

Linac modeling with PENELOPE

Priv.-Doz. Dr. Lorenzo Brualla



MEDIZINISCHE FAKULTÄT
DER UNIVERSITÄT DUISBURG-ESSEN

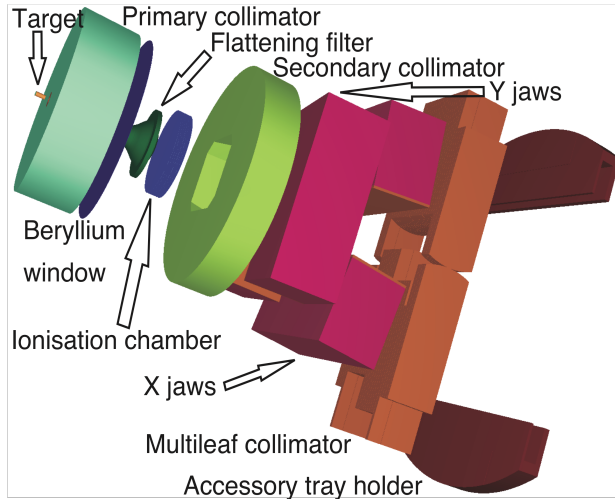


Universitätsklinikum Essen

Description of a simulated linac

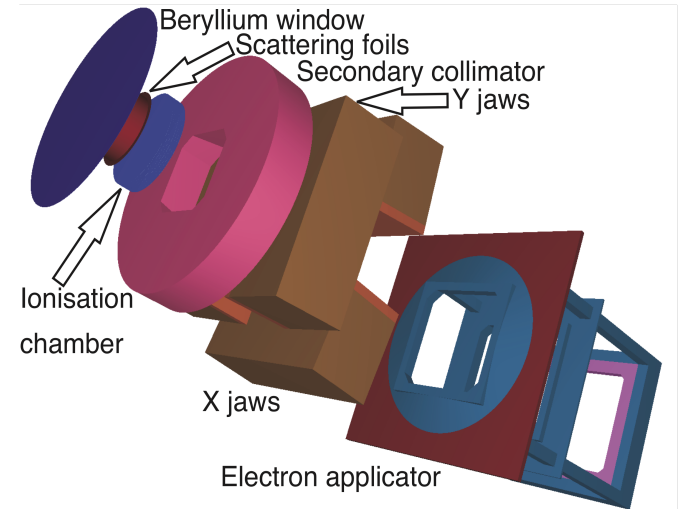
Photon mode

Varian

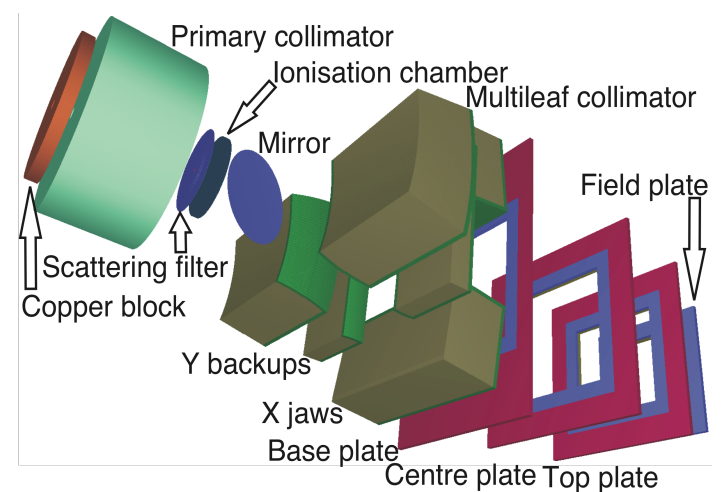
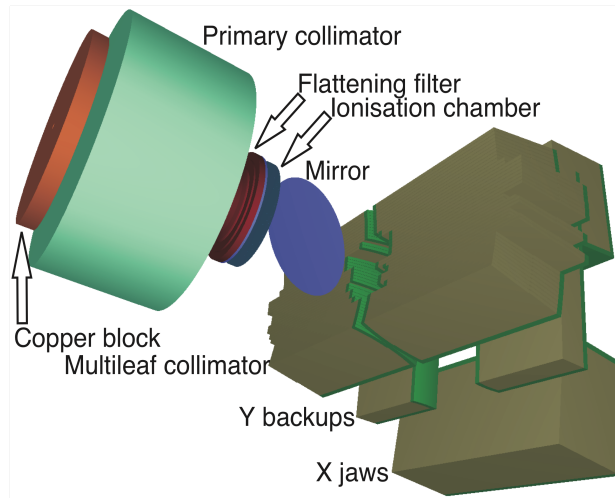


