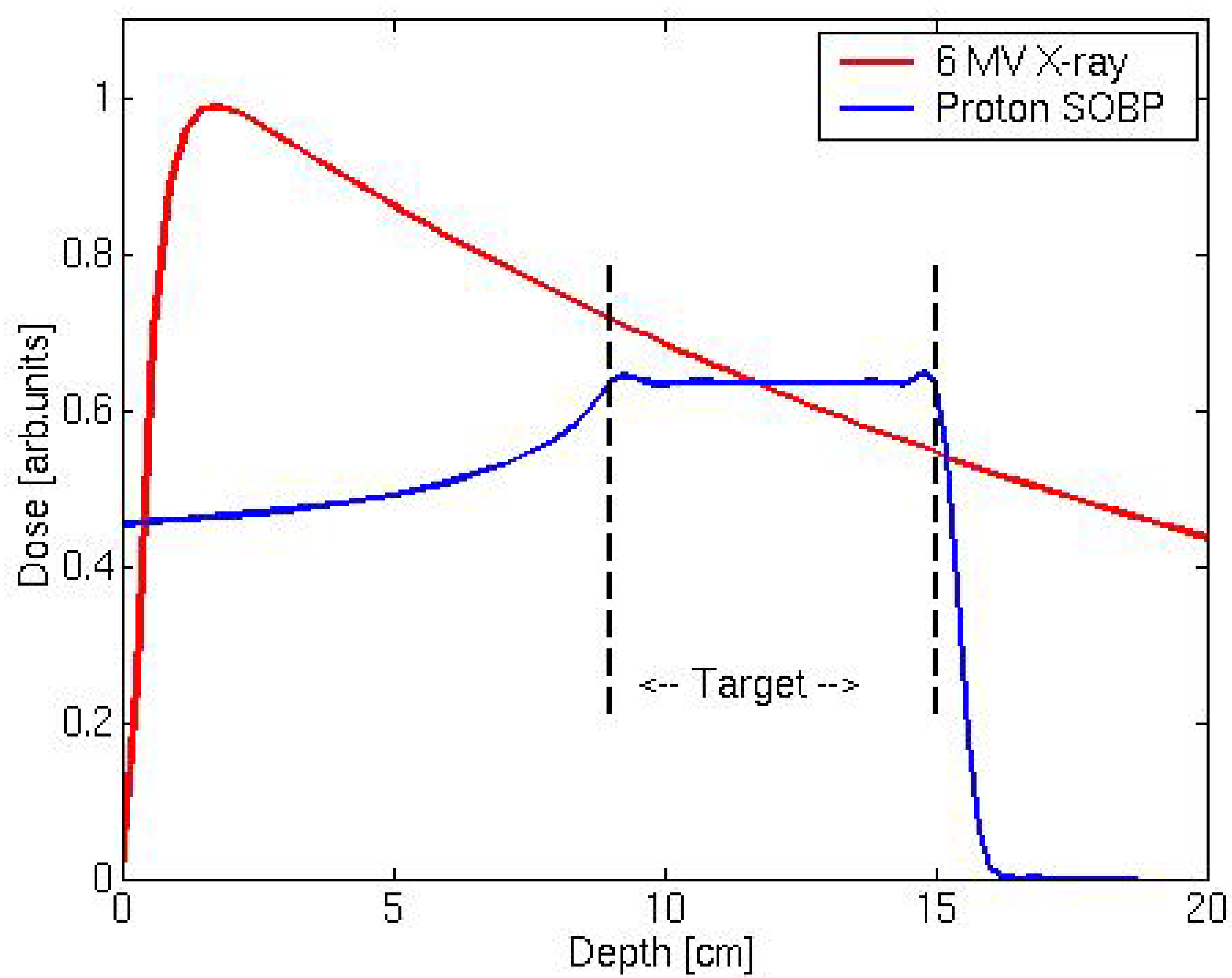


Example 1

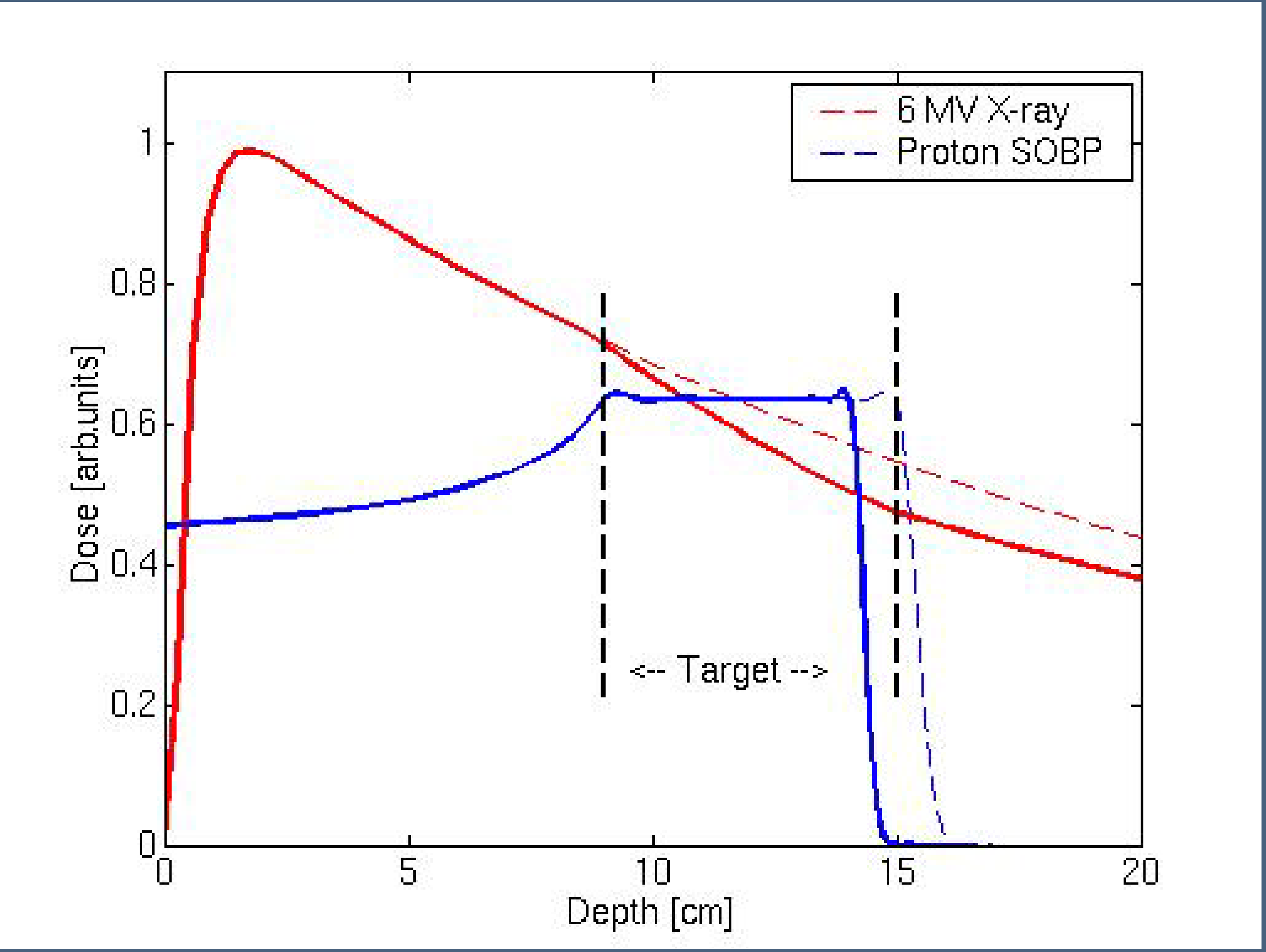
Case 1:
Para-spinal tumor
176 x 147 x 126 slices
voxels: 0.932 x 0.932 x 2.5-3.75 mm^3

