Adapting a computed tomogram to Geant4 for monitoring proton therapy via prompt-gamma rays and time-of-flight PET

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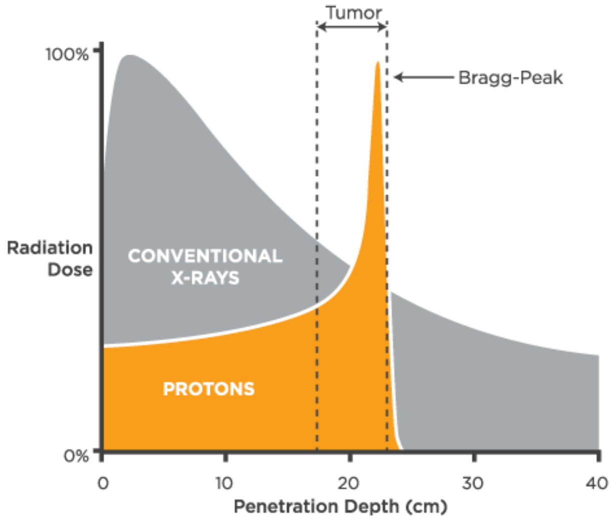
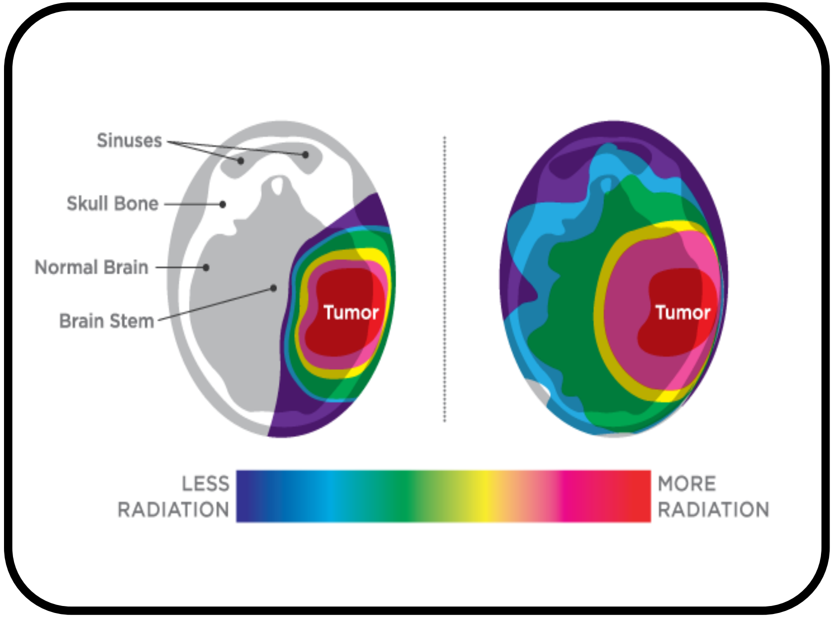
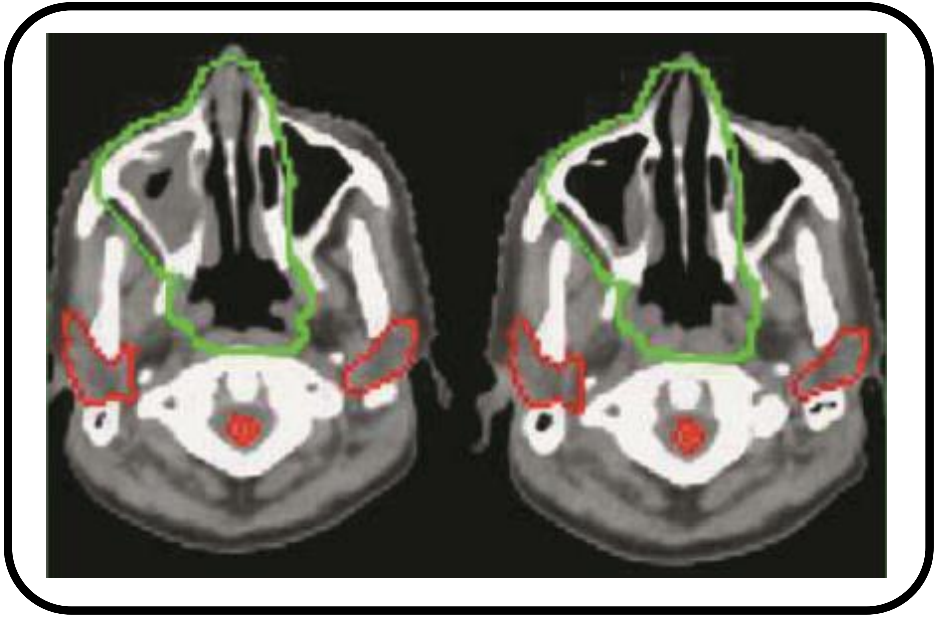
Proton therapy vs. conventional (x-rays) radiotherapy