Electron mode

Ionisation chamber

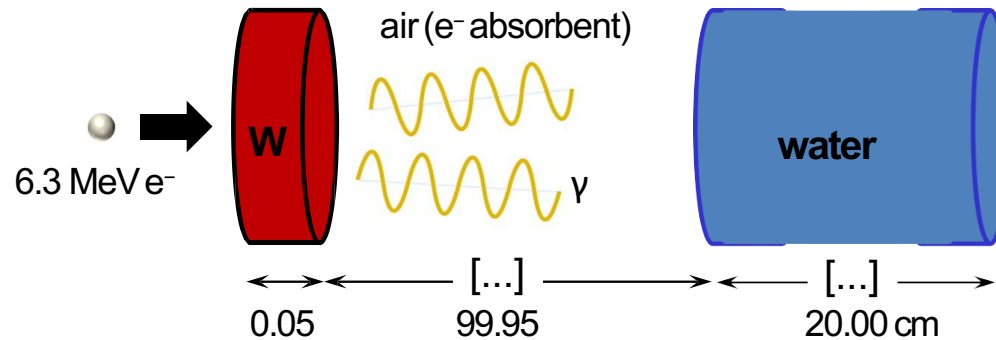


Elekta



Target simulation

Test: simulation setup

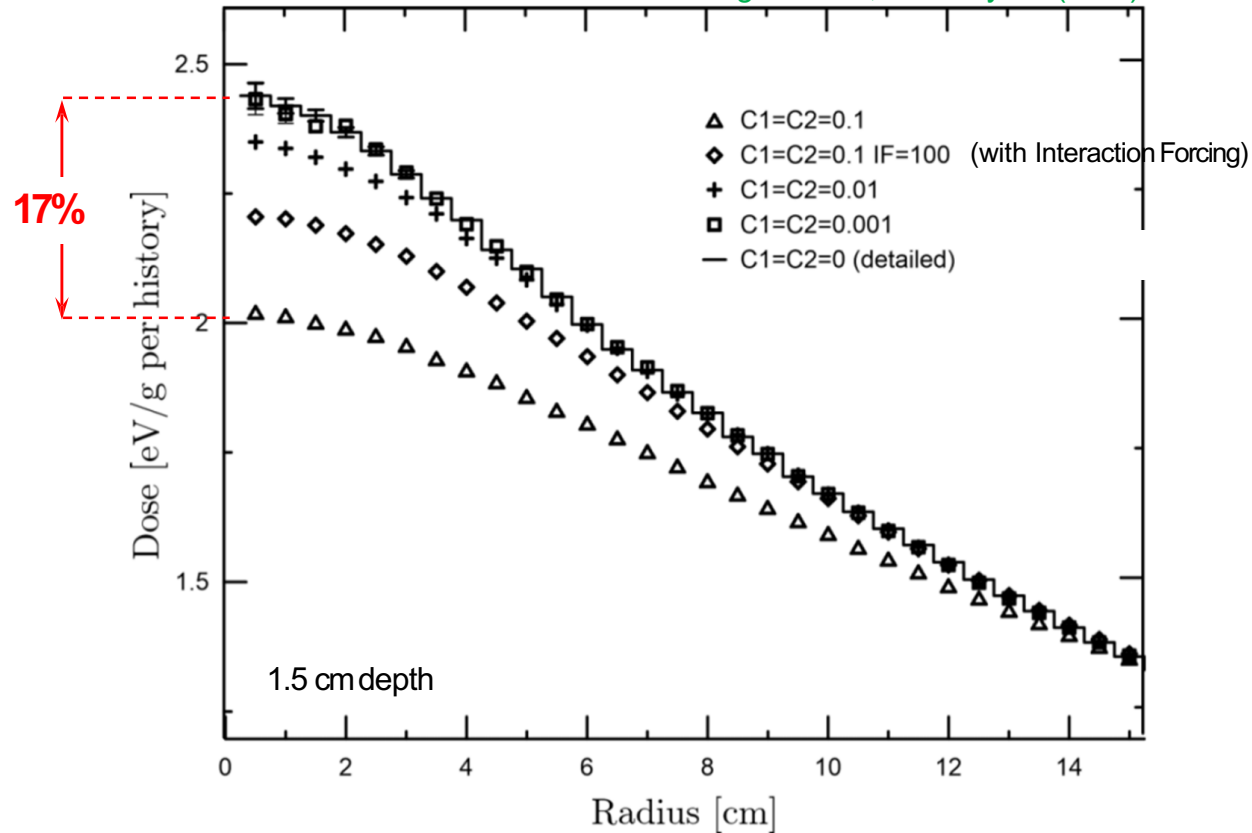


- The radial dose distribution in water is studied as a function of the Cparameter in tungsten.
- Standard parameter values are used for the other materials.

Target simulation

Test: results

M Rodríguez *et al.*, Med Phys 42 (2015)



Technical Note: Study of the electron transport parameters used in PENELOPE for the Monte Carlo simulation of Linac targets

Miguel Rodríguez and Josep Sempau
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Barcelona E-08028, Spain*

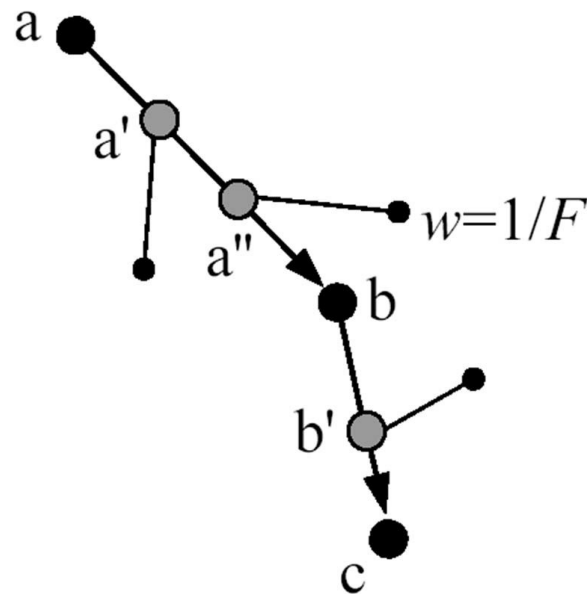
Lorenzo Brualla^{a)}
NCTeam, Strahlenklinik, Universitätsklinikum Essen, Hufelandstraße 55, Essen D-45122, Germany



Target simulation

Why does interaction forcing (IF) partially correct for too long steps?

- IF is applied in the target to increase bremsstrahlung production.
- This increases the efficiency, reducing the CPUtime for a given uncert.