Proton dose in the presence of range uncertainty

Clinical Examples



Proton dose in the presence of range uncertainty



Clinical Examples

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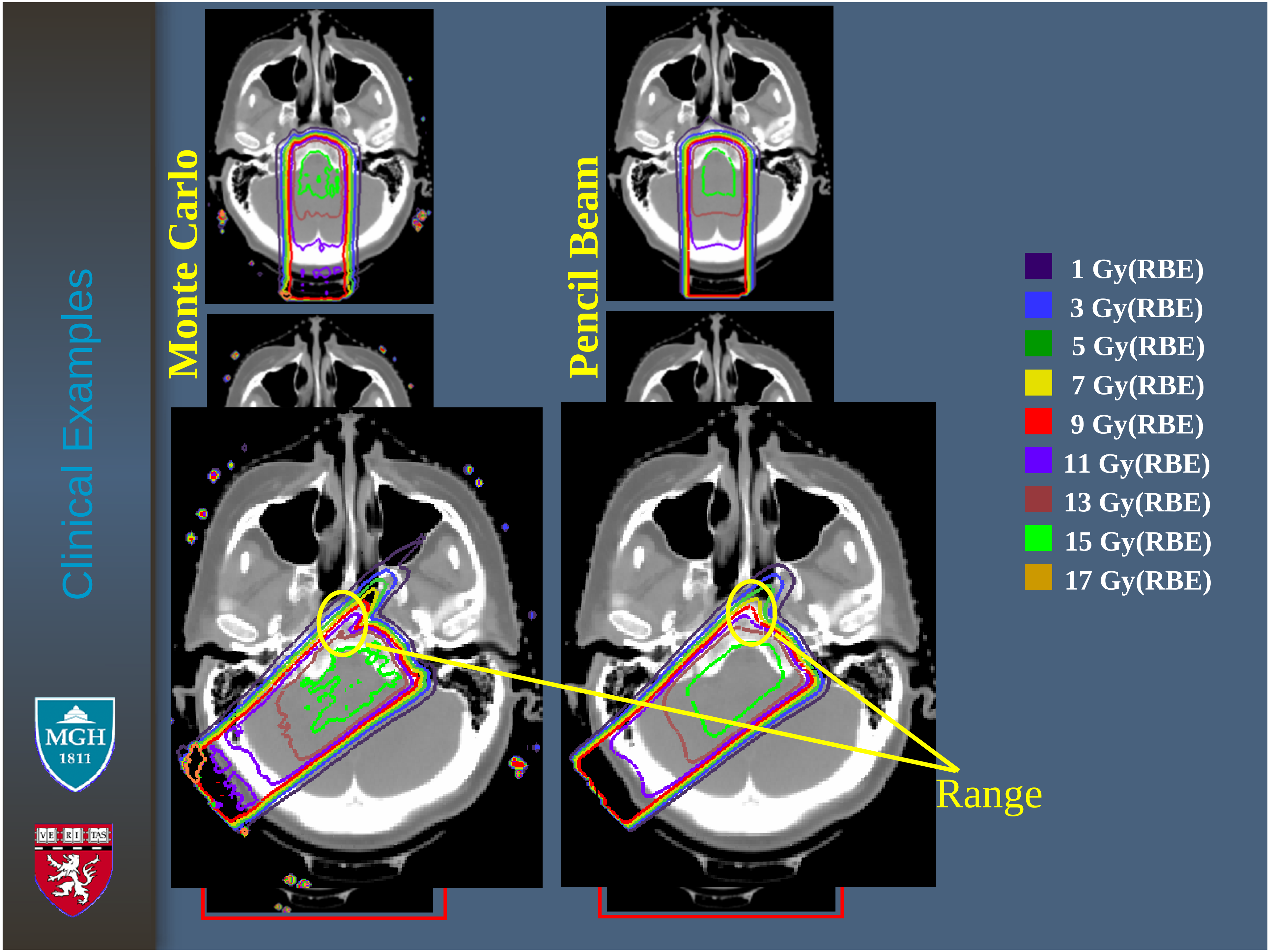
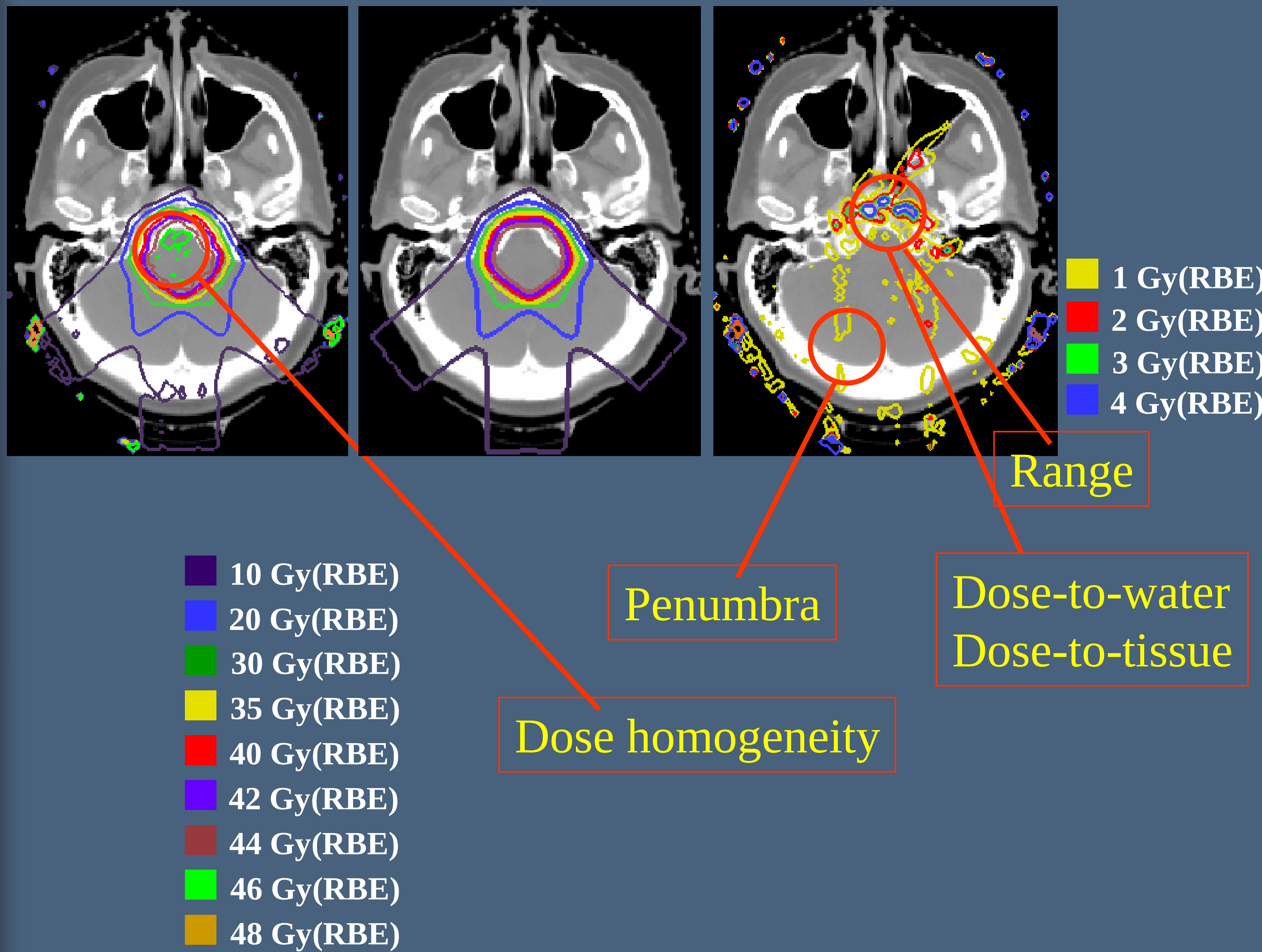
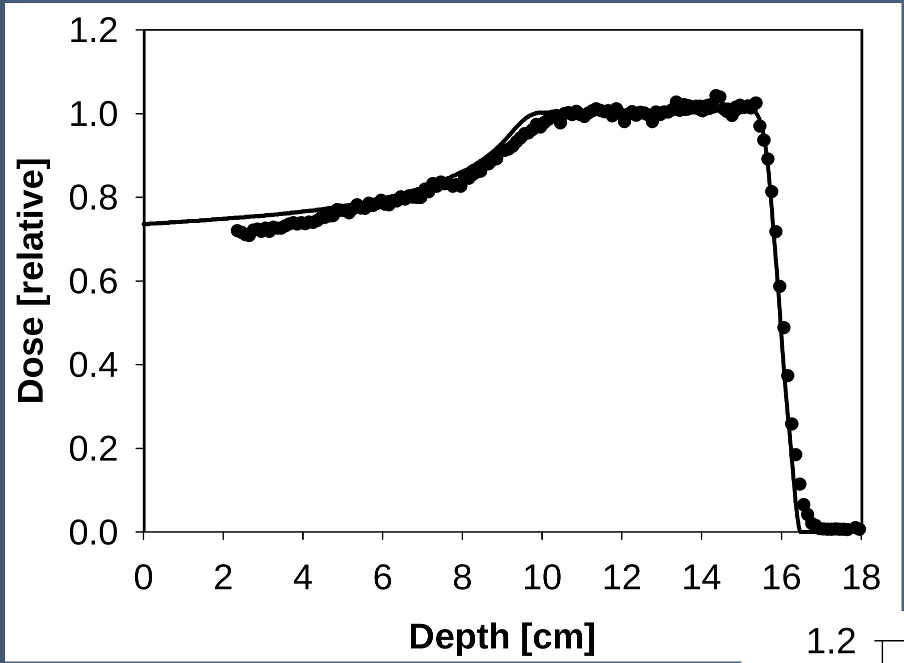