Challenges in proton therapy

Example of a morphological change which can compromise the treatment output

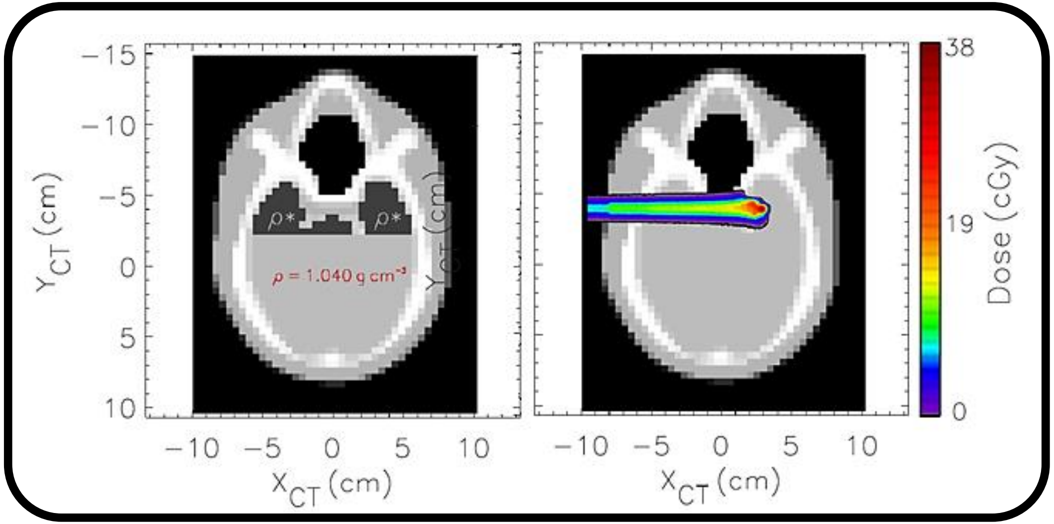


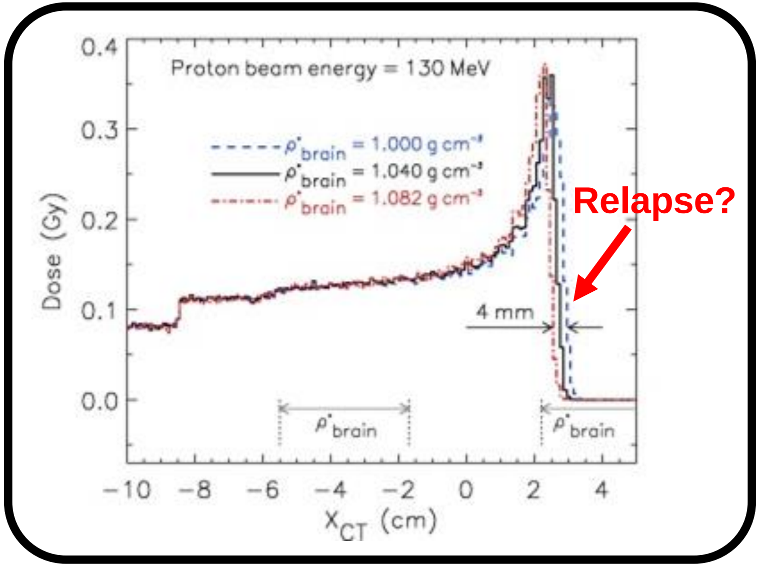
(Engelsman and Bert 2011)

Challenges in proton therapy

Change in brain density due to fractionated RT?

- Conjecture: brain tissue hypo/hyperdense due to fractionated RT



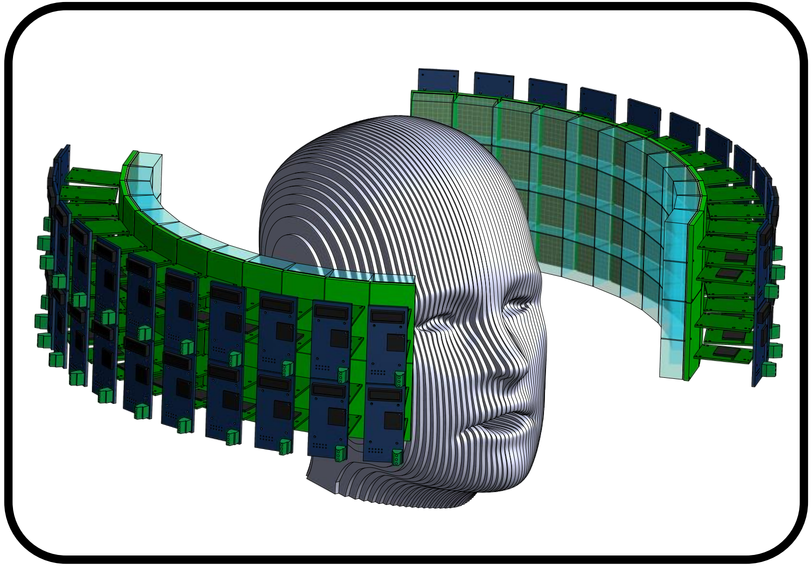


- A change of ± 4% in the brain density leads to a variation of ± 2 mm in the Bragg peak position

(Cambraia Lopes *et al*, Physica Medica 2018)

Proton-range verification: studies at LIP

A PET system prototype to be used in a proton therapy equipment, suitable for radiation monitoring of the head and neck cancers



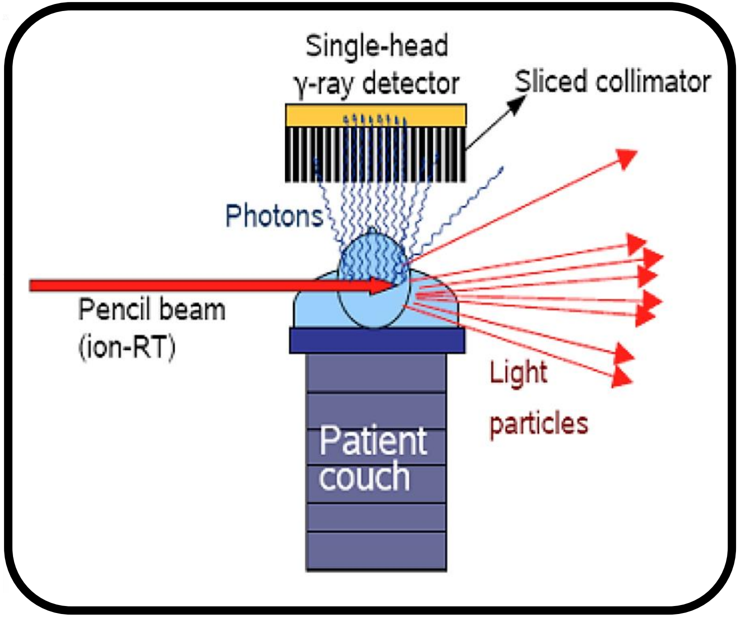
● Based on the detection of back-to-back photons (511 keV) resulting from e^- e^+ annihilation

● In proton therapy, the positron arises from β^+ emitters (mainly ^{11}C and ^{15}O) generated by nuclear interaction between protons and the patient tissue

(TPPT Consortium, already presented by Prof. Stefaan Tavernier)