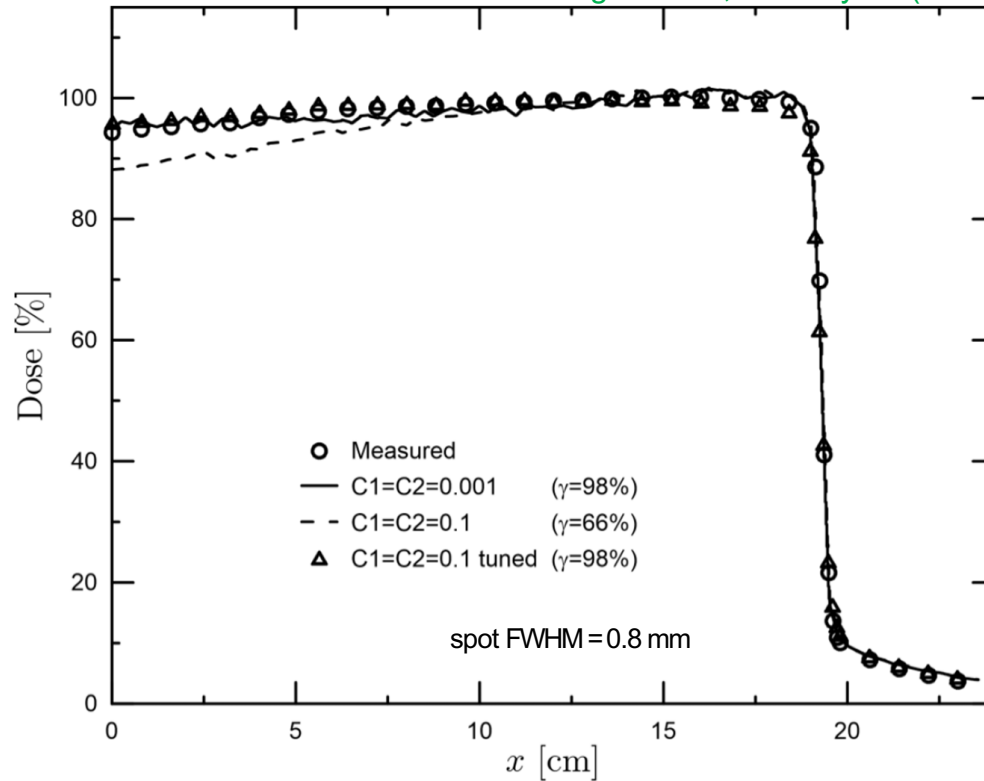
IF masks the effect of inappropriate transport parameters.



Target simulation

Varian Clinac 2100, 6 MV

M Rodríguez *et al.*, Med Phys 42 (2015)



Tuning of initial beam parameters may mask the artifact too.