Clinical Examples
Monte Carlo
Pencil Beam
1 Gy(RBE)
3 Gy(RBE)
5 Gy(RBE)
7 Gy(RBE)
9 Gy(RBE)
11 Gy(RBE)
13 Gy(RBE)
15 Gy(RBE)
17 Gy(RBE)
Range
MGH
1811
VE RI TAS

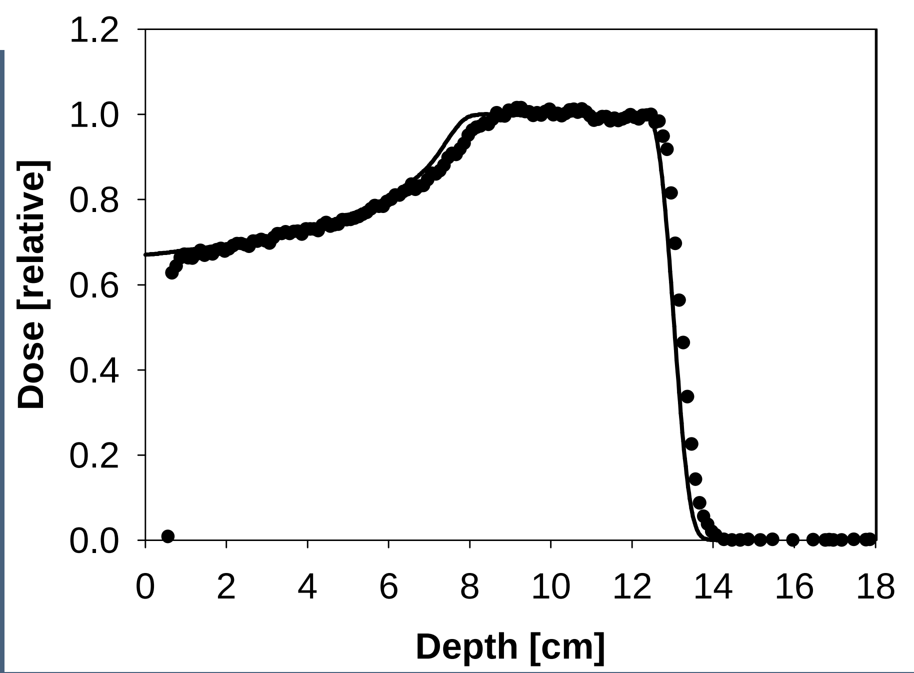
Clinical Examples



Planned SOBP versus delivered SOBP

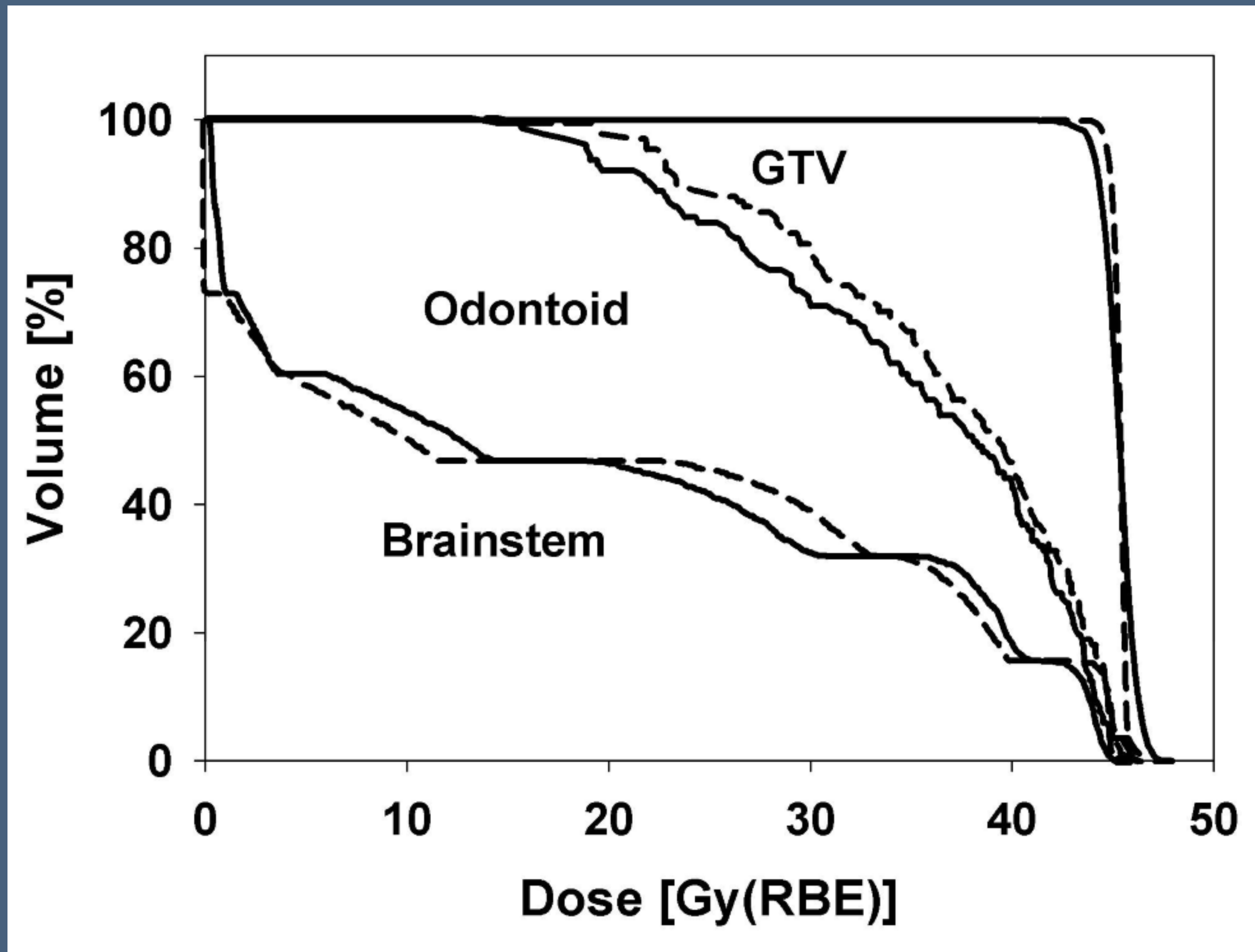