Proton-range verification: studies at LIP

O-PGI concept: multi-sliced detector for orthogonal prompt-gamma imaging

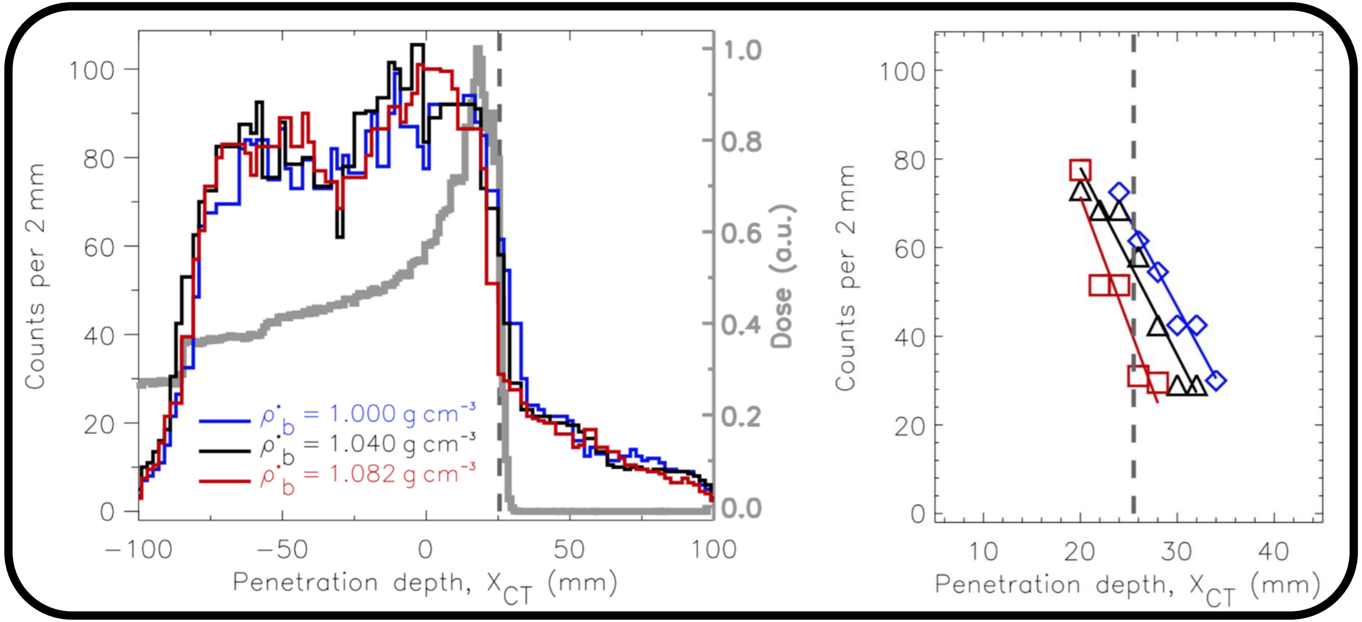


- Provides images of selected region without rotation of beam source
- Image with prompt gammas "stops" at beam range

(Cambraia Lopes *et al*, Physica Medica 2018)

Multi-sliced detector for orthogonal prompt-gamma imaging

Monte Carlo results with proposed detector (GEANT4)

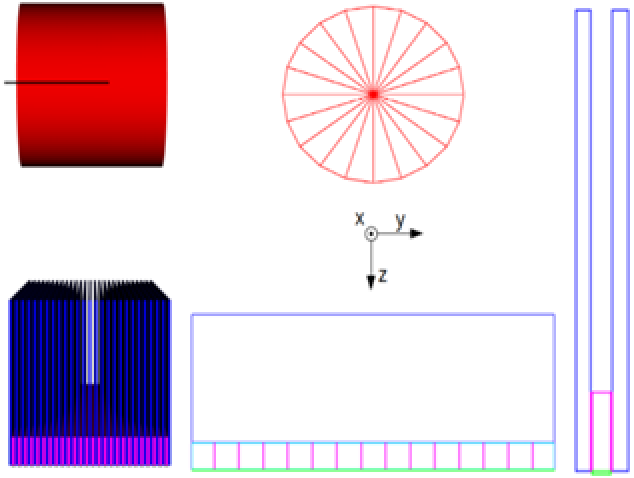


- Deviations in the Bragg peak position are visible in the O-PGI counts profiles (perfect detectors)

(Cambraia Lopes *et al*, Physica Medica 2018)

Multi-sliced detector for orthogonal prompt-gamma imaging

Comprehensive simulation and optimization of the detection system



1) Simulation of a homogeneous phantom irradiated by a proton beam

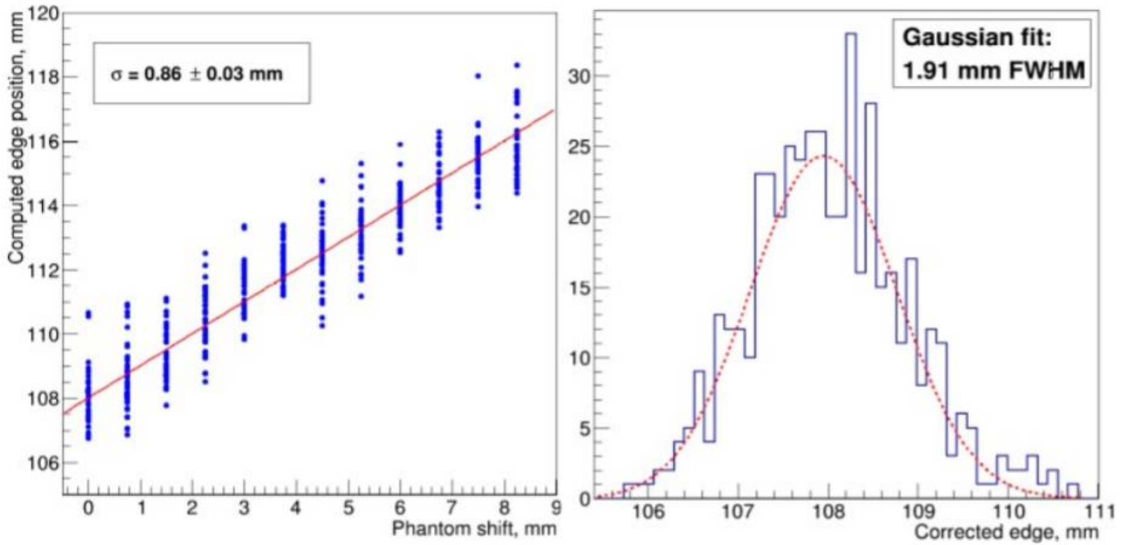
2) Simulation of the orthogonal prompt gamma imaging system

3) Generation of signal waveforms from the scintillation detectors based on the energy deposition data

(Morozov *et al*, Physica Medica 2021)

Multi-sliced detector for orthogonal prompt-gamma imaging

Comprehensive simulation and optimization of the detection system

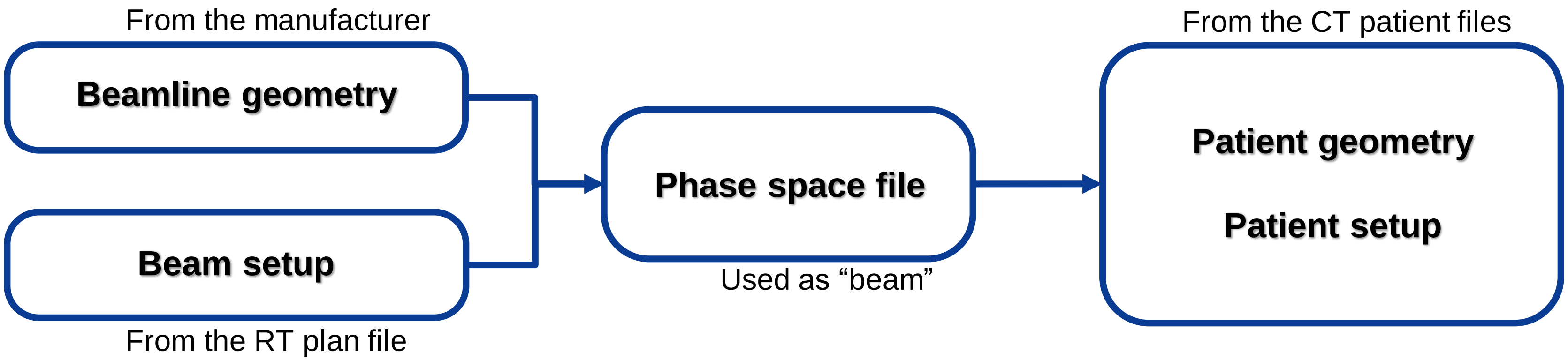


● A precision of about 2 mm FWHM in the distal edge of the Bragg peak position was obtained (even taking into account optical photons)