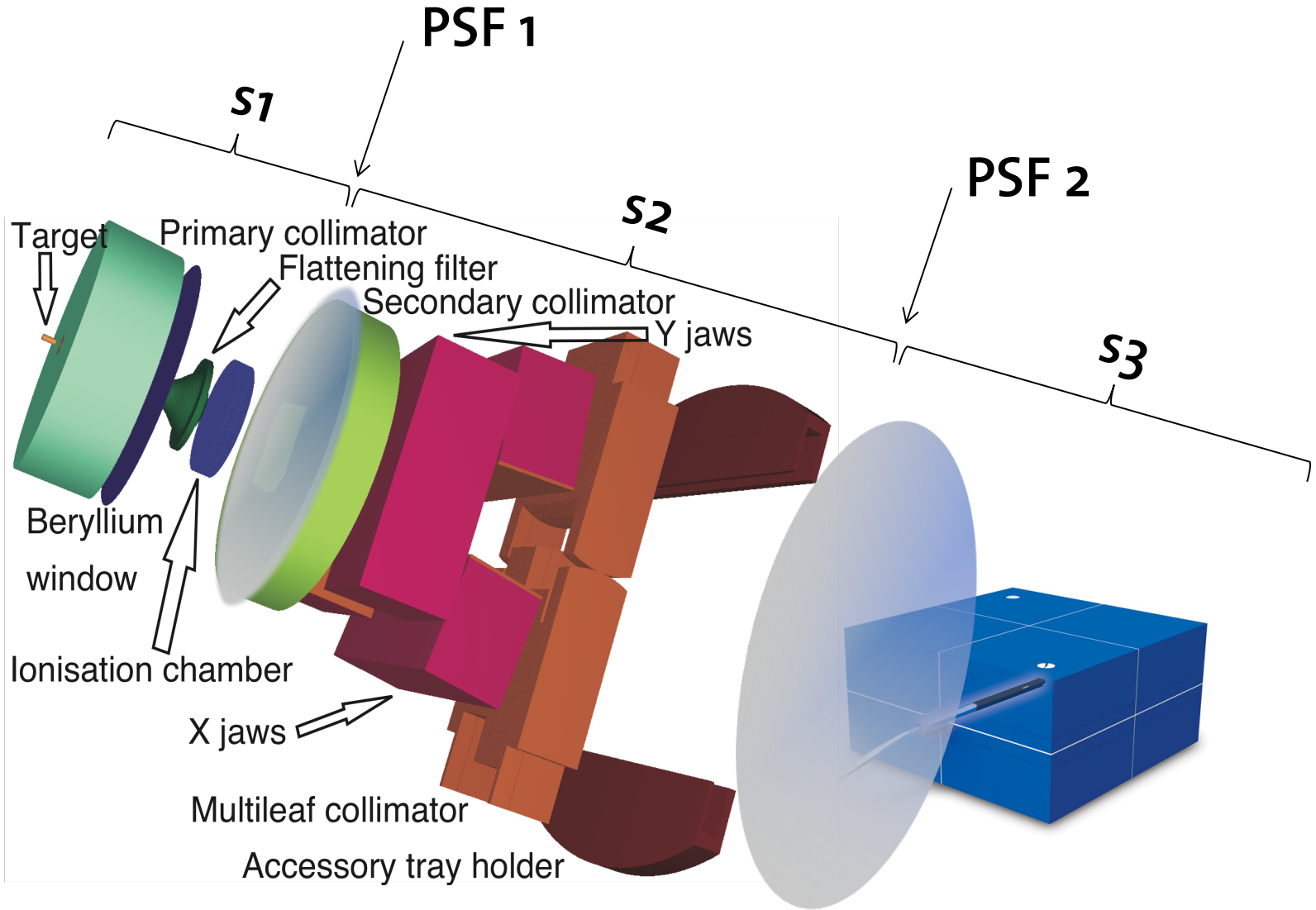
Target simulation

Are other MC codes affected too?

- All general-purpose MC codes rely on the condensed history technique to transport high energy electrons.
- Different codes use different multiple scattering theories and transport mechanics.
- All the approaches involve approximations of variable accuracy. In general, longer steps reduce the accuracy.
- Therefore, all codes may also exhibit similar artifacts. **Long steps should not be used without a previous thorough investigation.**



Phase-space file (PSF)



How does a PSF look like?