Clinical Examples





Clinical Examples

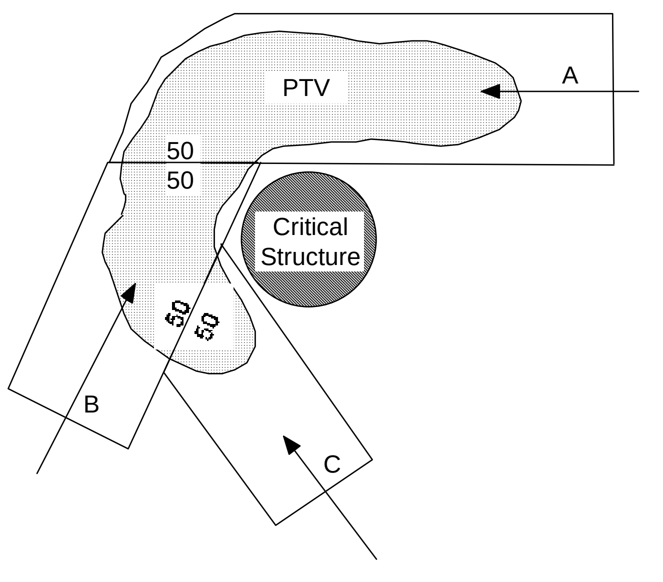
Total DVH



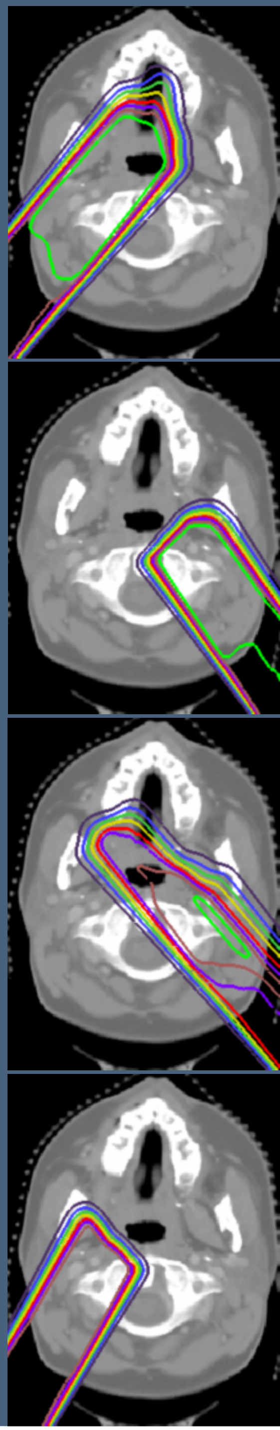
MC ——— **XiO** – – – –

Example 2

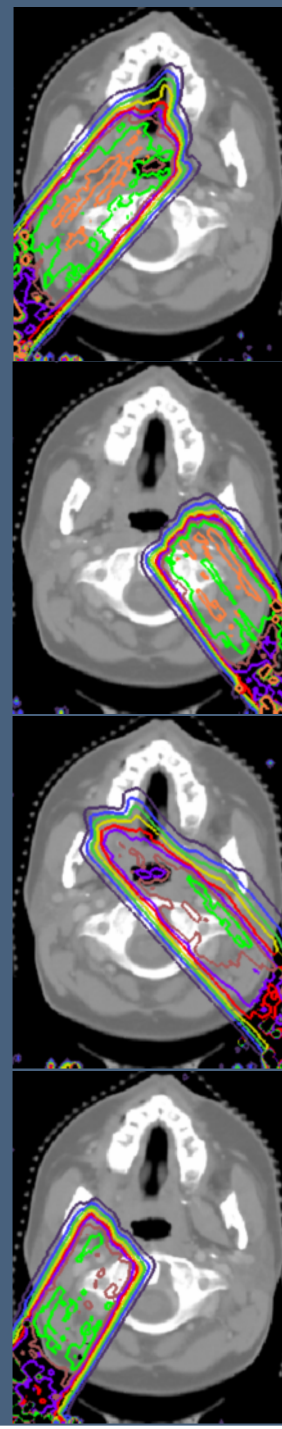
Case 3:
Maxillary sinus
121x121x101 slices
voxels: 0.656 x 0.656 x 1.25-3.75 mm^3