(Morozov *et al*, Physica Medica 2021)

Adapting a proton therapy treatment plan to Geant4

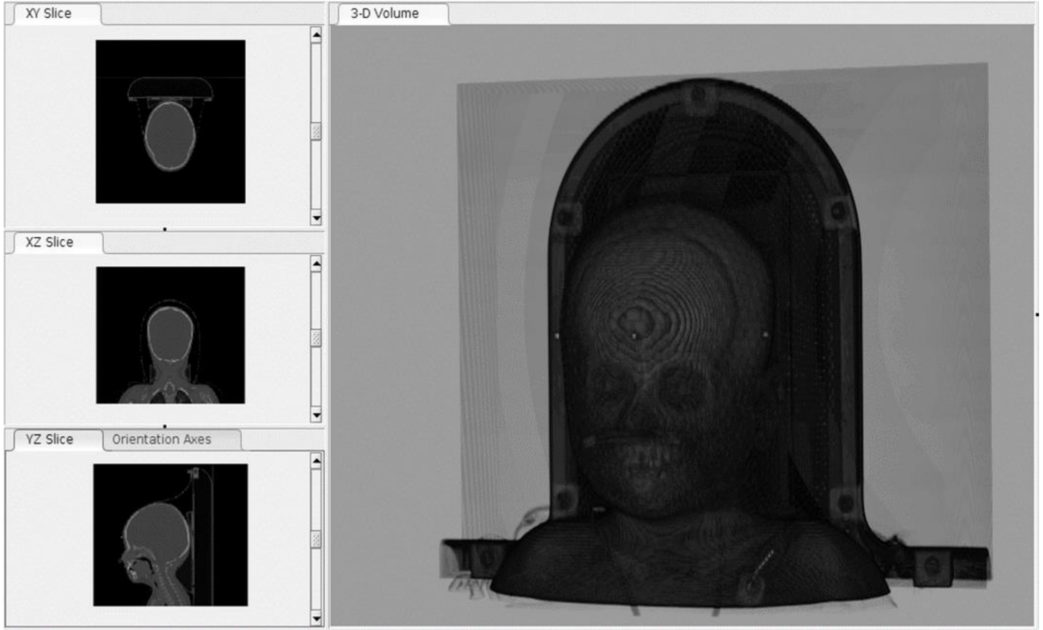
Treatment plan simulation is desirable for both the TPPT and the O-PGI systems



Dose computation
Prompt-gamma emmision
Induced β^+ activity

Adapting a proton therapy treatment plan to Geant4

Patient geometry/setup: CT data



- 5-years old patient
- 170 CT slices with 512 x 512 voxels per slice
- Voxel size: 0.78125 mm x 0.78125 mm;
- Covered area: 400 mm x 400 mm;
- Slice thickness: 2 mm

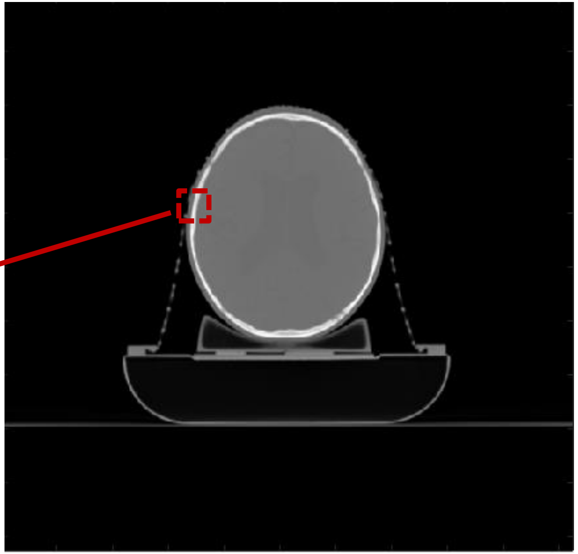
(Data set provided by MDACC, Texas, USA)

