Monte Carlo methods in proton beam radiation therapy

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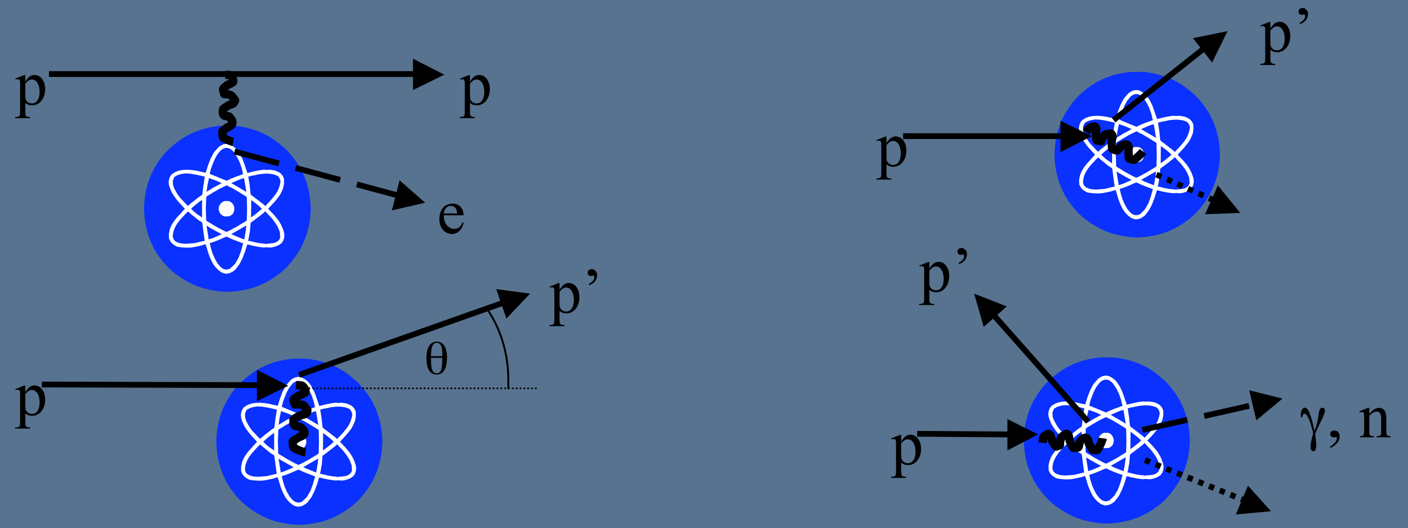
Introduction

Monte Carlo

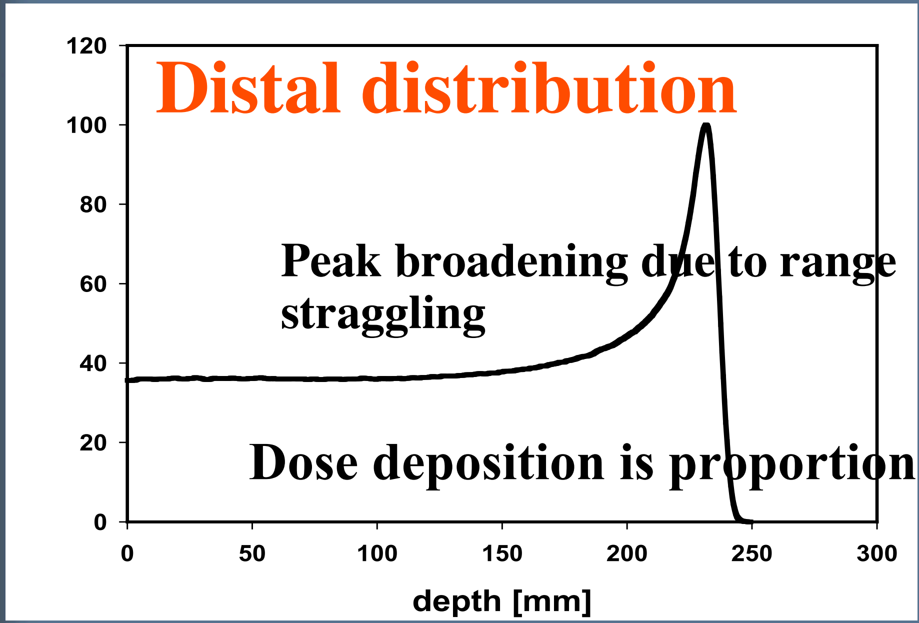
Probability Density Function

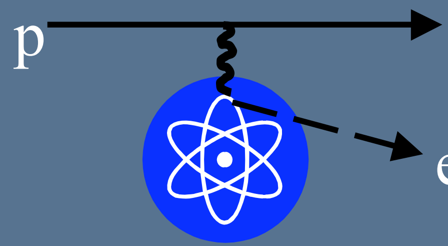
expresses the relative likelihood that a variable will have a certain value

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

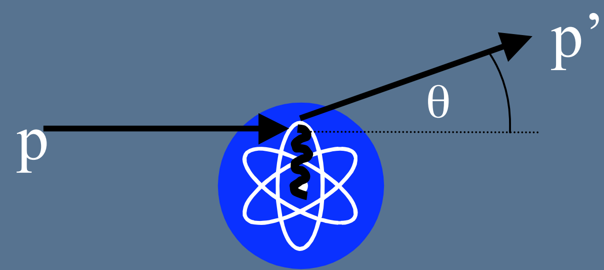


Electromagnetic energy loss of protons





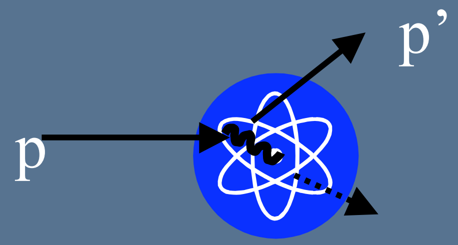
–Ionization
–Excitation



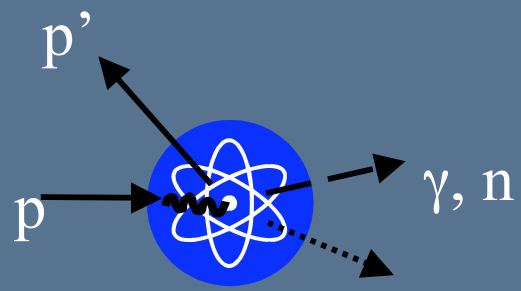
Coulomb scattering (small angles)

Introduction

Nuclear interactions of protons



Elastic nuclear collision (large θ)

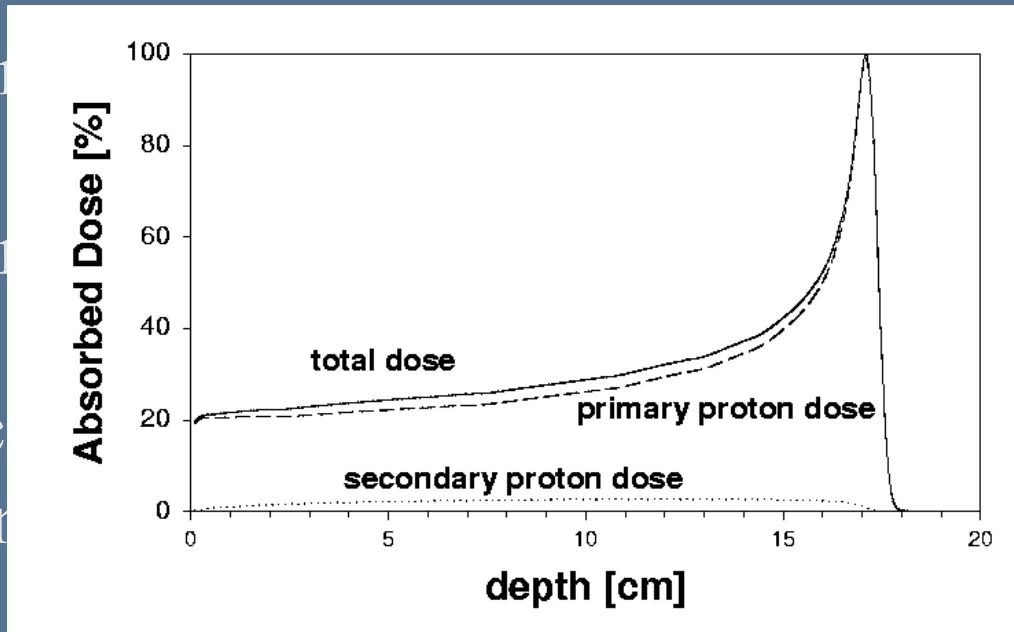


Inelastic int.

Nuclear i… ence

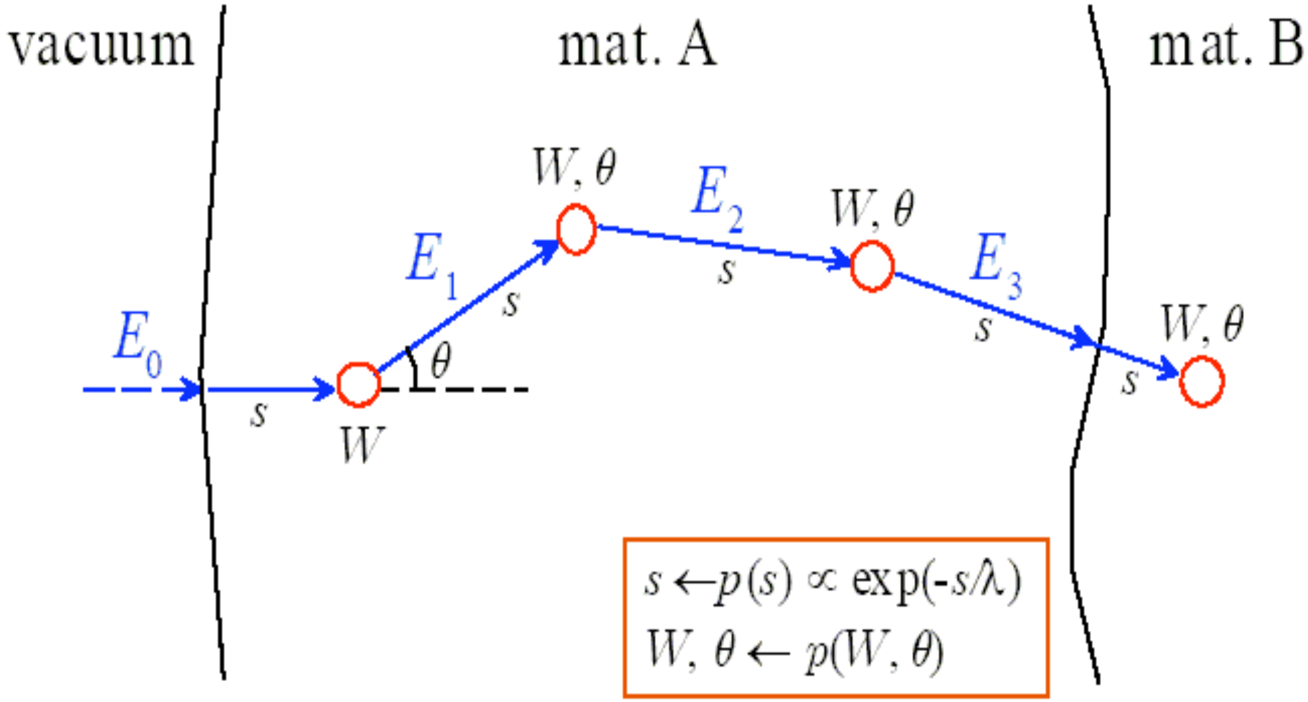
Nuclear i… icles and thus to

- loc… tons)
- nor… neutrons)



Detailed (analogue) simulation

- All interaction events are simulated in chronological succession:



- 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...