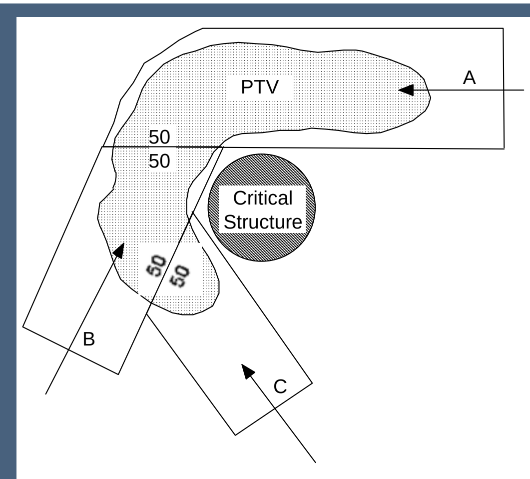
Clinical Examples



Monte Carlo

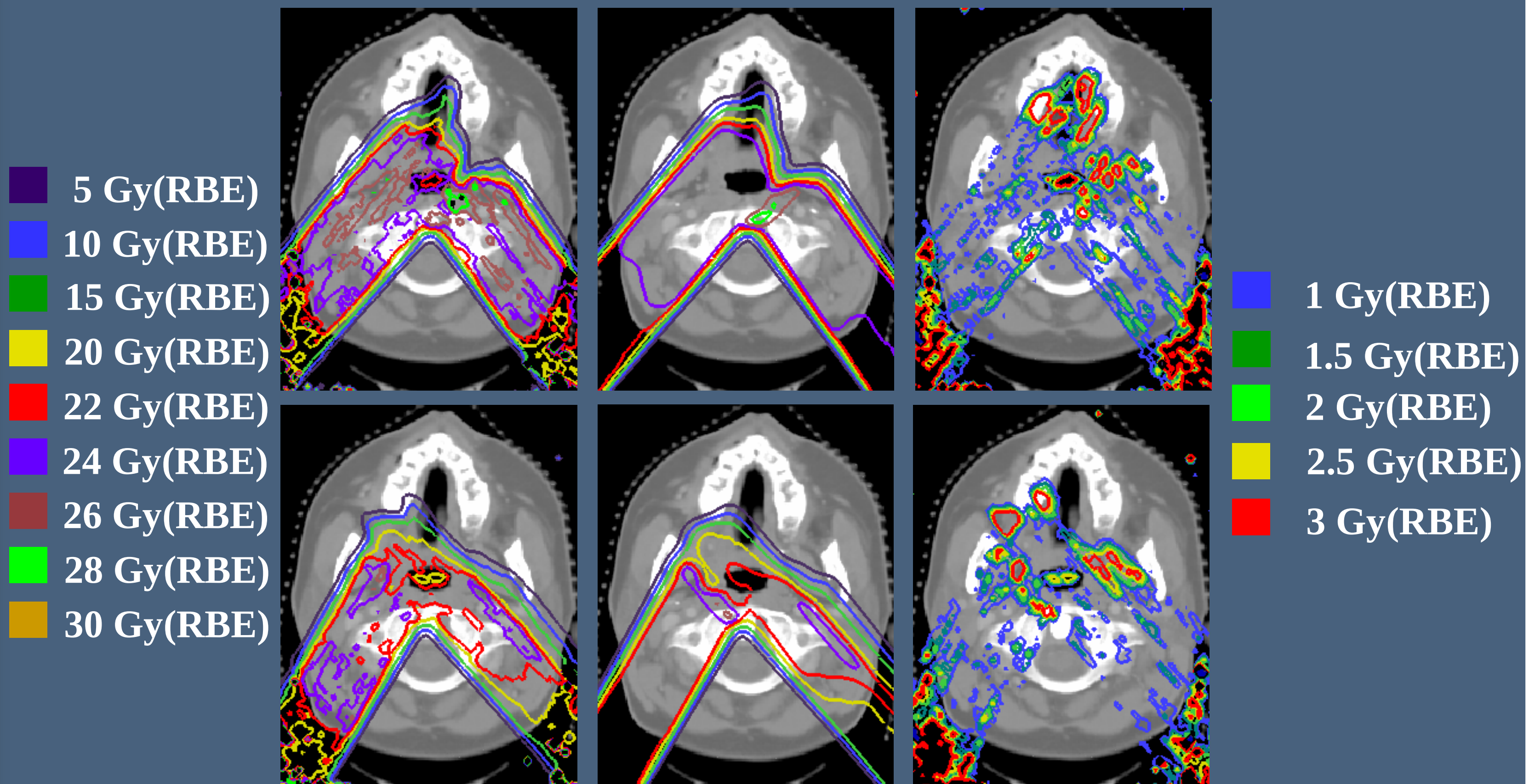


Pencil Beam



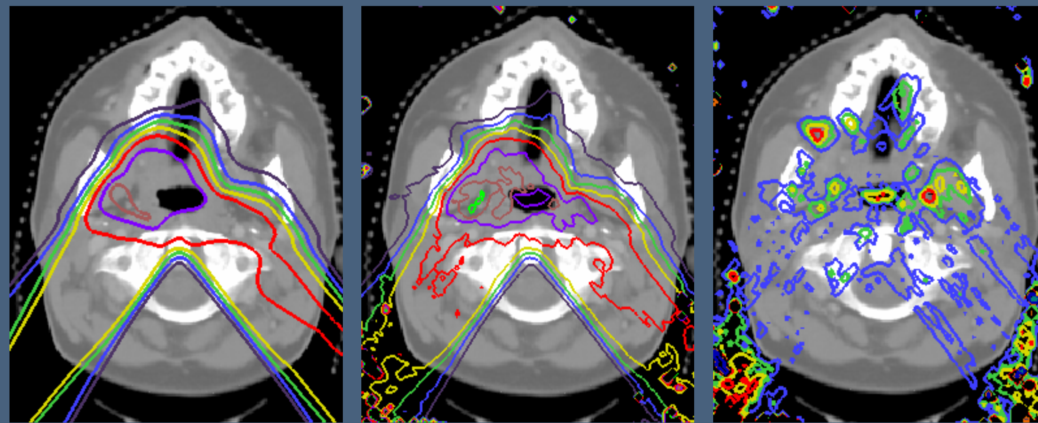
- 2 Gy(RBE)
- 6 Gy(RBE)
- 10 Gy(RBE)
- 14 Gy(RBE)
- 18 Gy(RBE)
- 20 Gy(RBE)
- 22 Gy(RBE)
- 24 Gy(RBE)
- 26 Gy(RBE)

Clinical Examples

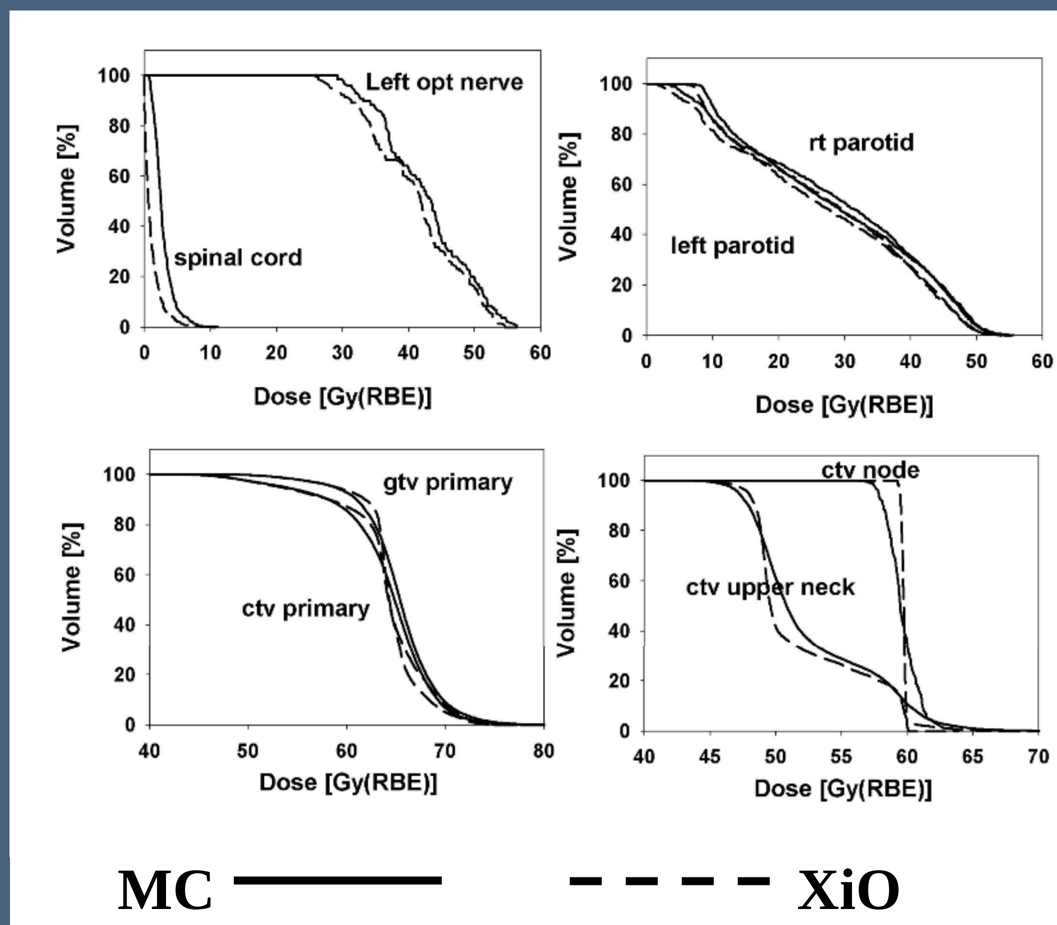


Clinical Examples

- 10 Gy(RBE)
- 20 Gy(RBE)
- 30 Gy(RBE)
- 40 Gy(RBE)
- 50 Gy(RBE)
- 60 Gy(RBE)
- 65 Gy(RBE)
- 70 Gy(RBE)
- 75 Gy(RBE)