Adapting a proton therapy treatment plan to Geant4

Patient geometry/setup: CT data

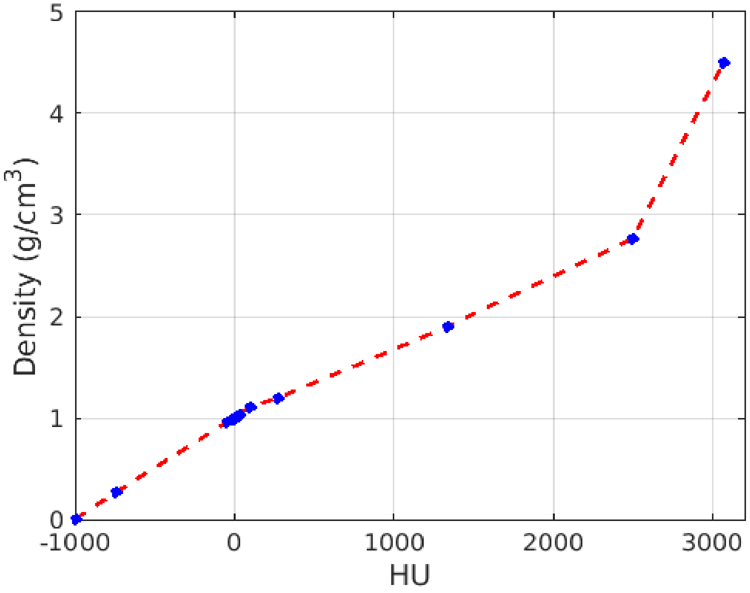
Hounsfield Unit (HU) values

-1000	-1000	-1000	-1000	-1000	-1000	-1000	-798	-478	-253	-33	-18	54	592	1093	945	949	648	189	63	50	60
-1000	-1000	-1000	-1000	-1000	-1000	-1000	-716	-451	-190	-10	-22	146	796	1119	954	907	468	119	53	47	52
-1000	-1000	-1000	-1000	-1000	-1000	-935	-616	-395	-113	0	-7	291	983	1116	979	837	331	87	50	40	45
-1000	-1000	-1000	-1000	-1000	-1000	-813	-485	-308	-55	-1	29	462	1104	1060	973	733	230	60	41	37	43
-1000	-1000	-1000	-1000	-1000	-997	-619	-323	-195	-19	-14	87	660	1171	1006	945	578	156	47	39	39	42
-1000	-1000	-1000	-1000	-1000	-889	-393	-165	-84	8	-21	165	838	1181	994	886	423	109	46	36	34	46
-1000	-1000	-1000	-1000	-1000	-731	-198	-56	-13	18	-10	271	984	1139	998	773	290	81	44	38	39	47
-1000	-1000	-1000	-1000	-1000	-585	-100	-24	20	12	8	412	1104	1108	996	622	188	67	43	43	44	52
-1000	-1000	-1000	-1000	-974	-560	-204	-95	19	0	44	574	1171	1086	938	448	123	60	45	44	43	49
-1000	-1000	-1000	-1000	-953	-686	-472	-210	3	-6	122	744	1184	1061	831	310	101	65	54	45	48	52
-1000	-1000	-1000	-1000	-949	-799	-623	-212	0	-2	220	915	1215	1080	721	225	93	67	54	44	46	59
-1000	-1000	-1000	-1000	-963	-879	-634	-152	-4	4	330	1048	1208	1068	598	161	73	58	49	38	47	59
-1000	-1000	-1000	-1000	-987	-928	-563	-85	-9	19	443	1117	1128	992	473	112	56	49	43	34	51	63
-1000	-1000	-1000	-1000	-1000	-909	-423	-21	-13	51	580	1157	1063	915	377	91	58	47	38	40	57	63
-1000	-1000	-1000	-1000	-1000	-844	-282	6	-24	91	713	1201	1073	856	299	73	52	45	35	41	57	61
-1000	-1000	-1000	-1000	-1000	-760	-185	3	-26	158	840	1221	1084	779	242	72	44	39	44	49	52	58
-1000	-1000	-1000	-1000	-1000	-659	-114	-8	-23	254	975	1224	1072	696	200	60	41	34	37	50	50	58
-1000	-1000	-1000	-1000	-997	-563	-64	-7	-3	352	1087	1222	1040	611	162	52	49	36	40	49	45	50
-1000	-1000	-1000	-1000	-971	-475	-24	-11	12	446	1134	1190	998	524	135	53	44	38	41	38	40	48
-1000	-1000	-1000	-1000	-911	-392	-5	-25	35	548	1158	1154	959	459	119	55	46	51	46	36	40	40
-1000	-1000	-937	-847	-767	-291	9	-23	77	657	1179	1114	918	417	108	47	43	53	51	45	43	39
-1000	-997	-657	-400	-437	-157	25	-20	117	756	1200	1104	874	364	89	50	38	48	54	54	48	40
-1000	-937	-415	-40	-120	-37	24	-23	167	856	1205	1080	831	321	81	51	47	50	52	58	56	46
-1000	-920	-409	-59	-83	5	13	-23	231	961	1210	1064	815	300	75	48	49	49	55	58	58	51
-1000	-988	-644	-383	-245	-7	-2	-25	299	1042	1188	1058	809	289	63	39	47	50	56	58	59	52
-1000	-1000	-848	-675	-365	-14	-6	-6	382	1088	1130	1052	807	279	61	41	47	53	57	58	58	53
-1000	-1000	-905	-782	-372	-6	-4	34	467	1105	1069	1047	822	277	60	39	38	46	51	56	54	55
-1000	-1000	-924	-794	-335	6	-3	65	536	1140	1059	1043	834	276	63	35	35	41	44	50	45	52
-1000	-1000	-927	-791	-313	1	-16	66	583	1170	1077	1061	816	259	57	34	31	31	35	36	42	49
-1000	-988	-917	-775	-287	3	-28	65	627	1172	1064	1059	758	228	59	37	29	32	34	32	32	31
-1000	-962	-895	-741	-251	14	-33	70	674	1176	1055	1042	685	192	52	42	46	44	42	35	29	29
-1000	-919	-857	-722	-222	18	-31	91	733	1186	1055	1047	630	166	55	55	56	54	51	42	36	34
-998	-851	-822	-718	-201	17	-30	116	781	1180	1064	1064	571	144	55	51	54	58	63	56	51	44
-955	-758	-785	-711	-189	15	-31	130	815	1174	1083	1023	483	122	53	52	57	58	67	65	59	50
-877	-645	-732	-686	-172	16	-33	139	842	1180	1098	950	394	104	55	58	59	58	66	64	65	57
-757	-519	-657	-636	-150	14	-41	144	864	1210	1133	848	302	84	53	53	55	61	67	67	64	50
-611	-403	-613	-618	-146	5	-45	158	909	1276	1161	722	219	69	46	45	48	59	71	65	57	55
-489	-344	-636	-650	-151	4	-43	166	933	1324	1157	606	155	59	43	39	42	54	64	63	57	52
-431	-353	-683	-687	-162	13	-39	164	937	1336	1110	511	126	51	51	48	48	51	53	61	57	55
-438	-445	-750	-710	-177	8	-39	168	942	1343	1017	416	114	60	60	66	60	49	50	52	48	51
-501	-568	-818	-746	-200	4	-37	162	926	1303	892	335	103	72	68	67	63	52	47	46	52	57



Adapting a proton therapy treatment plan to Geant4

Convert the Hounsfield Unit (HU) value from CT files to density



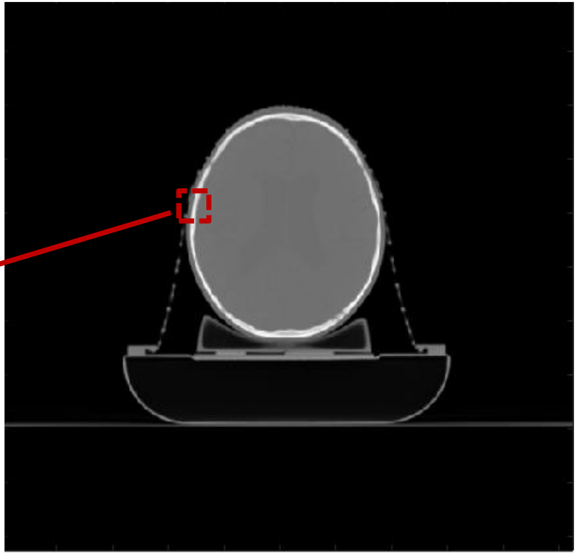
- CT scanner: Somatom Definition Edge (Siemens)
- Calibration curve “acquired” at MDACC