Condensed history algorithms

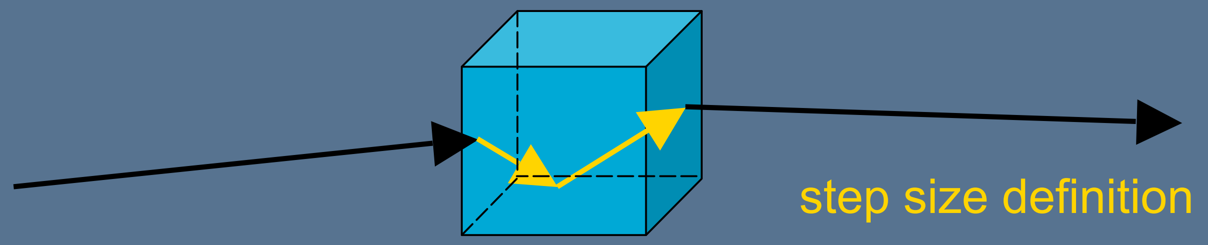
group many charged particles track segments into one single 'condensed' step

grouped collisions

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

discrete collisions

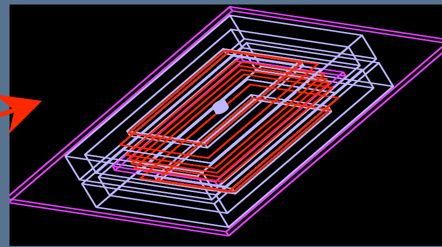
- 'hard' δ-ray production
  energy > cut
- 'hard' bremstrahlung emission
  energy > cut
- etc



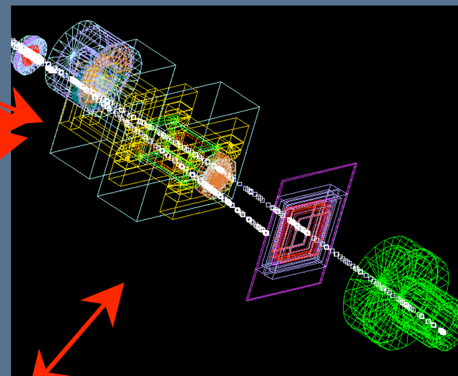
Introduction

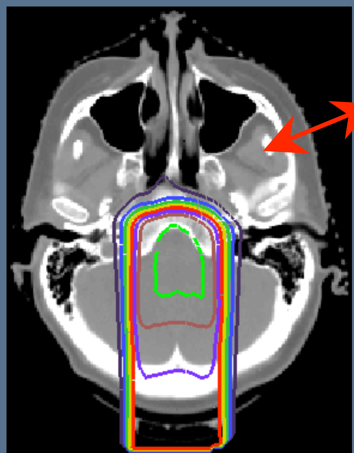
Introduction

Monte Carlo applications to proton radiation therapy



- Detector simulation
- Treatment head design
- Shielding
- Quality assurance
- Patient dose calculations





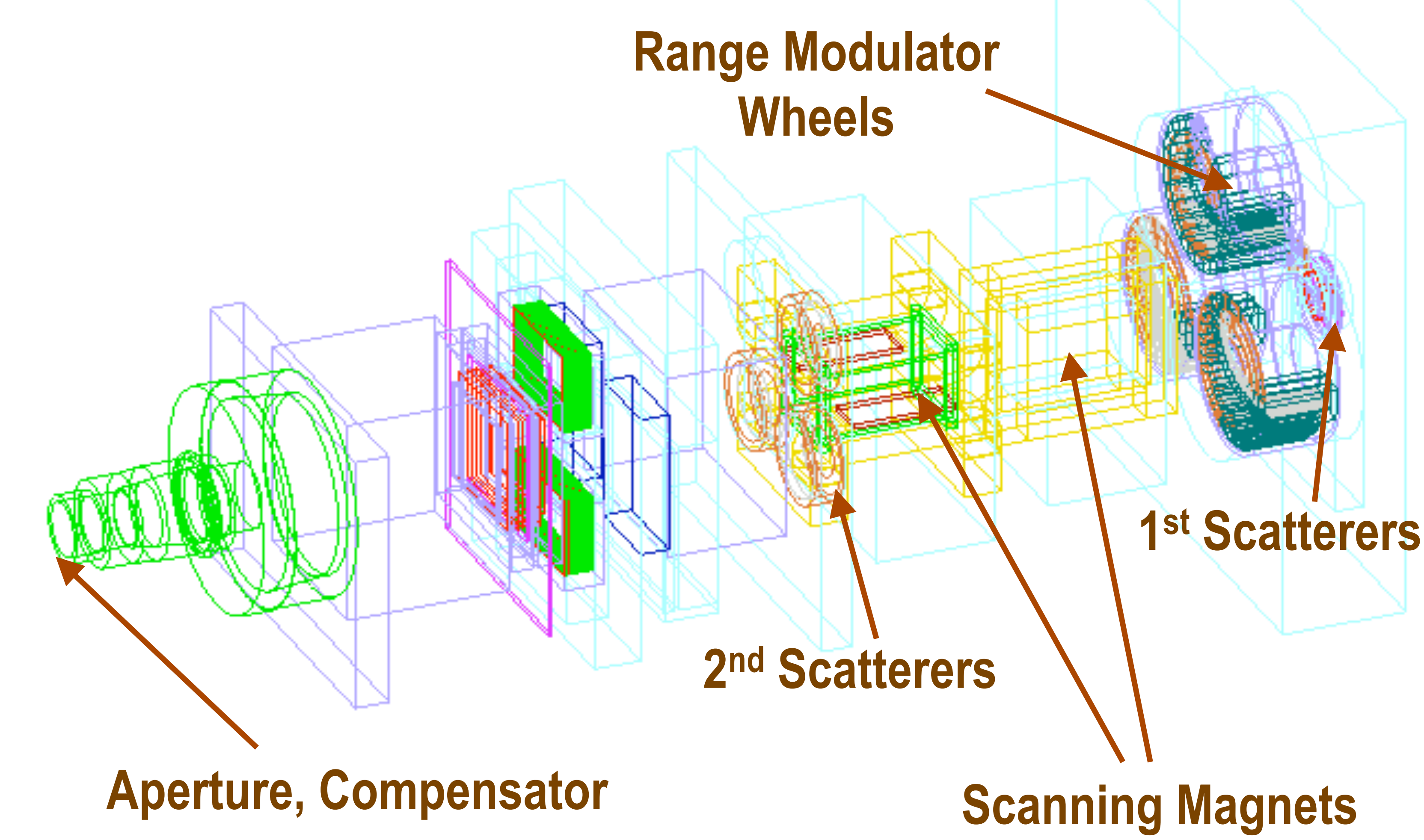
Treatment head simulation

Patient (CT) simulations

Clinical implementation

Treatment head essentials

(Example: Francis H Burr Proton Therapy Center)

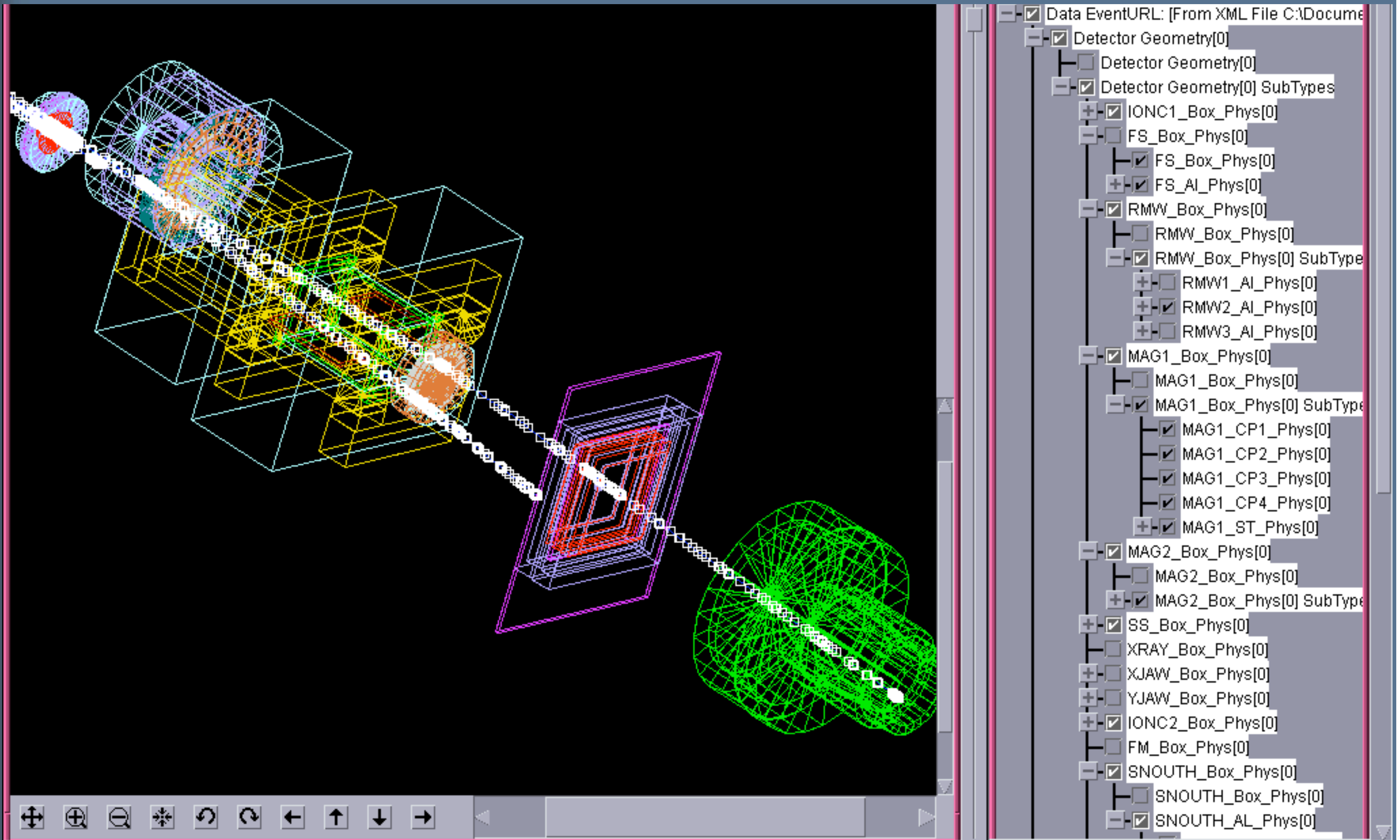


Treatment Head Simulation

Treatment Head Simulation

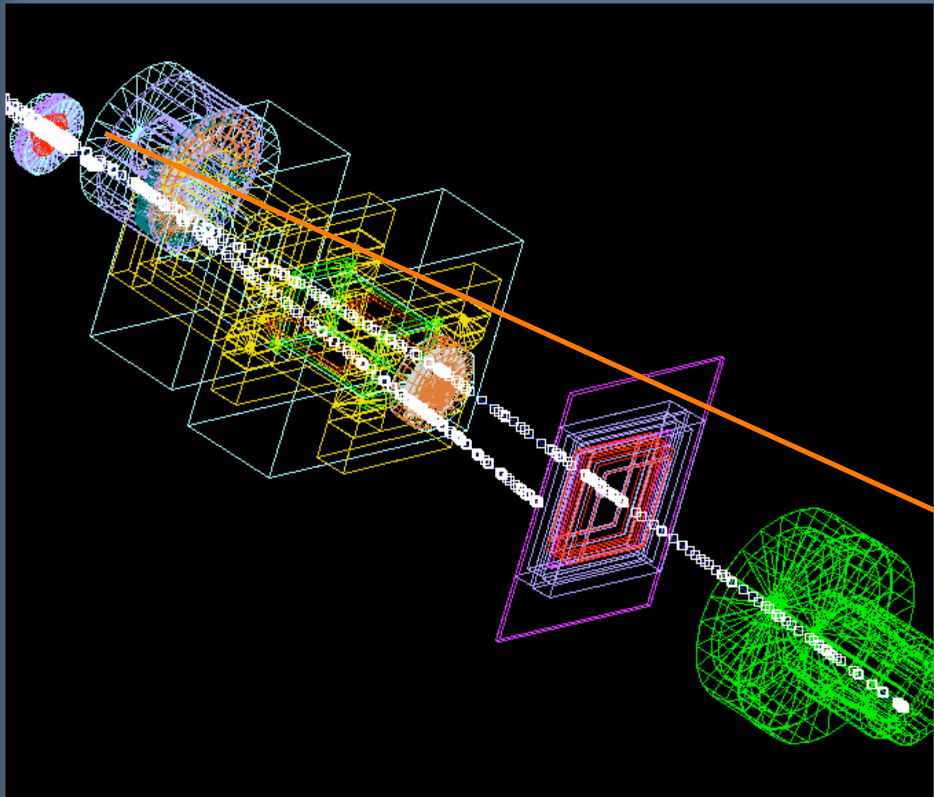
Treatment head details

(Example: Francis H Burr Proton Therapy Center)

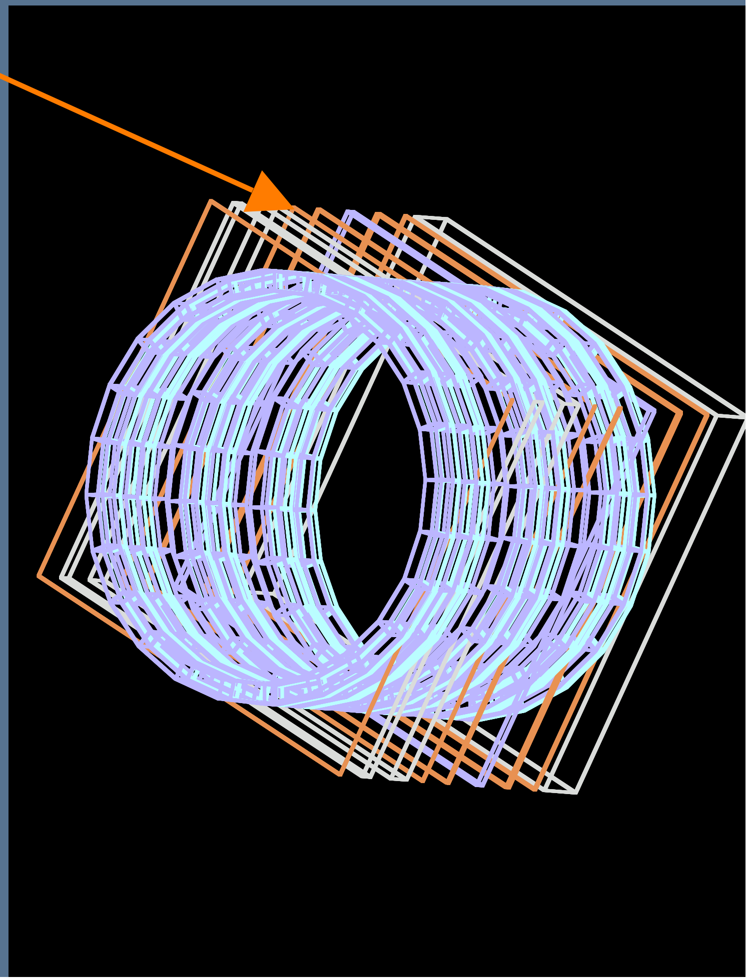


Monte Carlo model of the nozzle (~1000 objects)