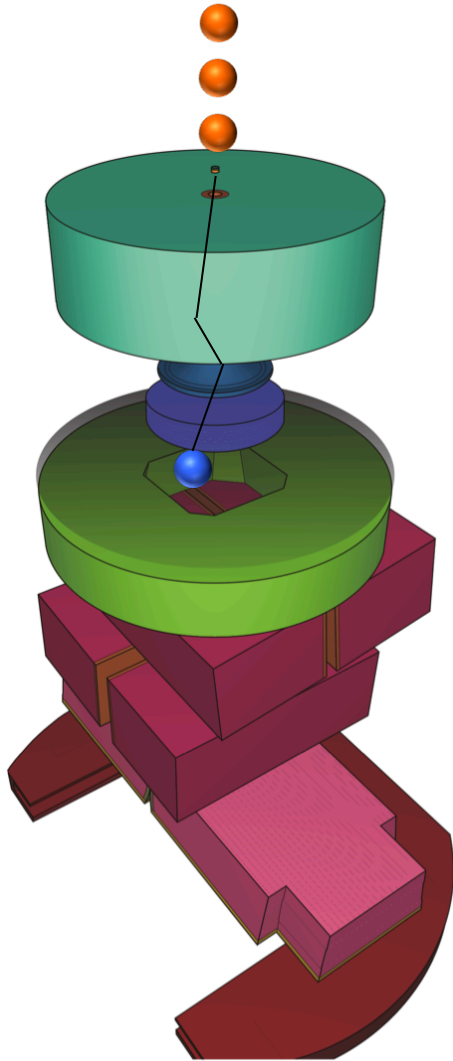
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2	2	1.00973E+05	4.65926E+00	-6.32448E+00	6.68000E+01	7.44427E-02	-8.18501E-02	9.93861E-01	5.91716E-05	2 2 1 4 0 0
3	2	1.00973E+05	4.42096E+00	-6.49329E+00	6.68000E+01	7.13488E-02	-8.45605E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
4	2	1.00973E+05	4.17654E+00	-6.65313E+00	6.68000E+01	6.81564E-02	-8.71541E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
5	2	1.00973E+05	3.92636E+00	-6.80378E+00	6.68000E+01	6.48698E-02	-8.96273E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
6	2	1.00973E+05	3.67075E+00	-6.94502E+00	6.68000E+01	6.14935E-02	-9.19766E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
7	2	1.00973E+05	3.41007E+00	-7.07666E+00	6.68000E+01	5.80323E-02	-9.41987E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
8	2	1.00973E+05	3.14467E+00	-7.19853E+00	6.68000E+01	5.44908E-02	-9.62907E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
9	2	1.00973E+05	2.87493E+00	-7.31044E+00	6.68000E+01	5.08740E-02	-9.82496E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
10	2	1.00973E+05	2.60121E+00	-7.41225E+00	6.68000E+01	4.71869E-02	-1.00073E-01	9.93861E-01	5.91716E-05	0 2 1 4 0 0
11	2	2.06650E+05	4.51939E+00	-8.11293E+00	6.68000E+01	6.62699E-02	-1.19732E-01	9.90592E-01	5.91716E-07	1 4 1 4 0 0