Adapting a proton therapy treatment plan to Geant4

Convert the Hounsfield Unit (HU) value from CT files to density

Density values

0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.209	0.530	0.754	0.973	0.988	1.066	1.406	1.738	1.640	1.643	1.443	1.153	1.075	1.062	1.072
0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.293	0.557	0.817	0.995	0.984	1.132	1.541	1.755	1.646	1.615	1.323	1.119	1.065	1.059	1.064
0.001	0.001	0.001	0.001	0.001	0.001	0.067	0.392	0.613	0.894	1.000	0.996	1.206	1.665	1.753	1.662	1.568	1.233	1.099	1.062	1.052	1.057
0.001	0.001	0.001	0.001	0.001	0.001	0.193	0.523	0.699	0.952	0.999	1.041	1.320	1.745	1.716	1.658	1.499	1.173	1.072	1.053	1.049	1.055
0.001	0.001	0.001	0.001	0.001	0.003	0.389	0.684	0.812	0.987	0.992	1.099	1.451	1.790	1.680	1.640	1.396	1.137	1.059	1.051	1.051	1.054
0.001	0.001	0.001	0.001	0.001	0.115	0.615	0.842	0.923	1.009	0.985	1.141	1.569	1.796	1.672	1.601	1.294	1.114	1.058	1.048	1.046	1.058
0.001	0.001	0.001	0.001	0.001	0.278	0.809	0.951	0.992	1.024	0.995	1.193	1.666	1.769	1.675	1.526	1.205	1.093	1.056	1.050	1.051	1.059
0.001	0.001	0.001	0.001	0.001	0.423	0.907	0.982	1.027	1.015	1.009	1.286	1.745	1.748	1.674	1.426	1.153	1.079	1.055	1.055	1.056	1.064
0.001	0.001	0.001	0.001	0.027	0.448	0.803	0.912	1.026	1.000	1.056	1.394	1.790	1.733	1.635	1.310	1.121	1.072	1.057	1.056	1.055	1.061
0.001	0.001	0.001	0.001	0.049	0.323	0.536	0.797	1.002	0.997	1.120	1.507	1.798	1.717	1.564	1.219	1.110	1.077	1.066	1.057	1.060	1.064
0.001	0.001	0.001	0.001	0.053	0.208	0.385	0.795	1.000	0.999	1.168	1.620	1.819	1.729	1.491	1.171	1.105	1.079	1.066	1.056	1.058	1.071
0.001	0.001	0.001	0.001	0.038	0.125	0.374	0.855	0.998	1.003	1.232	1.708	1.814	1.721	1.410	1.139	1.085	1.070	1.061	1.050	1.059	1.071
0.001	0.001	0.001	0.001	0.013	0.074	0.445	0.922	0.995	1.026	1.307	1.754	1.761	1.671	1.327	1.115	1.068	1.061	1.055	1.046	1.063	1.075
0.001	0.001	0.001	0.001	0.001	0.094	0.585	0.985	0.992	1.063	1.398	1.781	1.718	1.620	1.263	1.103	1.070	1.059	1.050	1.052	1.069	1.075
0.001	0.001	0.001	0.001	0.001	0.161	0.725	1.006	0.982	1.103	1.486	1.810	1.725	1.581	1.211	1.085	1.064	1.057	1.047	1.053	1.069	1.073
0.001	0.001	0.001	0.001	0.001	0.248	0.822	1.002	0.980	1.138	1.570	1.823	1.732	1.530	1.179	1.084	1.056	1.051	1.056	1.061	1.064	1.070
0.001	0.001	0.001	0.001	0.001	0.349	0.893	0.996	0.983	1.185	1.660	1.825	1.724	1.475	1.158	1.072	1.053	1.046	1.049	1.062	1.062	1.070
0.001	0.001	0.001	0.001	0.003	0.445	0.943	0.996	0.998	1.247	1.734	1.824	1.703	1.418	1.140	1.064	1.061	1.048	1.052	1.061	1.057	1.062
0.001	0.001	0.001	0.001	0.030	0.533	0.982	0.994	1.015	1.309	1.765	1.802	1.675	1.361	1.127	1.065	1.056	1.050	1.053	1.050	1.052	1.060
0.001	0.001	0.001	0.001	0.092	0.616	0.997	0.981	1.047	1.377	1.781	1.779	1.649	1.318	1.119	1.067	1.058	1.063	1.058	1.048	1.052	1.052
0.001	0.001	0.065	0.158	0.241	0.716	1.011	0.983	1.089	1.449	1.795	1.752	1.622	1.290	1.113	1.059	1.055	1.065	1.063	1.057	1.055	1.051
0.001	0.003	0.351	0.608	0.571	0.850	1.036	0.986	1.118	1.515	1.809	1.745	1.593	1.254	1.101	1.062	1.050	1.060	1.066	1.066	1.060	1.052
0.001	0.065	0.593	0.966	0.887	0.969	1.034	0.983	1.142	1.581	1.812	1.729	1.564	1.226	1.093	1.063	1.059	1.062	1.064	1.070	1.068	1.058
0.001	0.083	0.599	0.948	0.924	1.005	1.017	0.983	1.174	1.651	1.816	1.719	1.554	1.212	1.087	1.060	1.061	1.061	1.067	1.070	1.070	1.063
0.001	0.012	0.364	0.625	0.762	0.996	0.999	0.981	1.211	1.704	1.801	1.715	1.550	1.205	1.075	1.051	1.059	1.062	1.068	1.070	1.071	1.064
0.001	0.001	0.157	0.333	0.643	0.992	0.997	0.997	1.266	1.735	1.763	1.711	1.548	1.198	1.073	1.053	1.059	1.065	1.069	1.070	1.070	1.065
0.001	0.001	0.098	0.225	0.636	0.997	0.998	1.046	1.323	1.746	1.722	1.708	1.558	1.197	1.072	1.051	1.050	1.058	1.063	1.068	1.066	1.067
0.001	0.001	0.079	0.213	0.672	1.006	0.998	1.077	1.369	1.769	1.716	1.705	1.566	1.196	1.075	1.047	1.047	1.053	1.056	1.062	1.057	1.064
0.001	0.001	0.075	0.216	0.694	1.001	0.990	1.078	1.400	1.789	1.727	1.717	1.554	1.187	1.069	1.046	1.043	1.043	1.047	1.048	1.054	1.061
0.001	0.012	0.086	0.233	0.720	1.002	0.978	1.077	1.429	1.790	1.719	1.716	1.516	1.172	1.071	1.049	1.041	1.044	1.046	1.044	1.044	1.043
0.001	0.039	0.109	0.268	0.756	1.018	0.973	1.082	1.460	1.793	1.713	1.704	1.467	1.154	1.064	1.054	1.058	1.056	1.054	1.047	1.041	1.041
0.001	0.084	0.148	0.287	0.785	1.024	0.975	1.103	1.499	1.800	1.713	1.708	1.431	1.142	1.067	1.067	1.068	1.066	1.063	1.054	1.048	1.046
0.002	0.154	0.184	0.291	0.806	1.023	0.976	1.117	1.531	1.796	1.719	1.719	1.392	1.131	1.067	1.063	1.066	1.070	1.075	1.068	1.063	1.056
0.046	0.250	0.222	0.298	0.818	1.020	0.975	1.124	1.554	1.792	1.731	1.692	1.333	1.120	1.065	1.064	1.069	1.070	1.079	1.077	1.071	1.062
0.127	0.363	0.277	0.323	0.835	1.021	0.973	1.129	1.572	1.796	1.741	1.643	1.274	1.111	1.067	1.070	1.071	1.070	1.078	1.076	1.077	1.069
0.251	0.489	0.351	0.372	0.857	1.018	0.966	1.131	1.586	1.816	1.765	1.576	1.213	1.096	1.065	1.065	1.067	1.073	1.079	1.079	1.076	1.062
0.397	0.605	0.395	0.390	0.861	1.005	0.962	1.138	1.616	1.859	1.783	1.492	1.168	1.081	1.058	1.057	1.060	1.071	1.083	1.077	1.069	1.067
0.519	0.664	0.372	0.358	0.856	1.003	0.964	1.142	1.632	1.891	1.781	1.415	1.136	1.071	1.055	1.051	1.054	1.066	1.076	1.075	1.069	1.064
0.577	0.655	0.326	0.322	0.845	1.017	0.967	1.141	1.635	1.899	1.749	1.352	1.122	1.063	1.063	1.060	1.060	1.063	1.065	1.073	1.069	1.067
0.570	0.563	0.258	0.299	0.830	1.009	0.967	1.143	1.638	1.904	1.688	1.289	1.116	1.072	1.072	1.078	1.072	1.061	1.062	1.064	1.060	1.063
0.507	0.440	0.188	0.263	0.807	1.003	0.969	1.140	1.627	1.877	1.605	1.235	1.111	1.084	1.080	1.079	1.075	1.064	1.059	1.058	1.064	1.069