Treatment Head Simulation

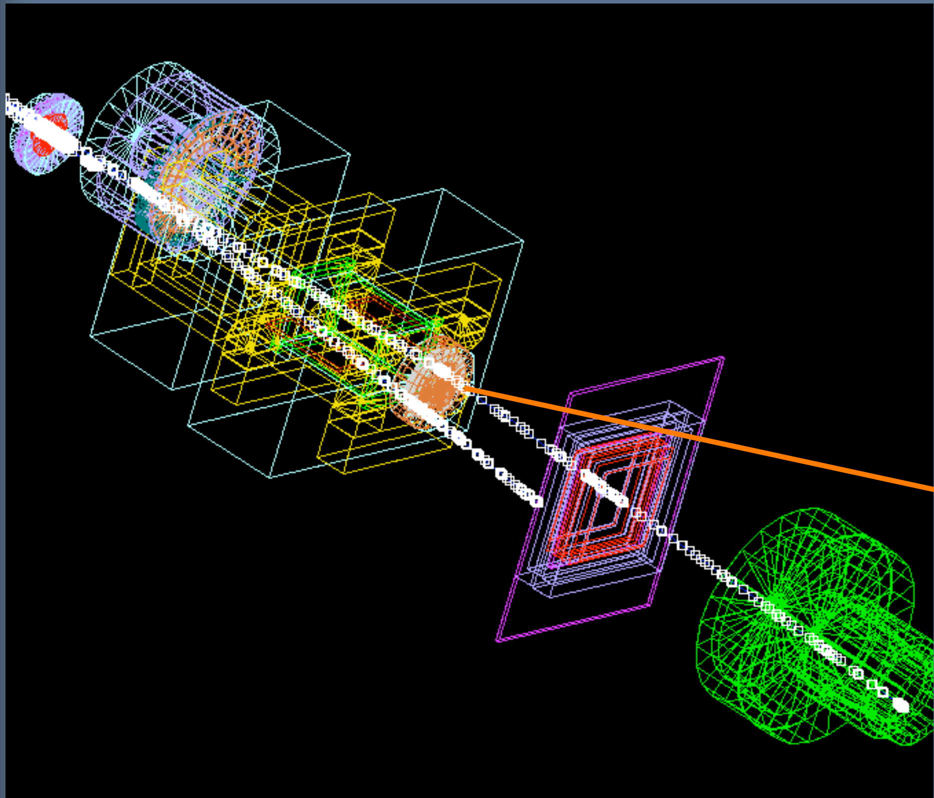


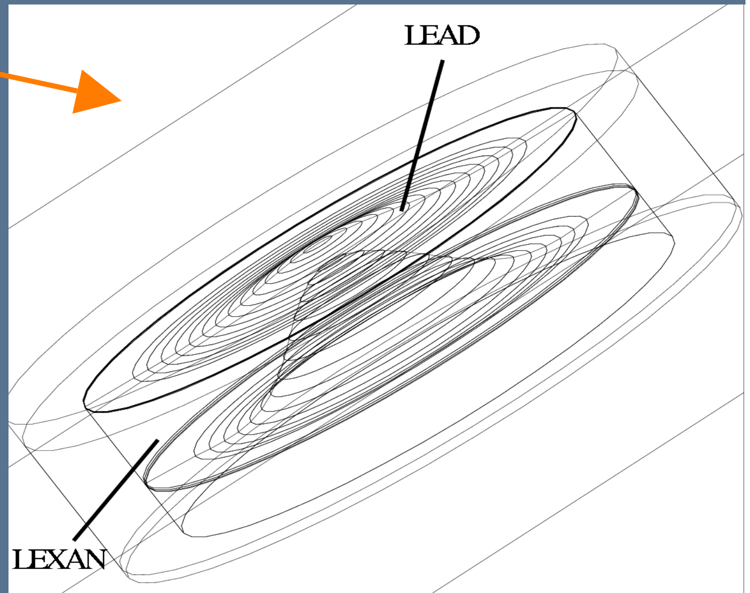
Monte Carlo model of the nozzle at the FHBPTC

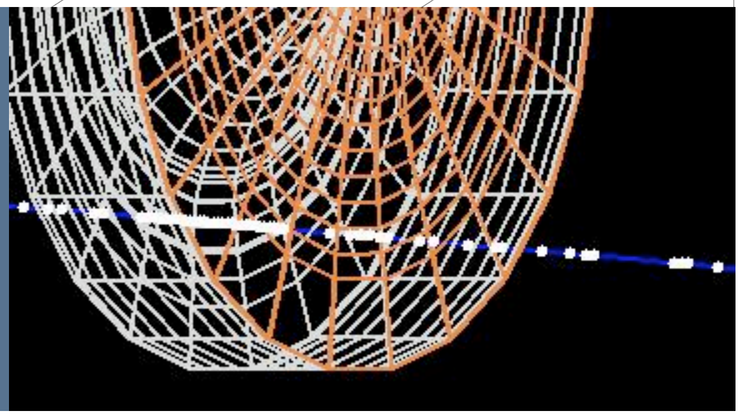


Treatment Head Simulation

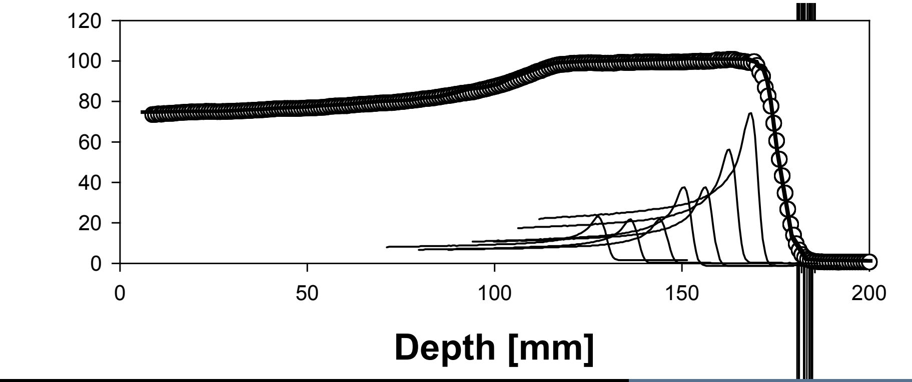
Monte Carlo model of the nozzle at the FHBPTC

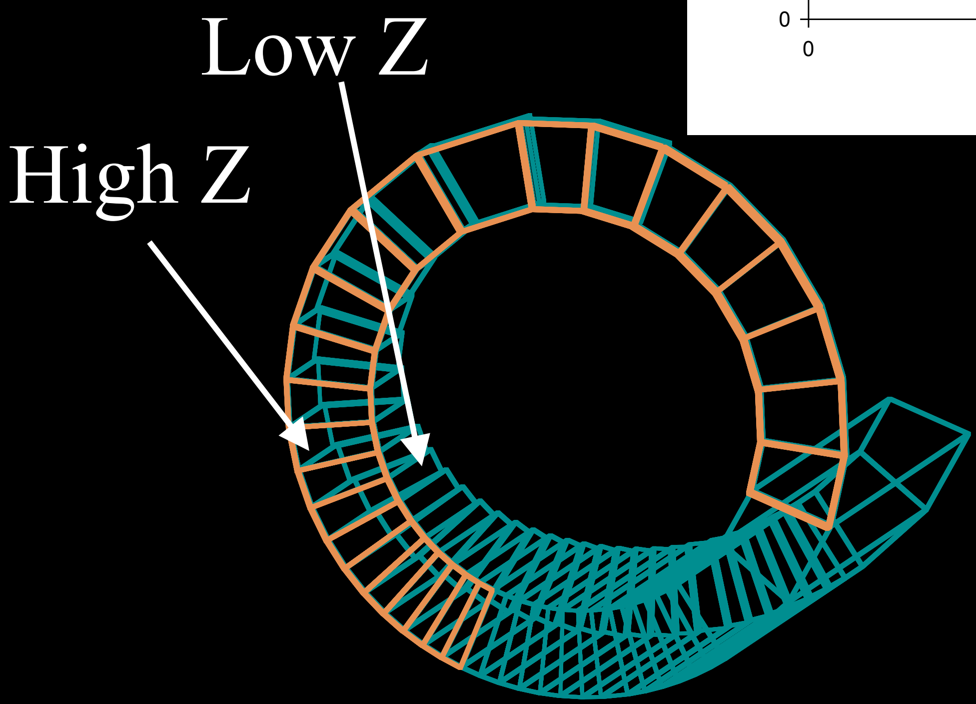


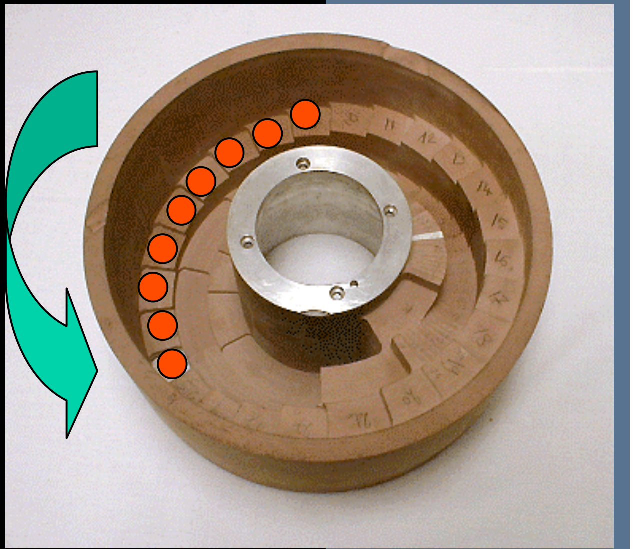




4D Monte Carlo: Geometry changes during the simulation via C++ class architecture