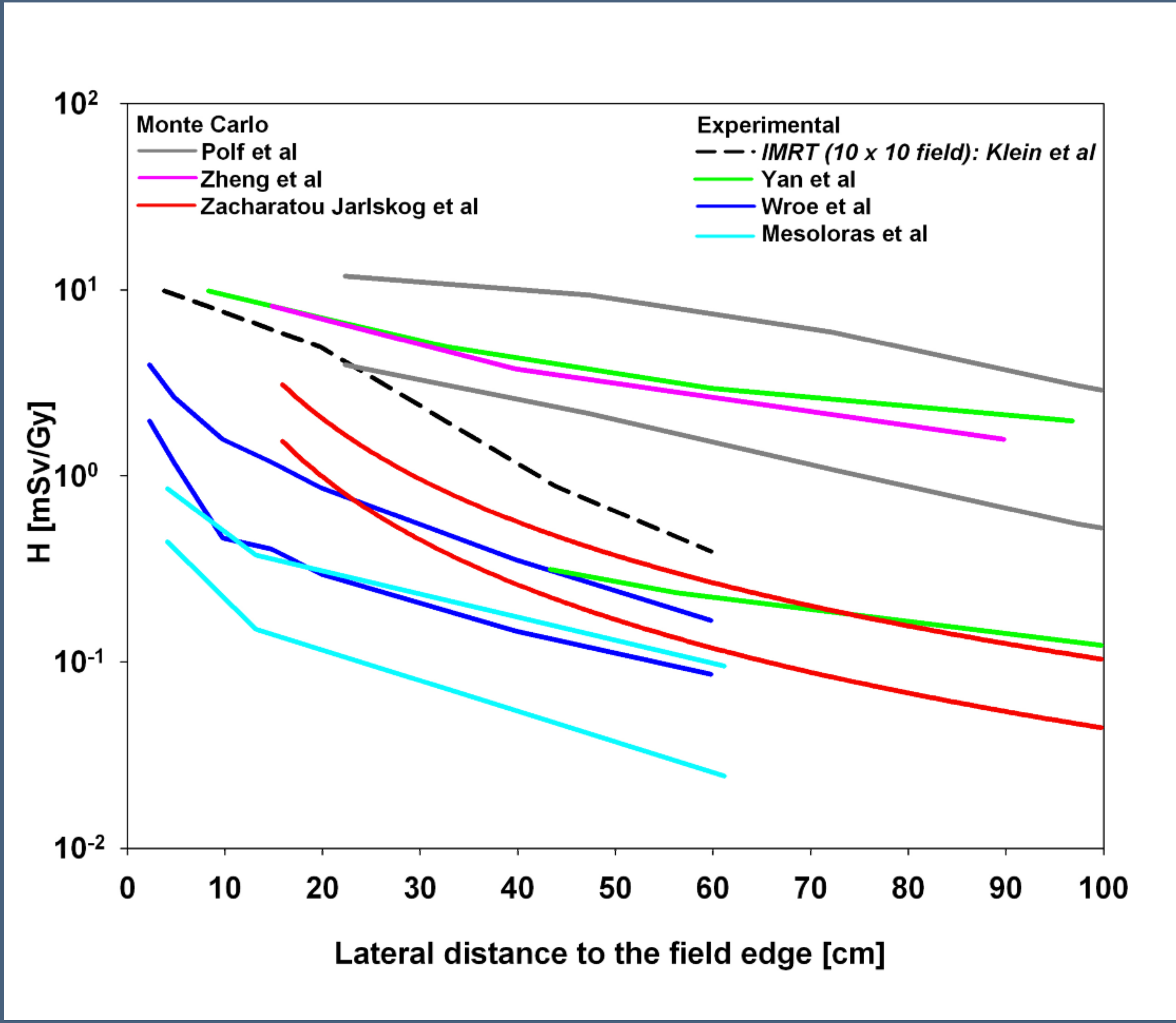


- 2 Gy(RBE)
- 4 Gy(RBE)
- 6 Gy(RBE)
- 8 Gy(RBE)



Scattered dose as a function of lateral distance

Neutron Dose Simulation



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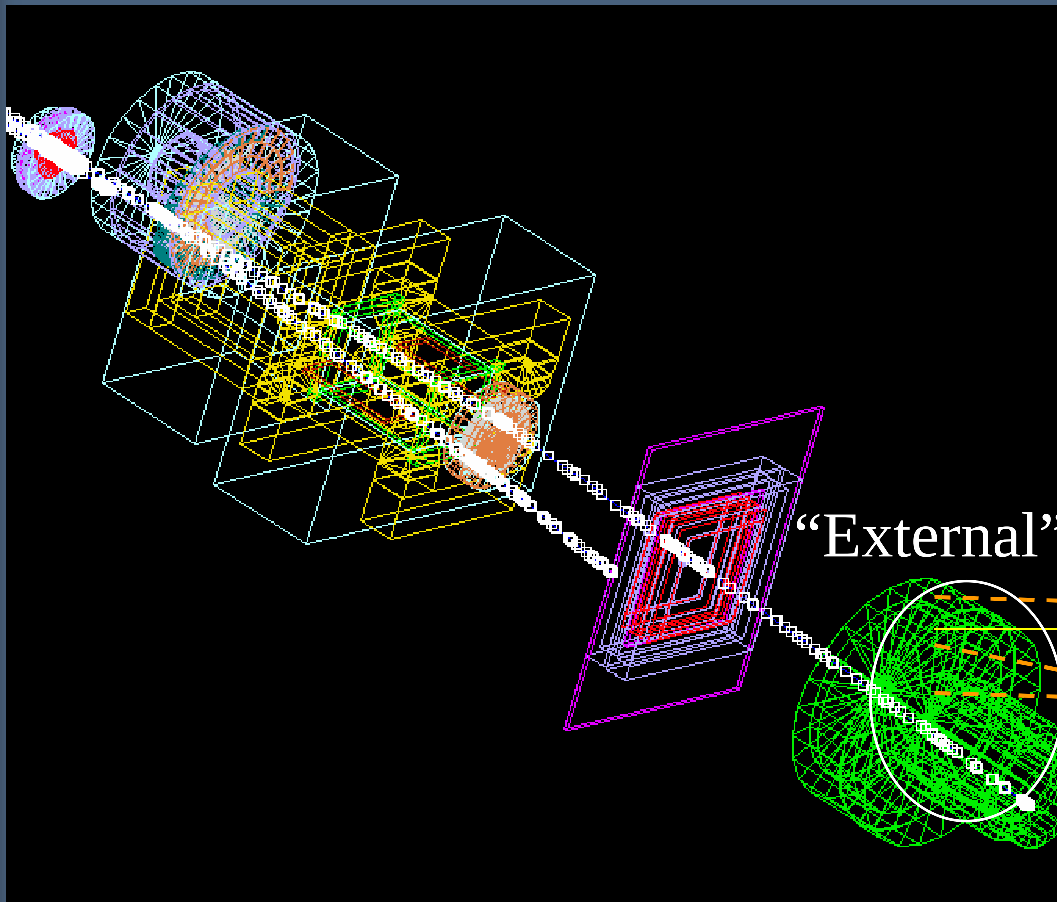
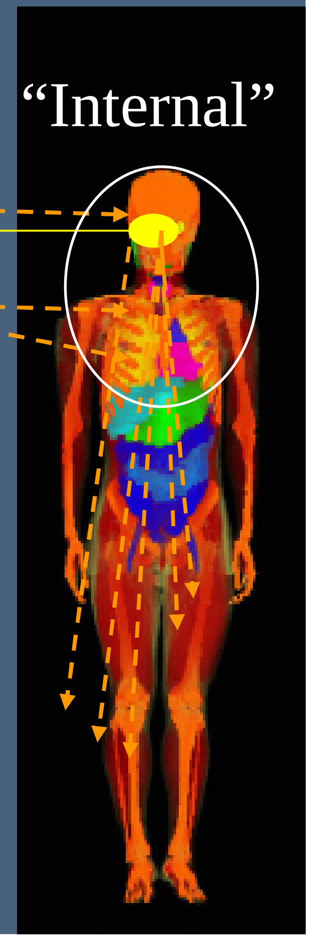
Simulation of the radiation field entering the patient