Adapting a proton therapy treatment plan to Geant4

Assign a tissue material (with a specific stoichiometry) to each CT voxel, according to its density value

Material index	Material	Until to (density g/cm^3)
0	Air	0.25
1	Lung	0.50
2	Adipose	0.95
3	Muscle	1.05
4	Cartilage	1.10
5	2/3 Cartilage, 1/3 Bone	1.35
6	1/3 Cartilage, 2/3 Bone	1.60
7	Bone	1.85
8	Denser Bone	2.10
9	1/3 Bone, 2/3 Aluminum	2.40
10	Aluminum	2.70
11	Denser Aluminum	2.83
12	Iron	7.87

	density	I (eV)	H	C	N	O	Na	Mg	Al	P	S	Cl	Ar	K	Ca	Fe	Zn
Z			1	6	7	8	11	12	13	15	16	17	18	19	20	26	30
Z/A			0.992	0.5	0.5	0.5	0.478	0.494	0.482	0.484	0.499	0.479	0.451	0.486	0.499	0.466	0.459
Air	0.00121	85.7			75.5	23.2							1.3				
Lung	0.26	75.3	10.3	10.5	3.1	74.9	0.2			0.2	0.3	0.3		0.2			
Adipose	0.95	63.2	11.4	59.8	0.7	27.8	0.1				0.1	0.1					
Muscle	1.05	74.7	10.2	14.3	3.4	71	0.1			0.2	0.3	0.1		0.4			
Cartilage	1.1	75.0	9.6	9.9	2.2	74.4	0.5			2.2	0.9	0.3					
Bone (ICRP23)	1.85	106.4	4.7234	14.433	4.199	44.6096		0.22		10.497	0.315				20.993		0.01
Bone (ICRP23)+	2.1	106.4	4.7234	14.433	4.199	44.6096		0.22		10.497	0.315				20.993		0.01
Aluminum	2.7	166							100								
Aluminum+	2.83	166							100								
Iron	7.87	286														100	

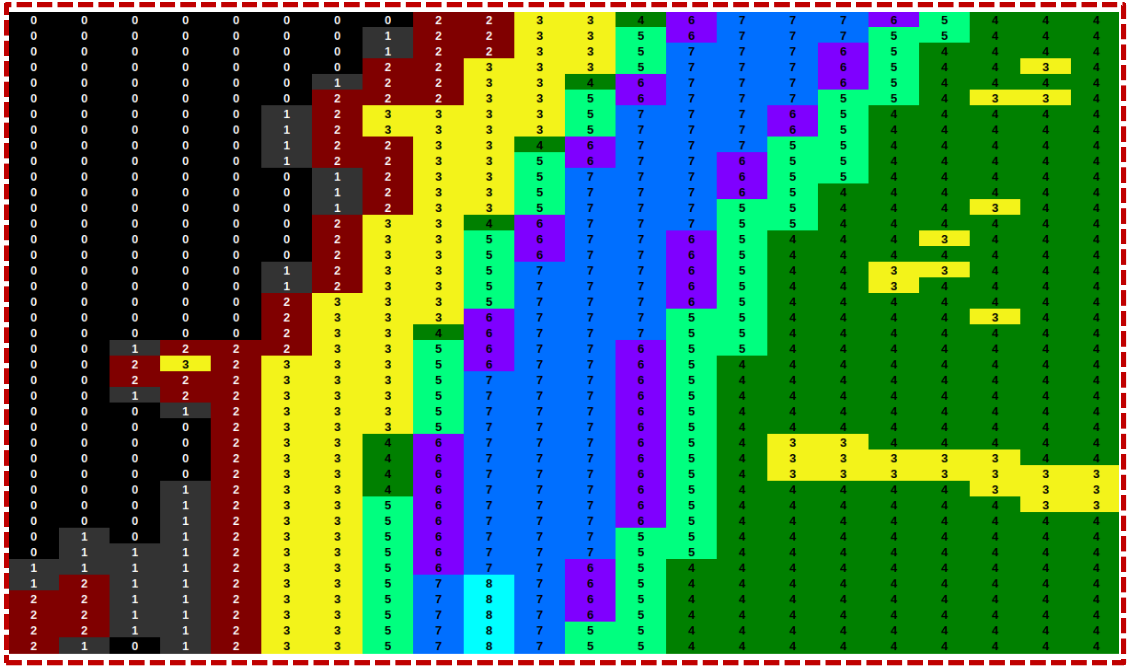
- Density and stoichiometry for each material is the same as defined by the treatment planning system (installed at MDACC)