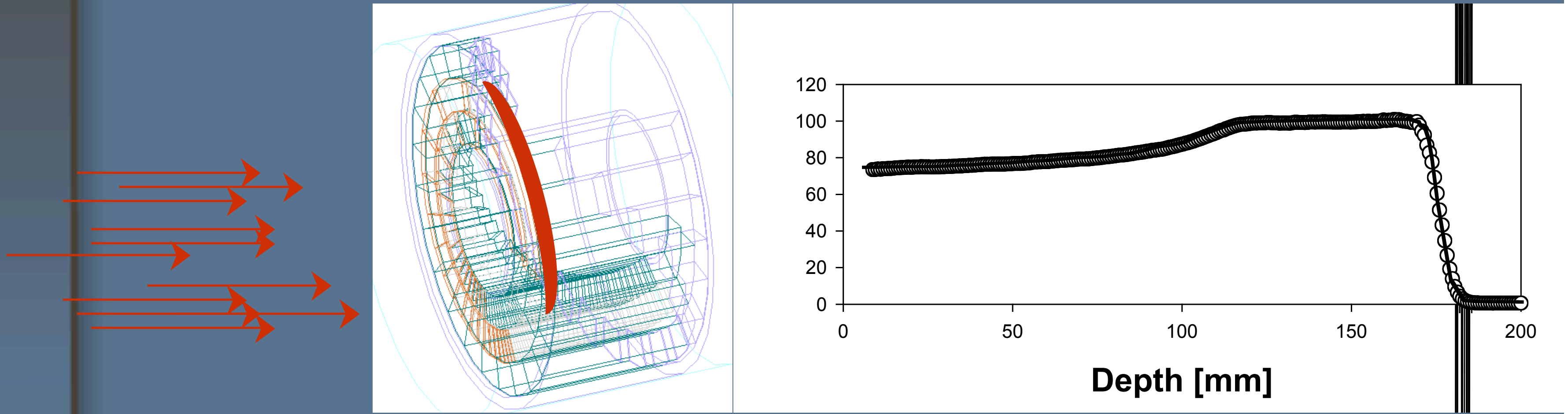




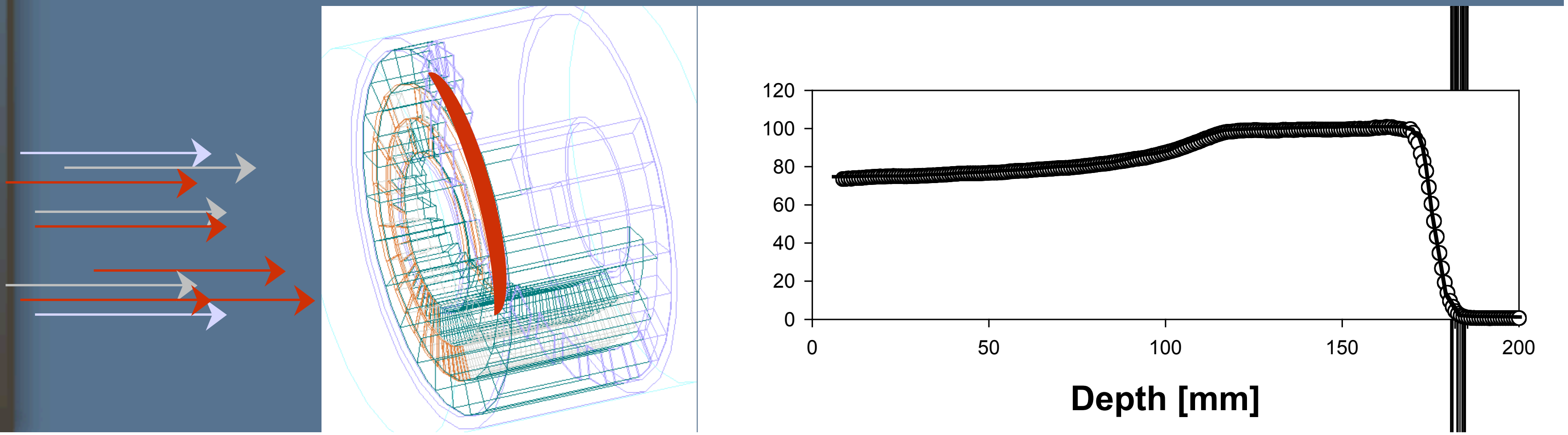


Range Modulator Wheel Issues

1. Beam Gating



2. Beam Current Modulation



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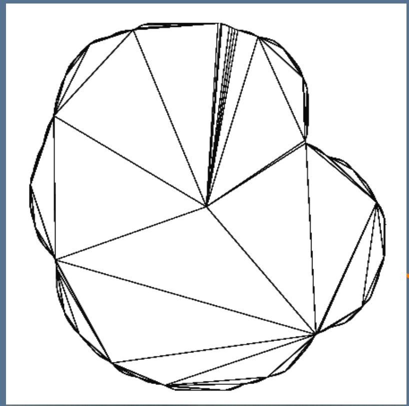
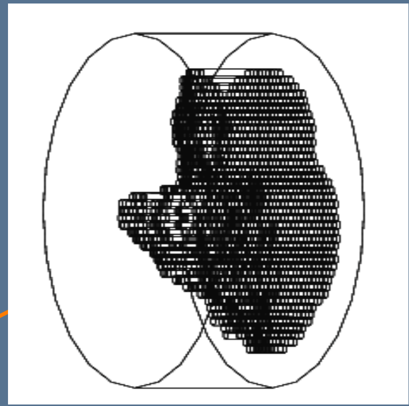
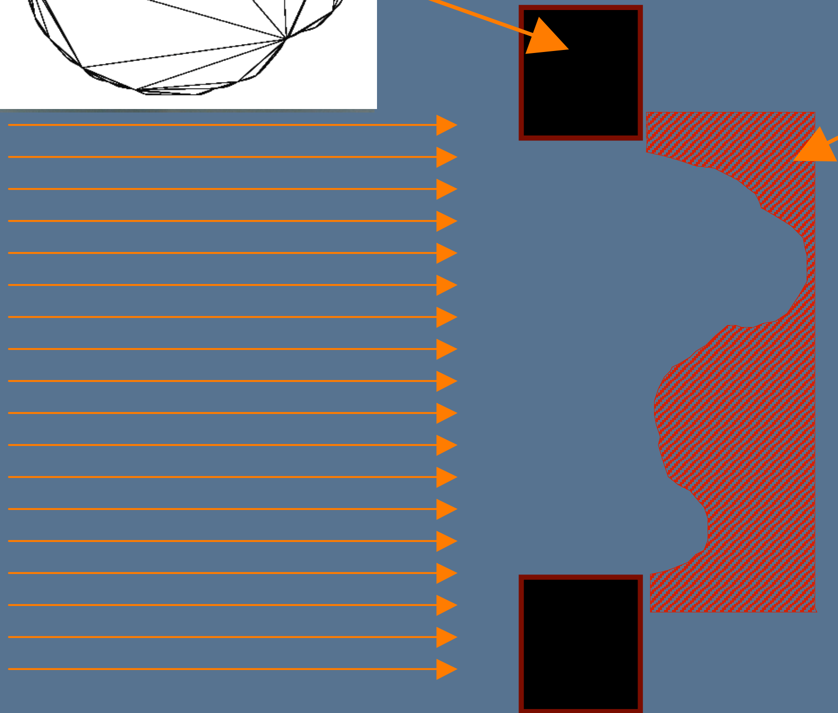
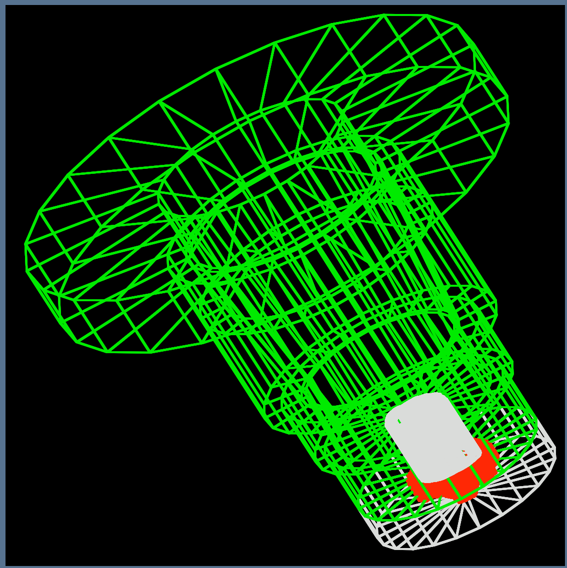
Aperture and Compensator

Monte Carlo simulation based on milling machine files



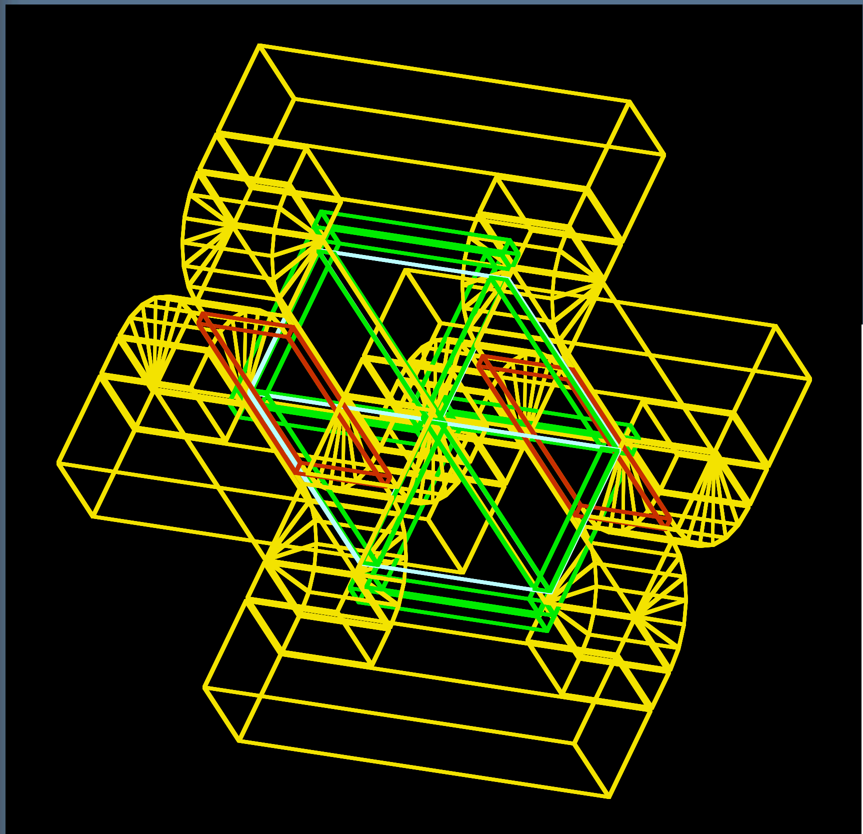


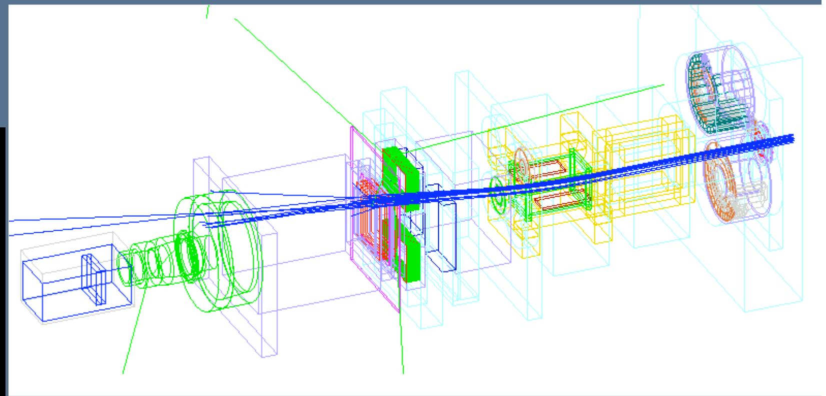


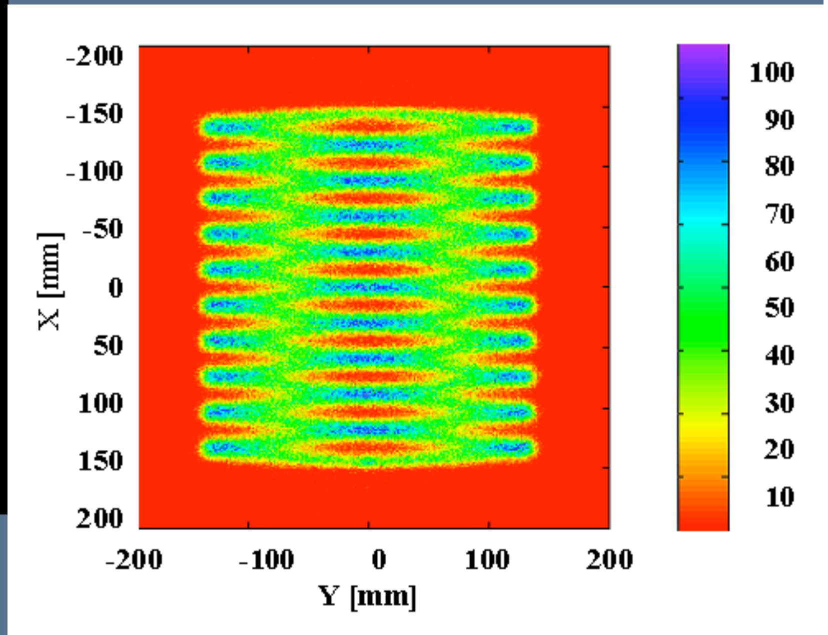


Treatment Head Simulation

Scanning Magnet simulation (can be modeled “geometrically”)