Neutron Dose Simulation





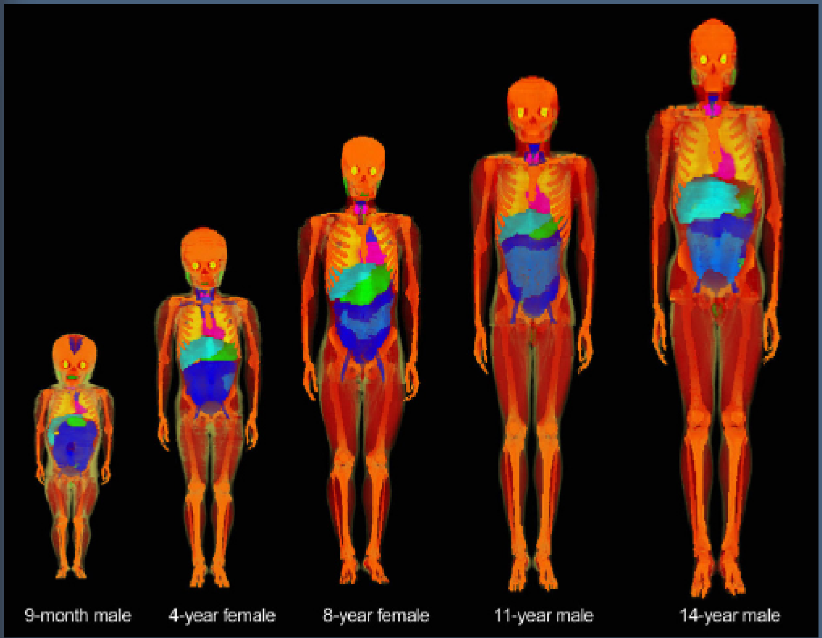
Output:

Neutrons leaving the treatment head

Protons leaving the treatment head

Pediatric phantoms

Lee, Lee, Williams, et al. Whole-body voxel phantoms of paediatric patients - UF Series B. *Phys Med Biol. 51, 4649-4661 (2006)*



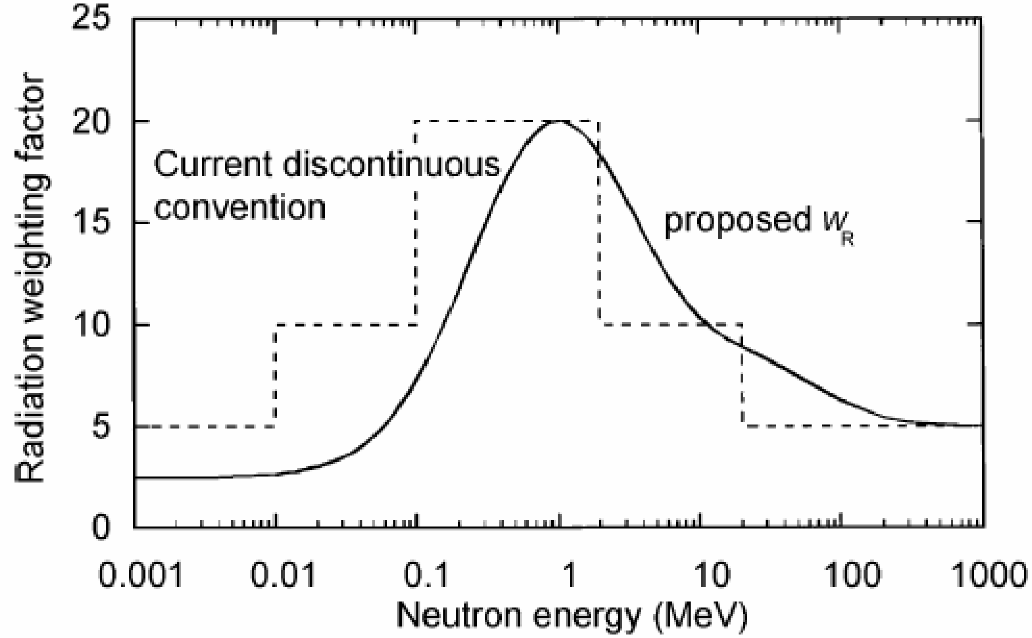
phantom	number of voxels		
	X	Y	Z
9 month old	289	180	24
4 year old	351	207	21
8 year old	322	171	22
11 year old	398	242	25
14 year old	349	193	25
Adult	147	86	47

Table 2. Elemental compositions (% by mass) and tissue densities (g cm^{-3}) of individuals at the ICRP reference ages.

Element	Phantom age (years)				
	Newborn	1	5	10	15 (male)
Group 1 (cranium/mandible)					
H	5.551	5.272	5.173	5.340	5.434
C	19.150	19.154	20.180	21.953	23.442
N	4.259	4.280	4.230	4.019	3.831
O	51.209	49.850	46.759	44.757	43.526
Ca	12.892	13.852	15.619	15.801	15.773
Na	0.031	0.025	0.104	0.103	0.177
Mg	0.260	0.268	0.187	0.181	0.176
P	6.303	6.969	7.435	7.544	7.346
S	0.287	0.287	0.283	0.276	0.271
Cl	0.018	0.012	0.007	0.006	0.006
K	0.027	0.019	0.011	0.009	0.006
Fe	0.013	0.012	0.011	0.012	0.011
Density	1.458	1.490	1.520	1.519	1.525
Group 2 (vertebrae—cervical, thoracic, lumbar)					
H	8.760	8.390	7.997	7.901	7.993
C	16.209	17.885	21.884	27.069	29.956
N	2.844	3.020	3.230	3.319	3.247
O	64.925	61.789	55.514	49.237	46.486
Ca	3.948	4.345	6.469	7.575	7.637
Na	0.337	0.289	0.246	0.180	0.193
Mg	0.088	0.114	0.116	0.141	0.146
P	2.908	3.383	3.918	4.110	3.933
S	0.663	0.598	0.485	0.369	0.325
Cl	0.194	0.163	0.112	0.062	0.045
K	0.006	0.006	0.004	0.004	0.003
Fe	0.016	0.019	0.024	0.033	0.036
Density	1.157	1.184	1.219	1.232	1.230