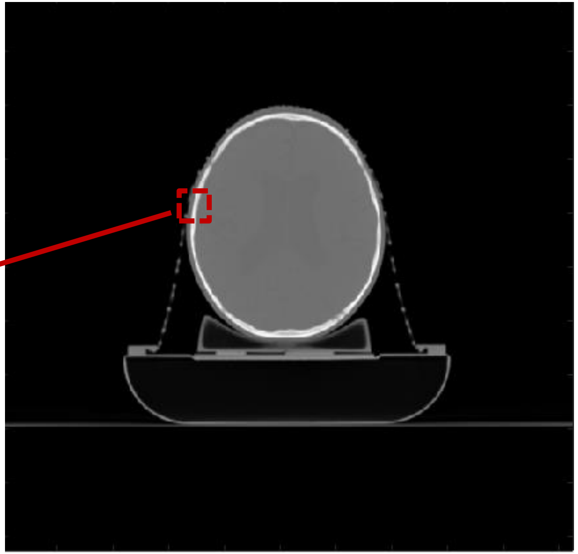
(RayStation 10A Reference Manual)

Adapting a proton therapy treatment plan to Geant4

Assign a tissue material (with a specific stoichiometry) to each CT voxel, according to its density value

Material index

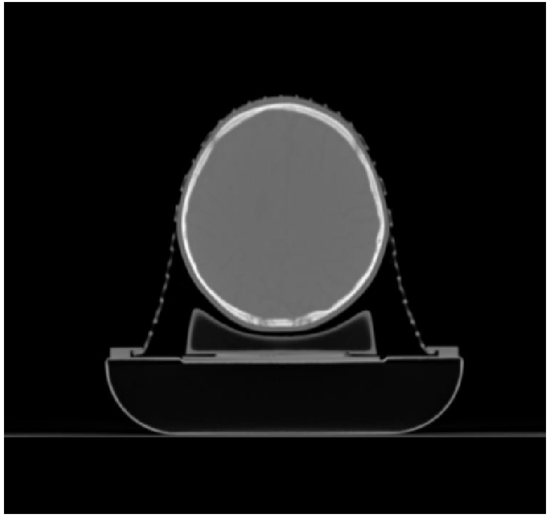




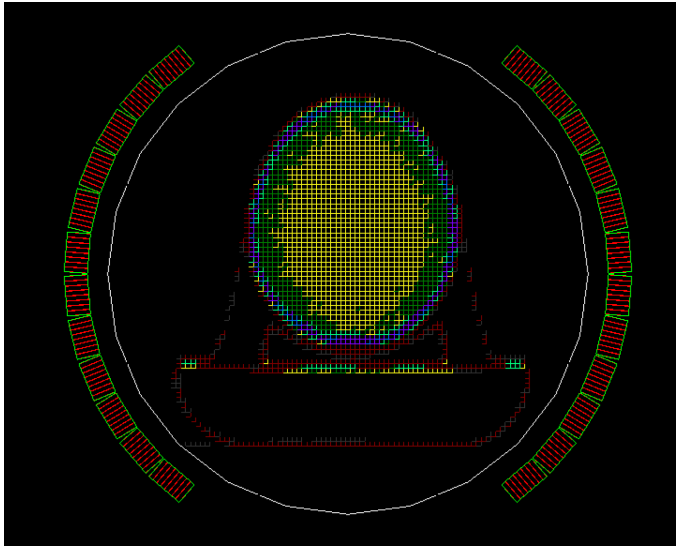
Adapting a proton therapy treatment plan to Geant4

Patient geometry merged with the TPPT system

Original patient CT slice

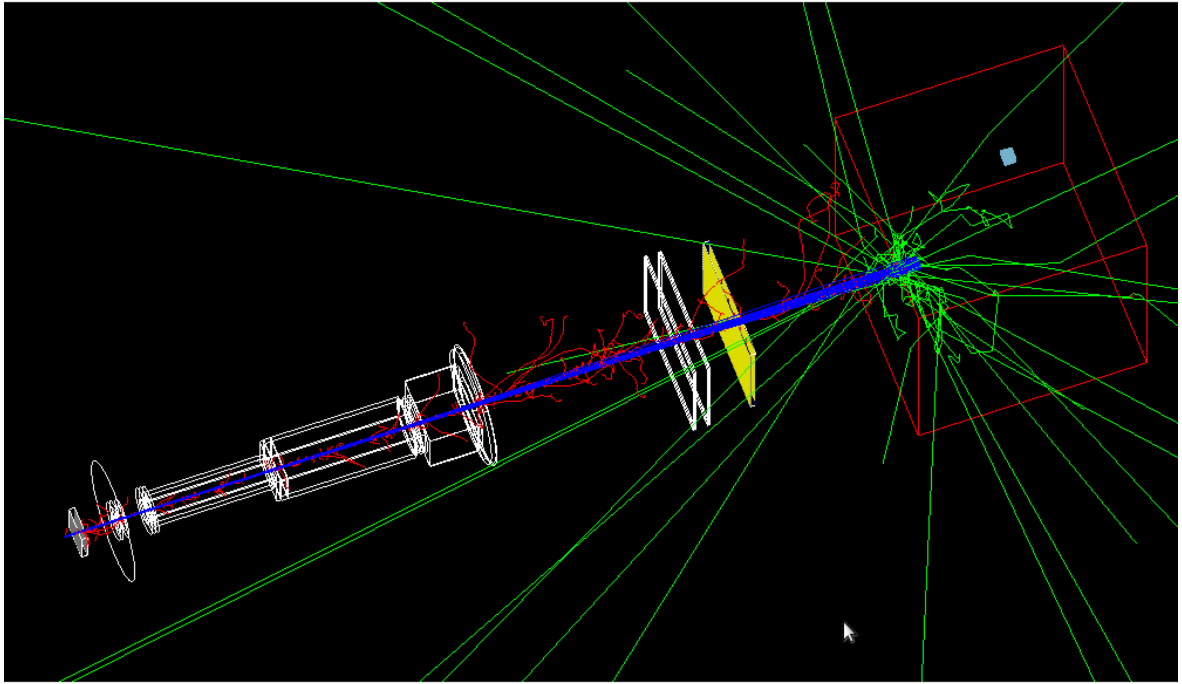


CT slice imported into Geant4



Adapting a proton therapy treatment plan to Geant4

Beamline geometry implemented into Geant4 (work in progress)



Final remarks

● Due to its ability to deposit large amounts of dose in a well-located position, proton range verification in proton radiotherapy is desirable;

● LIP is involved in the development of two systems for proton range verification: TPPT and O-PGI systems;

● Treatment plan simulation is desirable for both systems;

● Patient CT scan is already merged with the detector system; the implementation of the model of the nozzle is work in progress,

Thank you for your attention.

FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

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