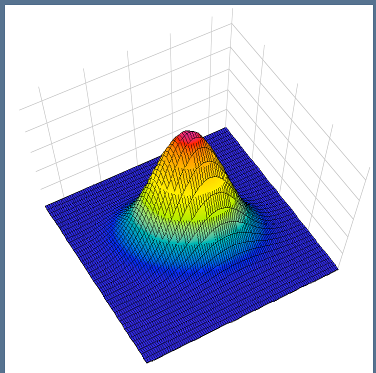






Parameters to characterize the beam at treatment head entrance

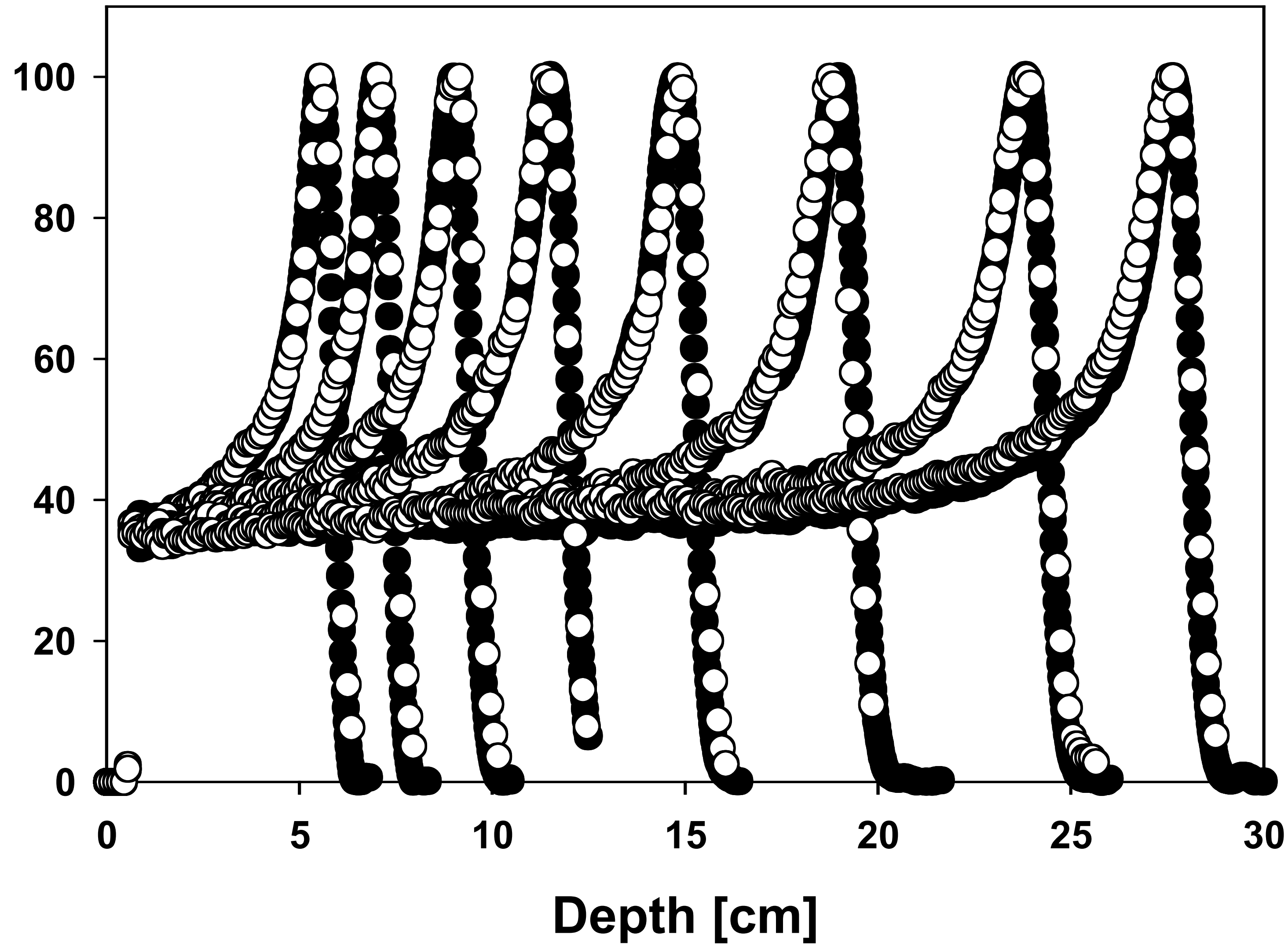
1. Beam size and spread (IC measurement)
2. Beam angular spread (manufacturer info)
3. Beam energy (range!) (control system)
4. Beam energy spread (manufacturer info, measured)



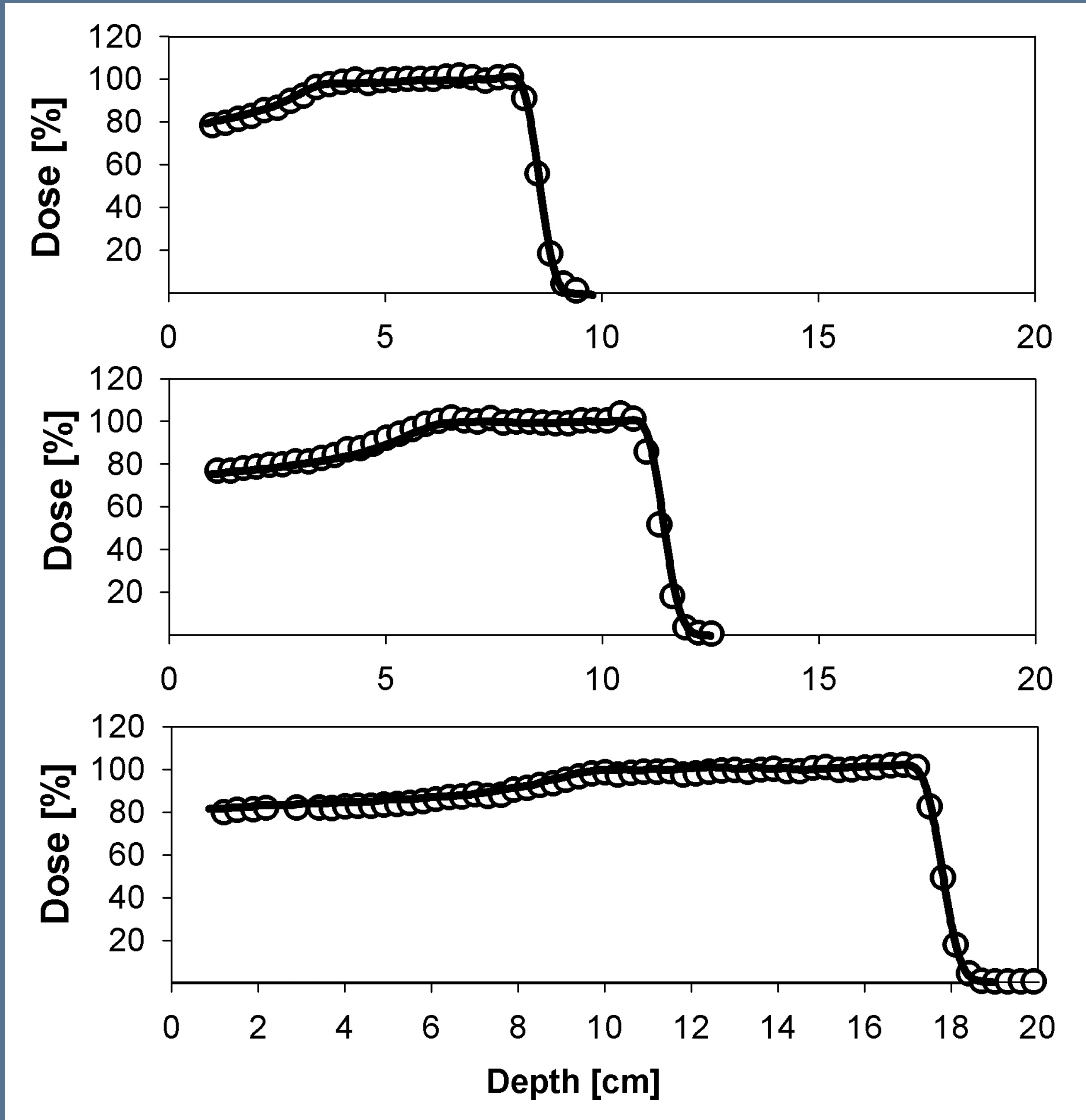
Are these parameters correlated ?

“Commissioning” of the Monte Carlo

Treatment Head Simulation

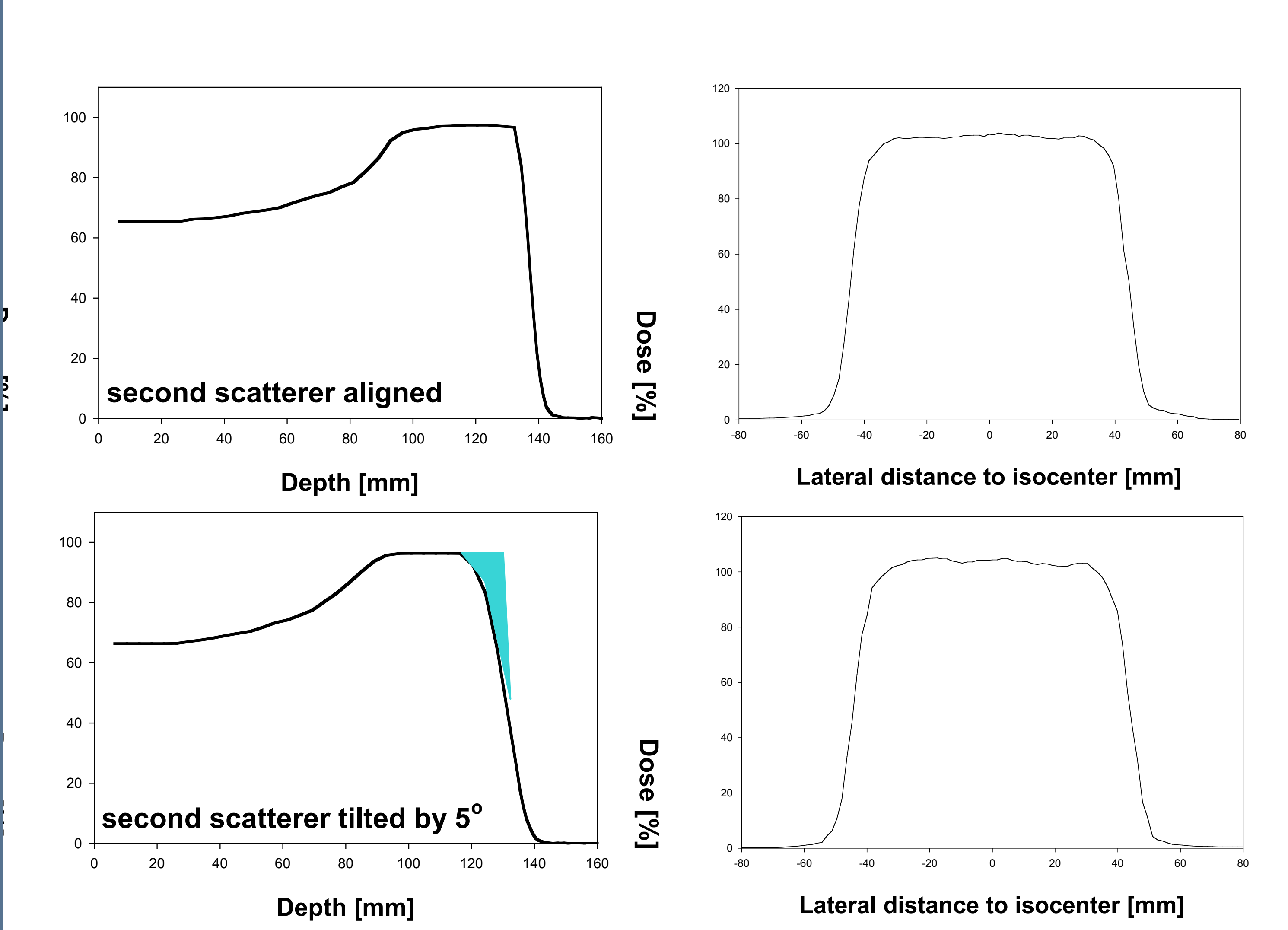


Treatment Head Simulation



Example: Quality Assurance / Tolerance Studies

Alignment of second scatterer



Quality Assurance

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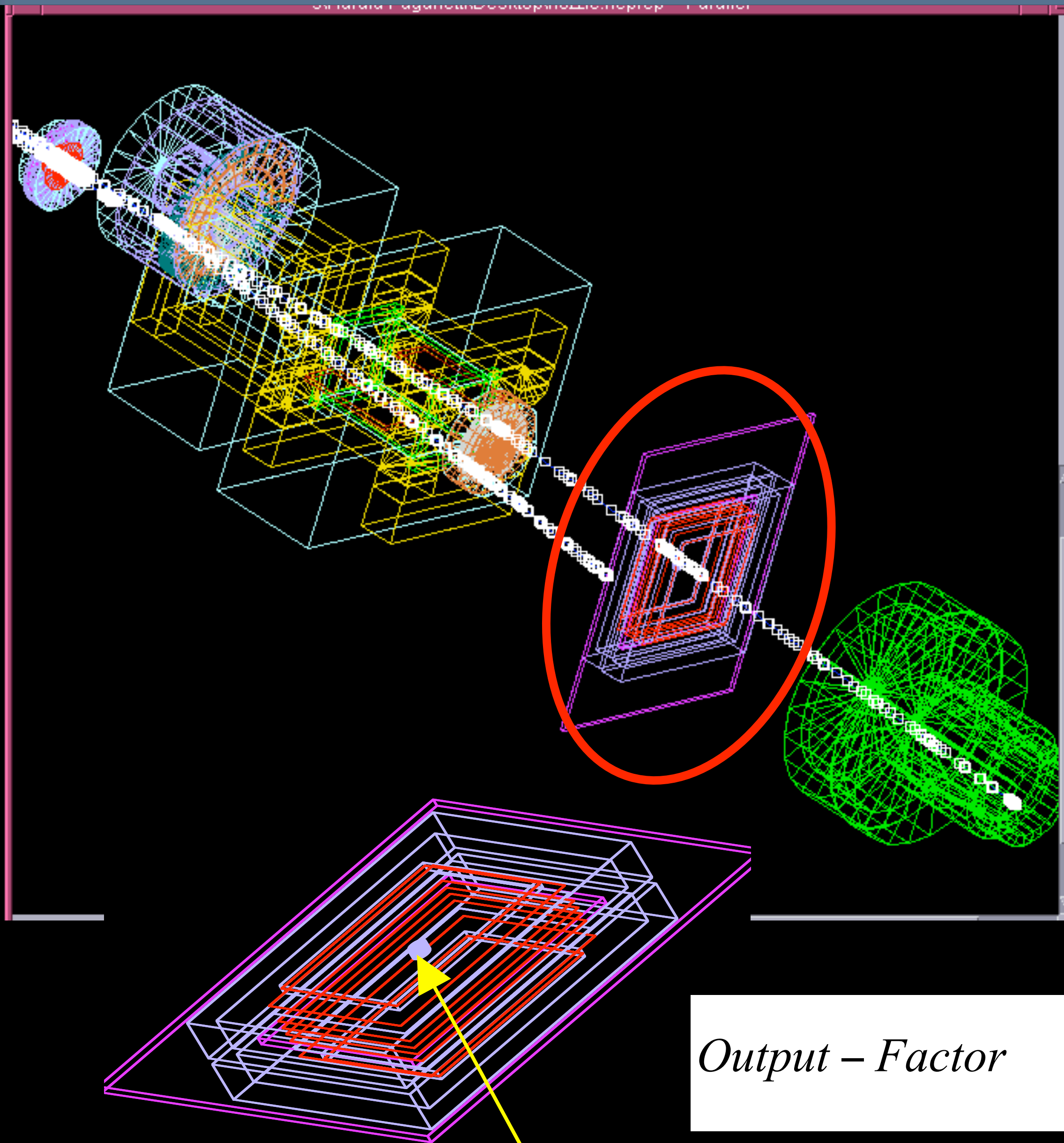
Patient Dose Calculations