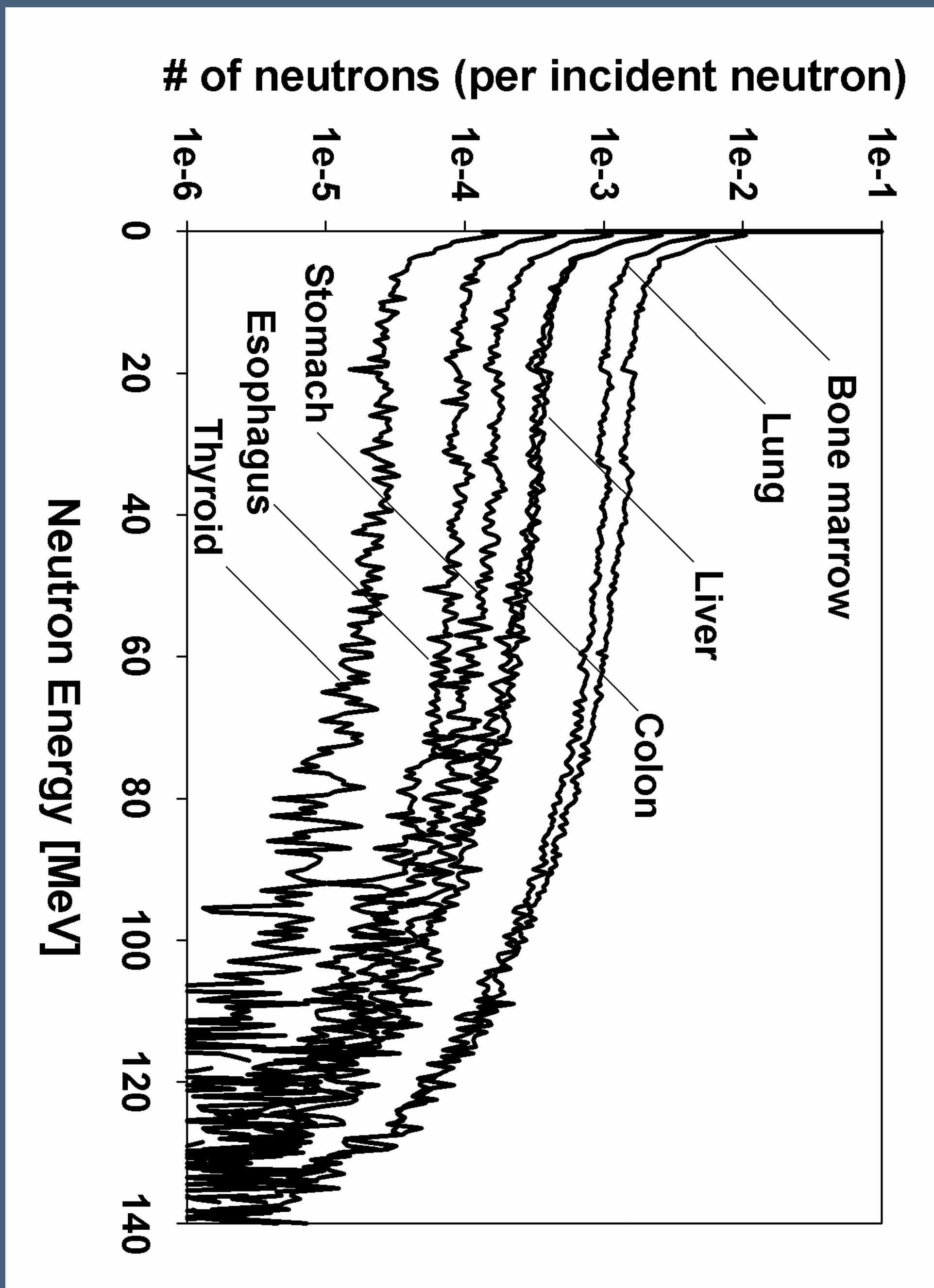
Table 1. A comparison of existing w_R values and those proposed to the ICRP

Type and energy range of incident radiation		Radiation weighting factor (w_R)	
		Publication 60	Proposed[c]
Photons, all energies		1	1
Electrons and muons (all energies)[a]		1	1
Protons (incident)		5	2
Neutrons, energy	< 10 keV	5	
	10 keV–100 keV	10	Use the proposed w_R function in Fig. 1 below
	> 100 keV–2 MeV	20	
	> 2 MeV–20 MeV	10	
	> 20 MeV	5	



From: *Annals of the ICRP; ICRP Publication 92; Relative Biological Effectiveness (RBE), QualityFactor (Q), and Radiation Weighting Factor (w_R)*

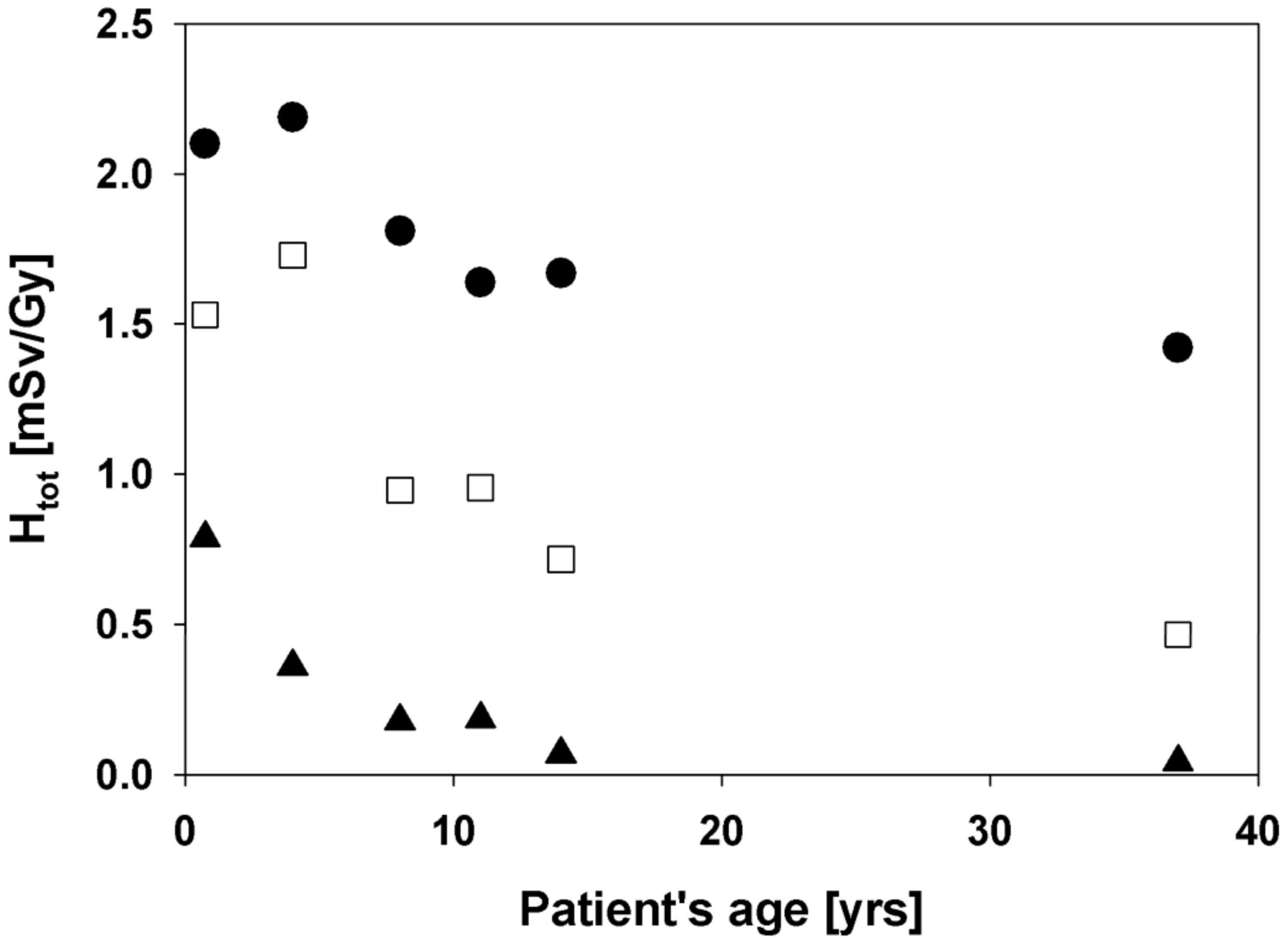
Neutron Dose Simulation



Neutron Dose Simulation

Organ equivalent dose

thyroid (circles)
lung (squares)
liver (triangles)



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Paganetti and Bortfeld: Proton Therapy. In: New Technologies in Radiation Oncology (Series: Medical Radiology; Subseries: Radiation Oncology); Eds. Schlegel, W.; Bortfeld, T.; Grosu, A.L.; ISBN 3-540-00321-5; Springer Verlag, Heidelberg 2005: 345-63

Monte Carlo dose calculation

Chetty et al., Report of the AAPM Task Group No. 105: issues associated with clinical implementation of Monte Carlo-based photon and electron external beam treatment planning. Med Phys 2007: 34, 4818-53

Proton treatment head simulation

Paganetti et al: Accurate Monte Carlo simulations for nozzle design, commissioning, and quality assurance in proton radiation therapy. Med Phys 2004: 31, 2107-18

Simulation of neutron doses in proton therapy

Zacharatou Jarlskog et al: Assessment of organ specific neutron equivalent doses in proton therapy using computational whole-body age-dependent voxel phantoms. Phys Med Biol 2008: 53, 693-717

Monte Carlo code Geant4

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