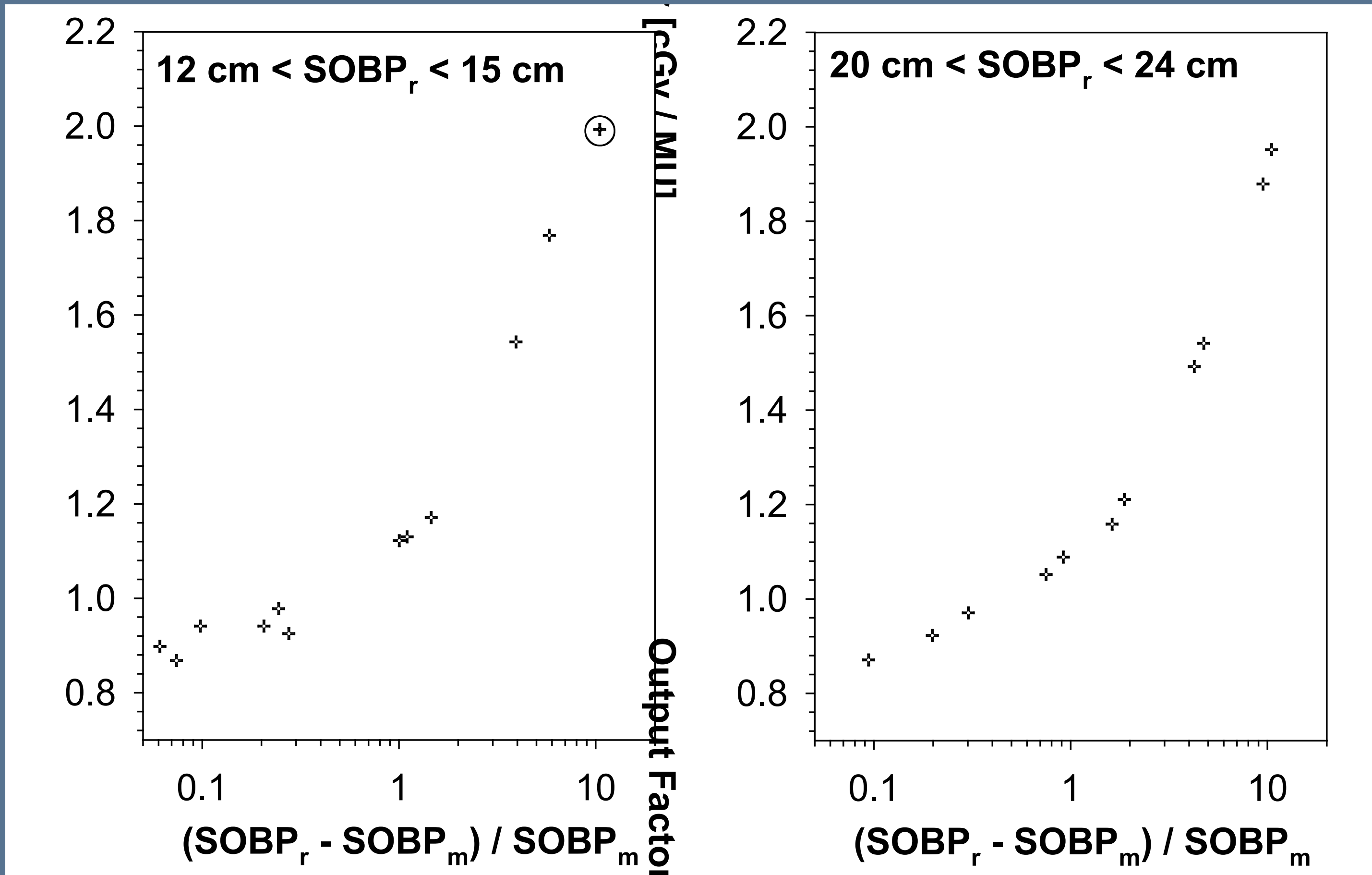


$$Output - Factor \cong \frac{D_{cal}}{i_{ic}} \left[{}^{cGy}\!/_{MU} \right]$$

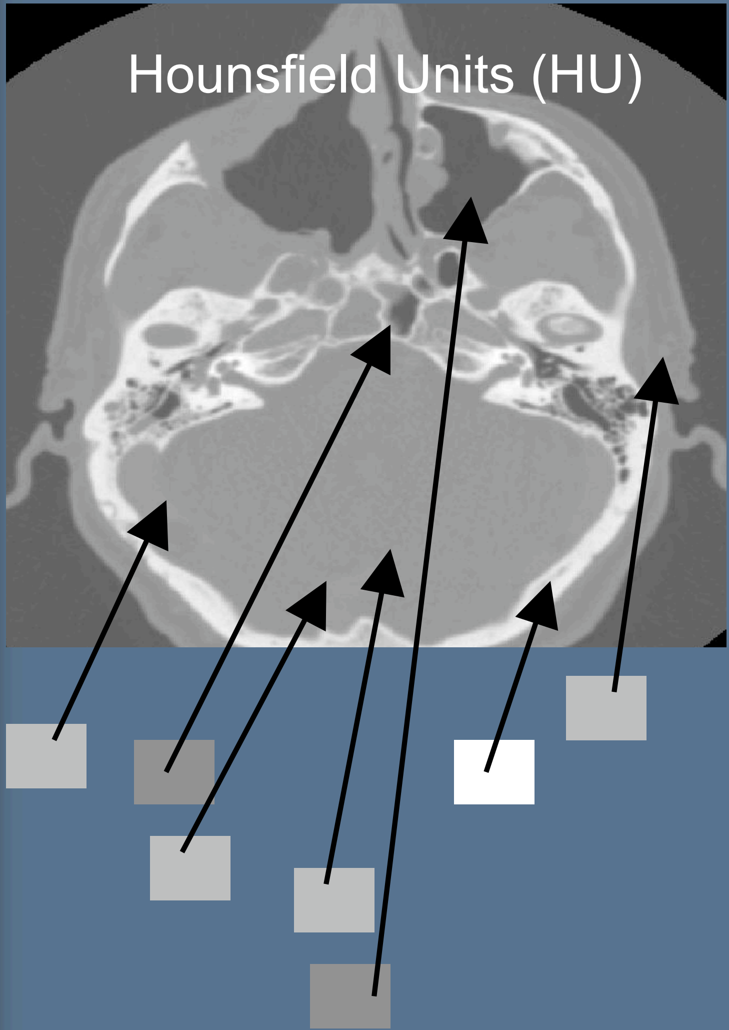
Volume for absolute dosimetry

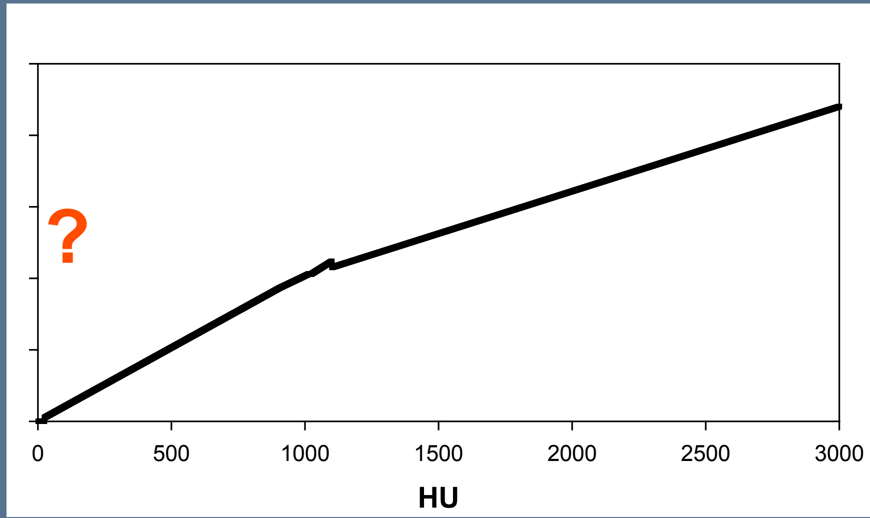
Absolute dosimetry (output factor prediction)
by simulating the ionization chamber output charge

Patient Dose Calculations



CT conversion





Photon Analyt. Planning System
- **HU versus rel. electron density**
  - **→ Dose-to-water**

Proton Analyt. Planning System
- **HU versus rel. stopping power**
  - **→ Dose-to-water**

Monte Carlo
- **HU versus mass density**
- **HU versus material**
  - **→ Dose-to-medium (tissue)**

Patient Dose Calculations

– HU conversion –

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

- **27 HU groups with unique element composition**
- **4000 densities**

Patient information

Example:

CT scan:

134 CT slices, 512 × 512 voxels/slice

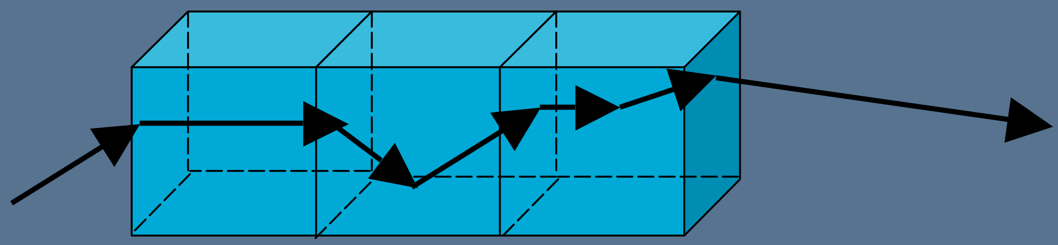
0.488 mm × 0.488 mm × 1.25/2.5 mm

Challenge 1:

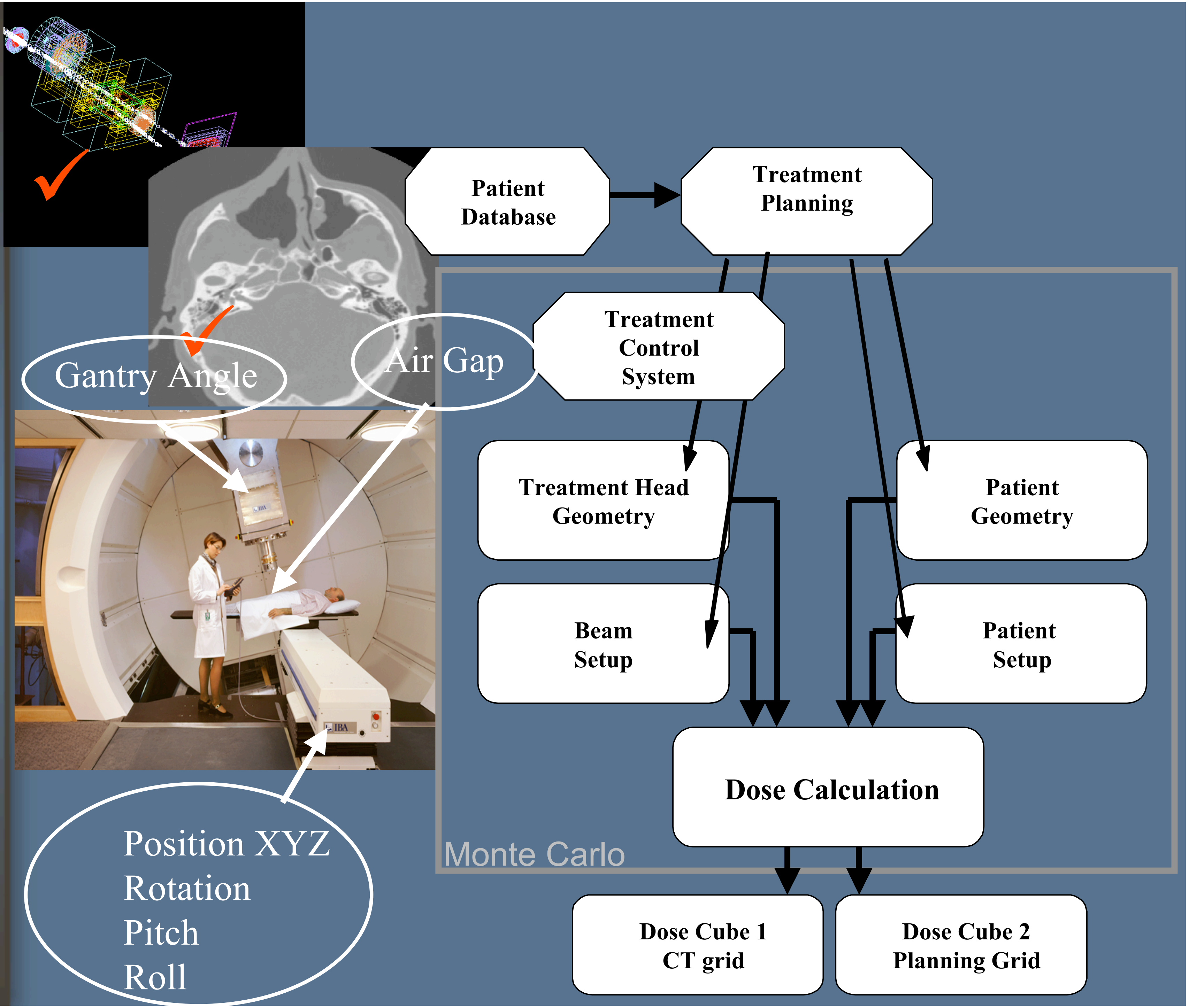
- **Memory Consumption**

Challenge 2:

- **Speed (many boundary crossings)**

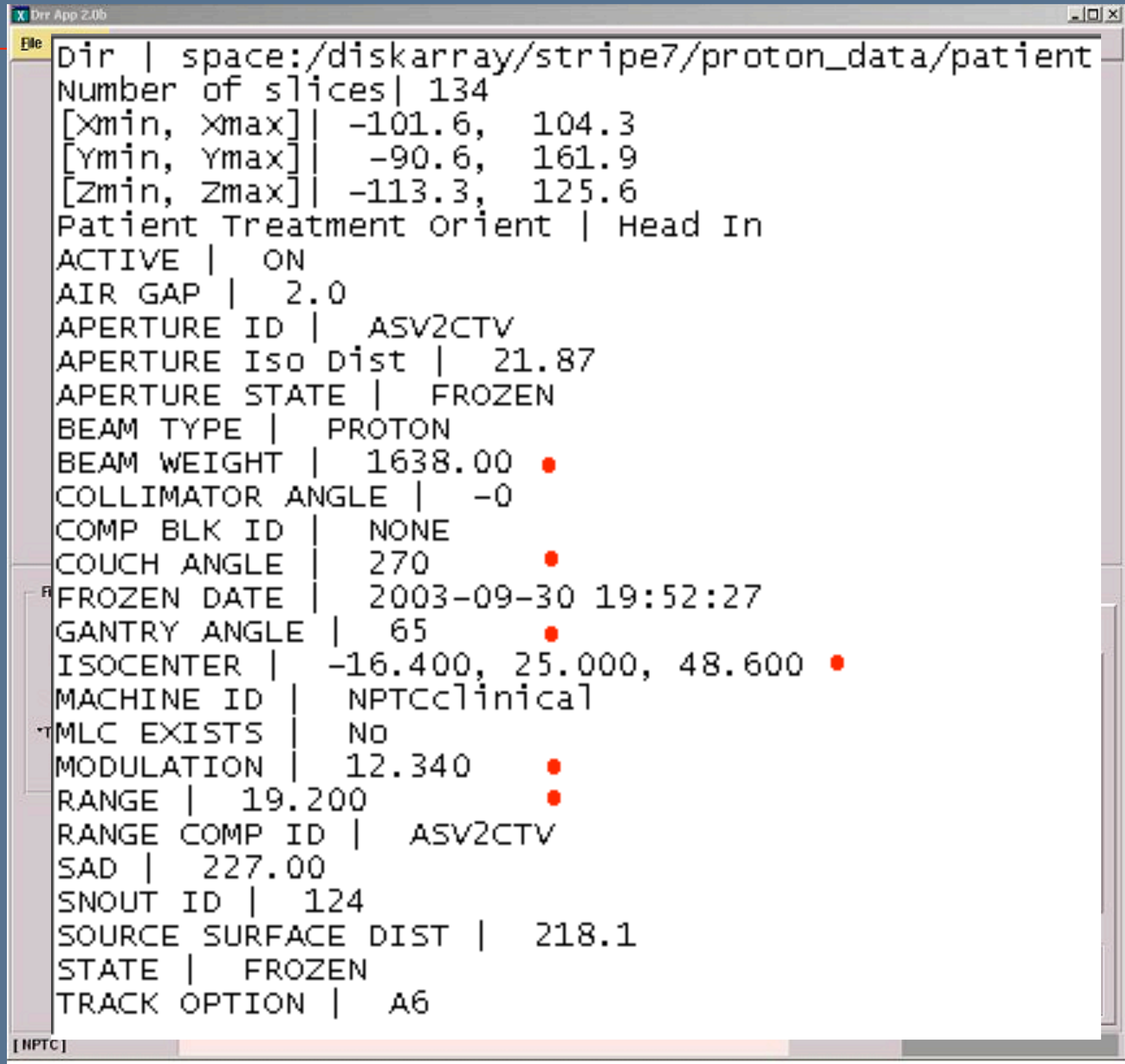


Clinical Implementation



Clinical Implementation

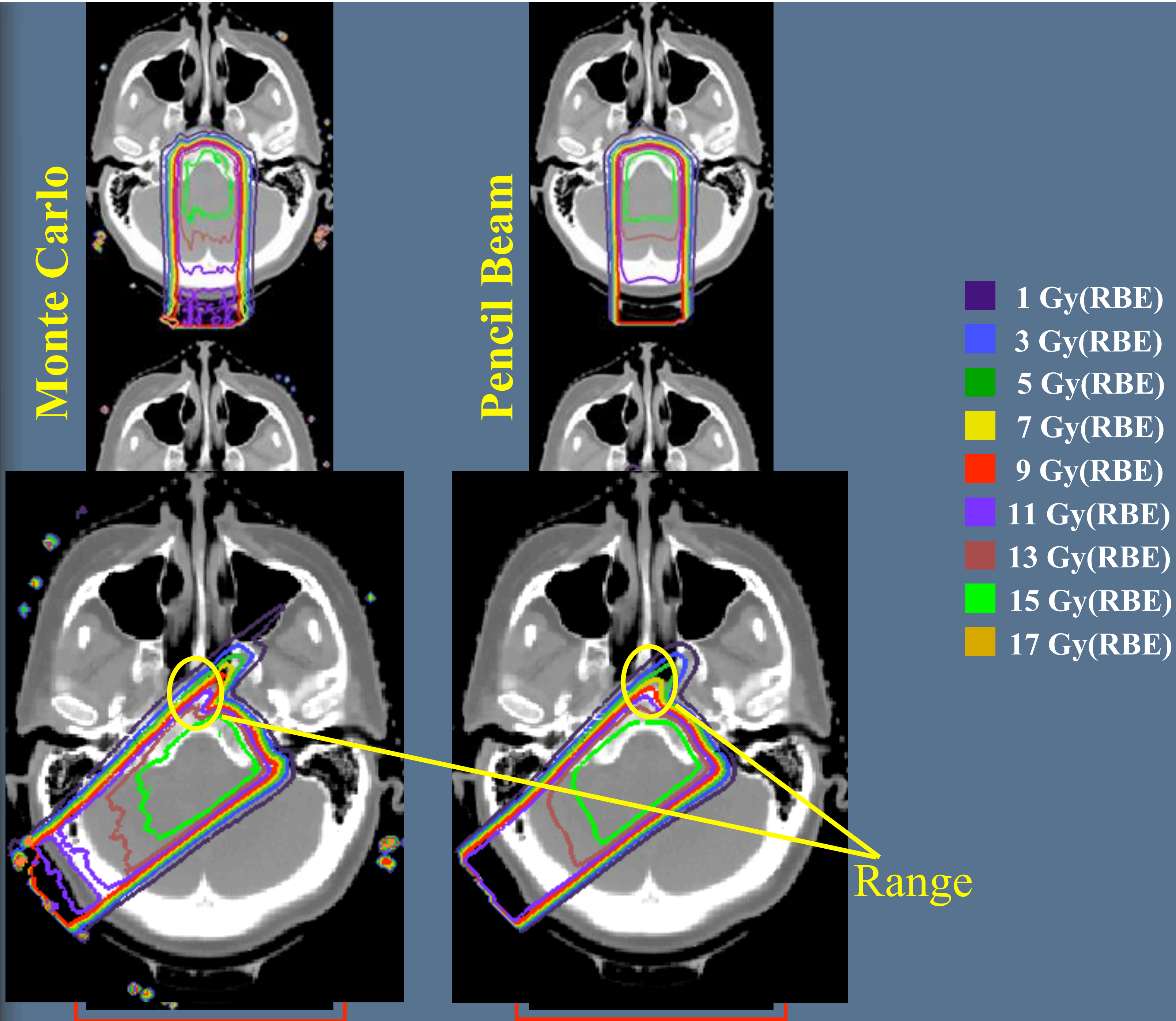
GUI program



Example 1

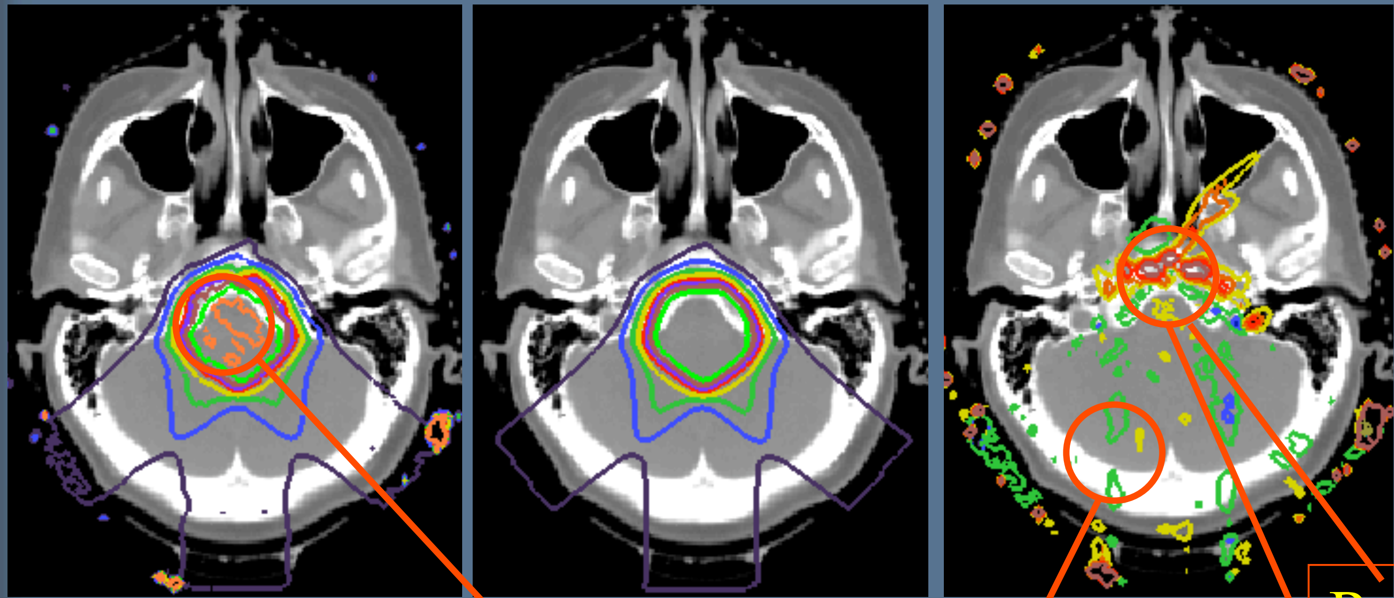
Case 1:
Para-spinal tumor
176 x 147 x 126 slices
voxels: 0.932 x 0.932 x 2.5-3.75 mm^3

Patient Dose Calculations



Patient Dose Calculations

Monte Carlo **Pencil Beam**



- -4 Gy(RBE)
- -3 Gy(RBE)
- -2 Gy(RBE)
- -1 Gy(RBE)
- +1 Gy(RBE)
- +2 Gy(RBE)
- +3 Gy(RBE)
- +4 Gy(RBE)

Range

Penumbra

Dose-to-water
Dose-to-tissue

Dose homogeneity

- 10 Gy(RBE)
- 20 Gy(RBE)
- 30 Gy(RBE)
- 35 Gy(RBE)
- 40 Gy(RBE)
- 42 Gy(RBE)
- 44 Gy(RBE)
- 46 Gy(RBE)
- 48 Gy(RBE)

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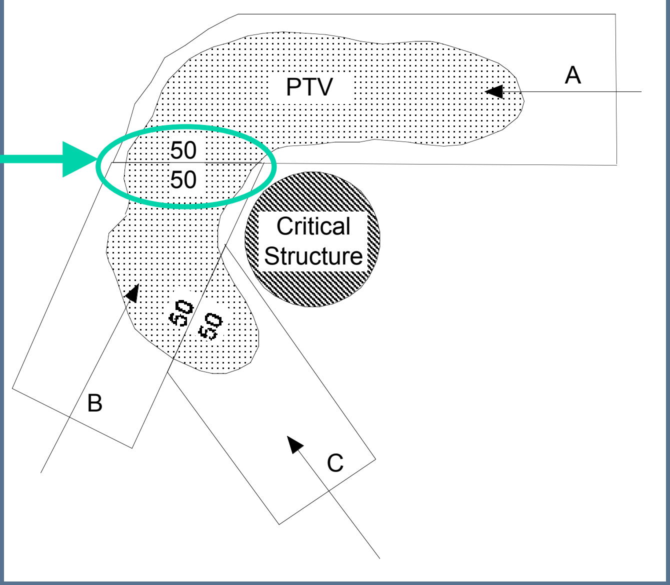
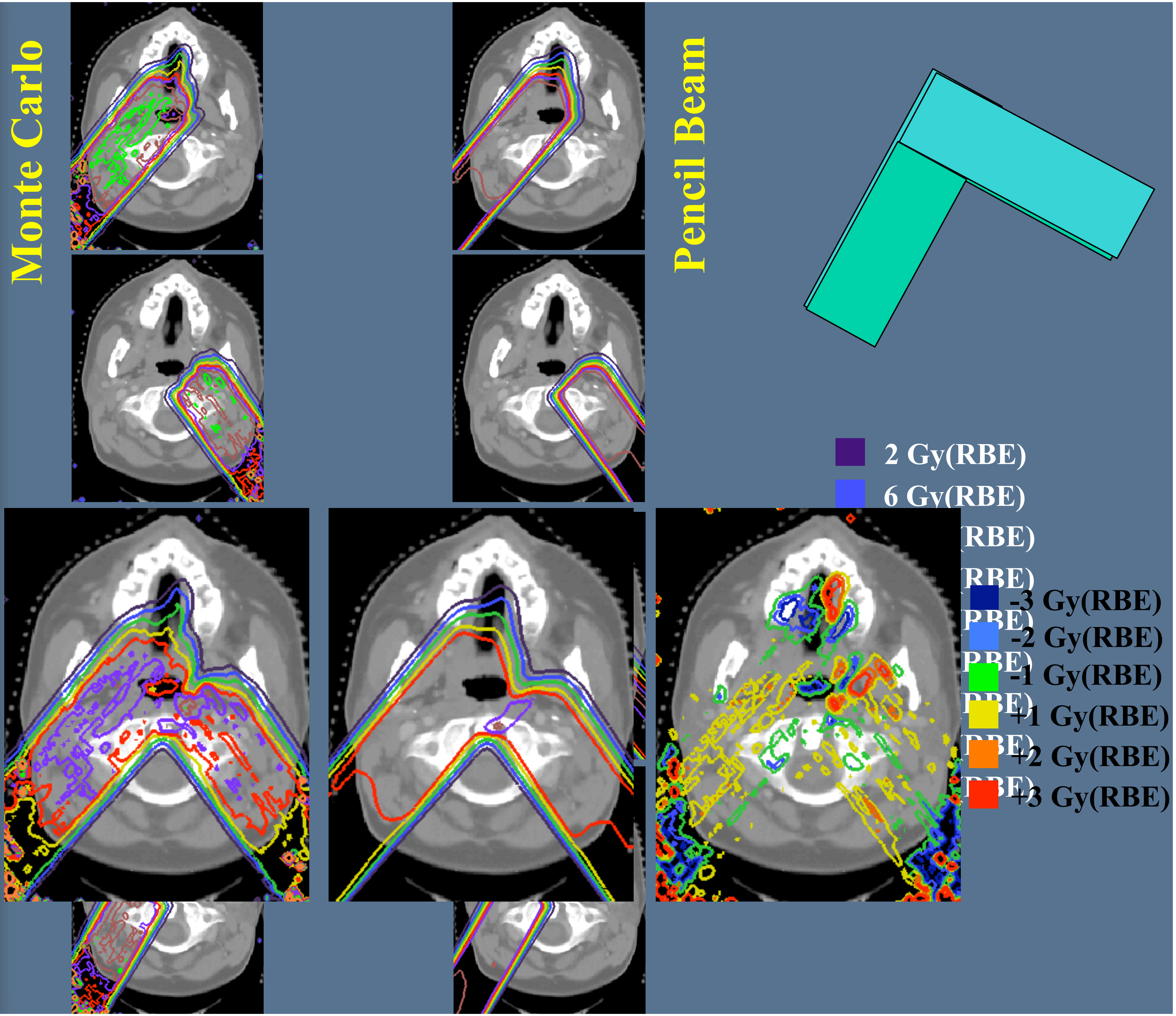
Example 2

Case 2:
Maxillary sinus
121x121x101 slices
voxels: 0.656 x 0.656 x 1.25-3.75 mm^3

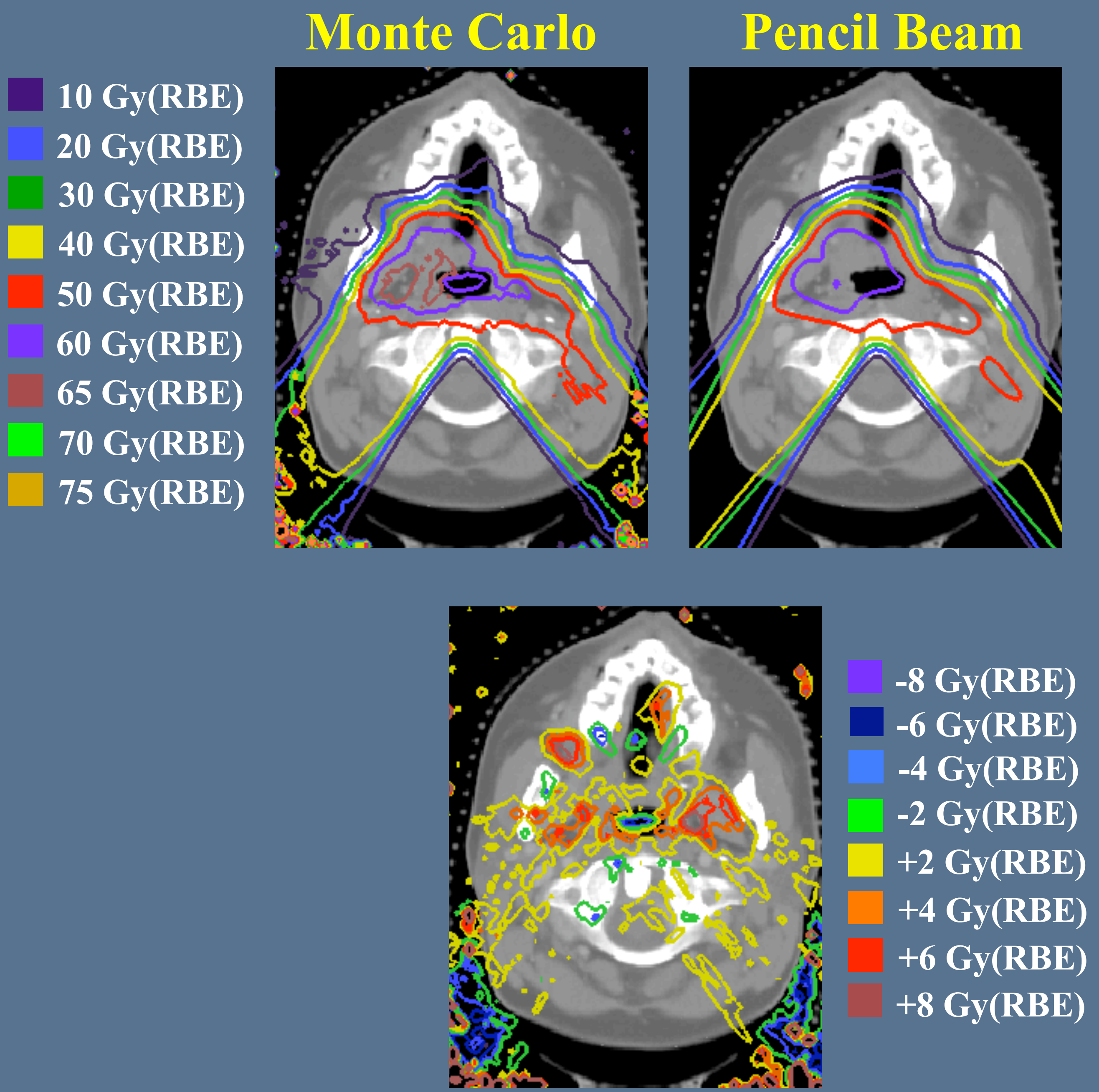
50% lateral penumbra
matched to
50% distal fall-off



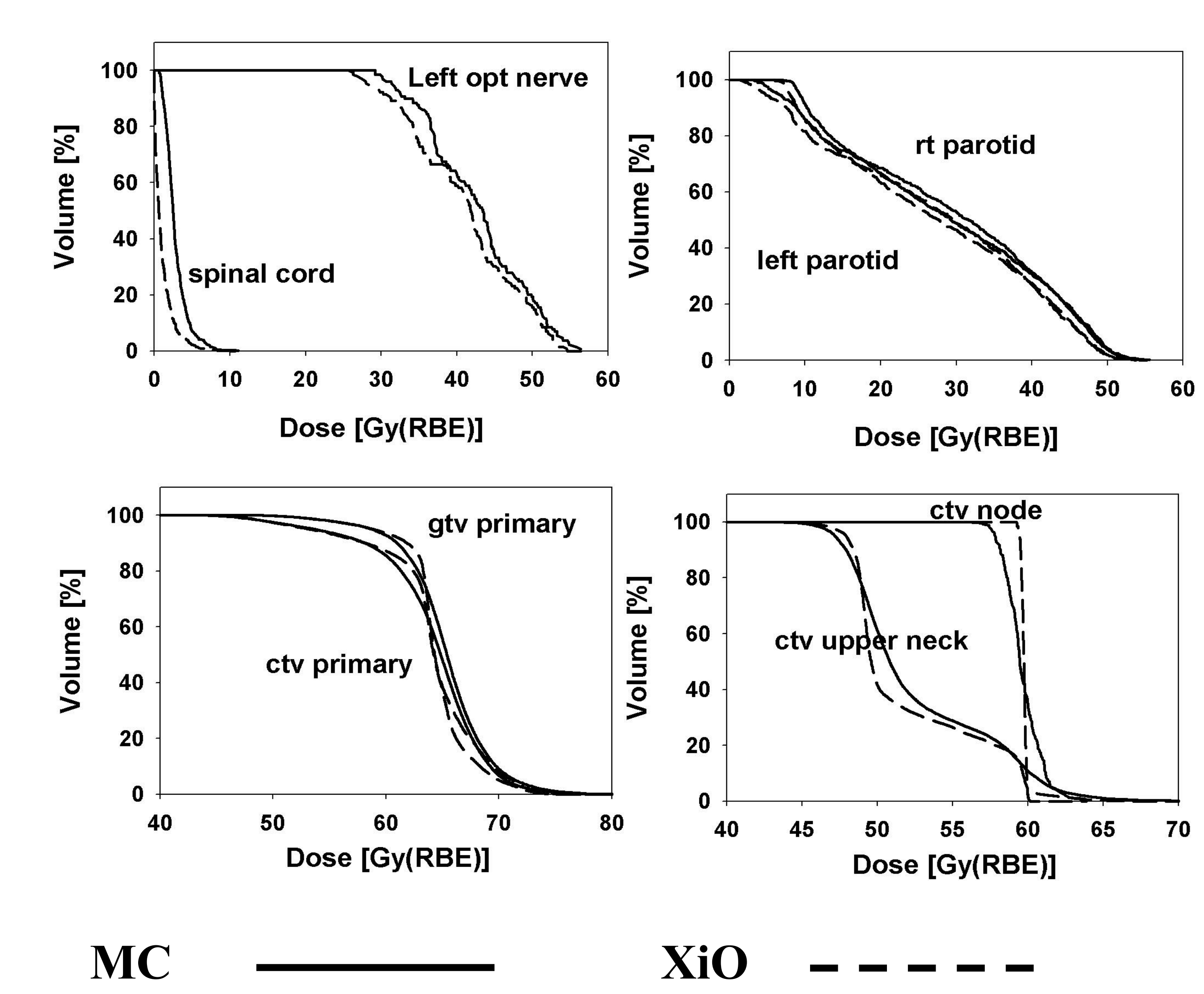
Patient Dose Calculations



Patient Dose Calculations



Clinical Examples



Conclusion

Monte Carlo simulations of the treatment head are useful for
- Treatment head design
- Quality assurance
- Absolute dosimetry

Monte Carlo dose calculation can benchmark analytical methods
Monte Carlo is already fast enough for dose re-calculation
Monte Carlo is not (yet) fast enough for treatment planning

Acknowledgements

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RO1 CA116743