12	2	2.06650E+05	4.21471E+00	-8.27531E+00	6.68000E+01	6.17737E-02	-1.22112E-01	9.90592E-01	5.91716E-07	0 4 1 4 0 0
13	2	2.06650E+05	3.90420E+00	-8.42625E+00	6.68000E+01	5.71921E-02	-1.24324E-01	9.90592E-01	5.91716E-07	0 4 1 4 0 0
14	2	2.06650E+05	3.58830E+00	-8.56555E+00	6.68000E+01	5.25314E-02	-1.26364E-01	9.90592E-01	5.91716E-07	0 4 1 4 0 0
15	2	5.86523E+05	4.49902E+00	-7.31232E+00	6.68000E+01	6.68626E-02	-1.08633E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
16	2	5.86523E+05	4.22411E+00	-7.47449E+00	6.68000E+01	6.27785E-02	-1.11043E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
17	2	5.86523E+05	3.94337E+00	-7.62634E+00	6.68000E+01	5.86077E-02	-1.13300E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
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22	2	5.86523E+05	2.46589E+00	-8.22378E+00	6.68000E+01	3.66574E-02	-1.22180E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
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26	2	8.44930E+05	4.05506E+00	-8.52581E+00	6.68000E+01	6.12662E-02	-1.47708E-01	9.87132E-01	5.91716E-05	0 2 1 4 0 0
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33	2	8.44930E+05	1.84410E+00	-7.39987E+00	6.68000E+01	2.74214E-02	-1.10081E-01	9.93544E-01	5.91716E-05	0 2 1 4 0 0
34	2	8.44930E+05	1.56778E+00	-7.46331E+00	6.68000E+01	2.33108E-02	-1.11024E-01	9.93544E-01	5.91716E-05	0 2 1 4 0 0

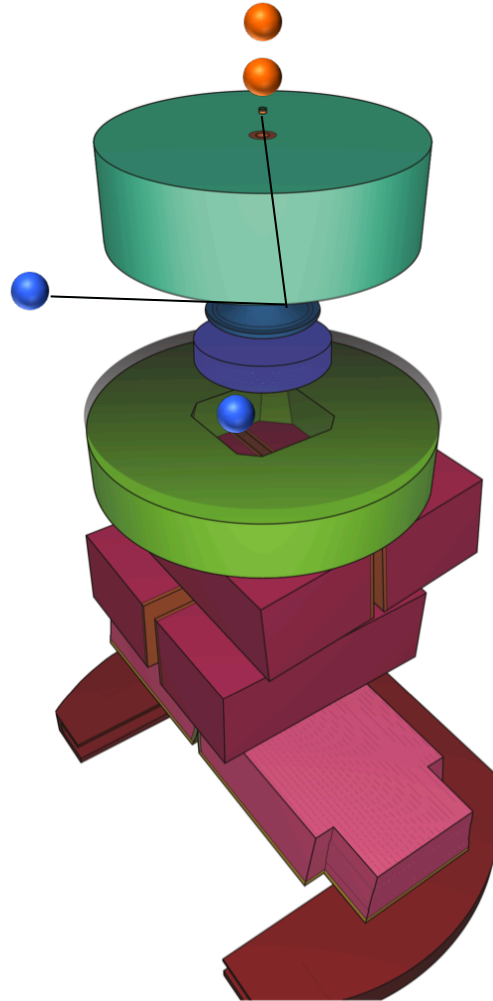


Key concepts: history versus particle

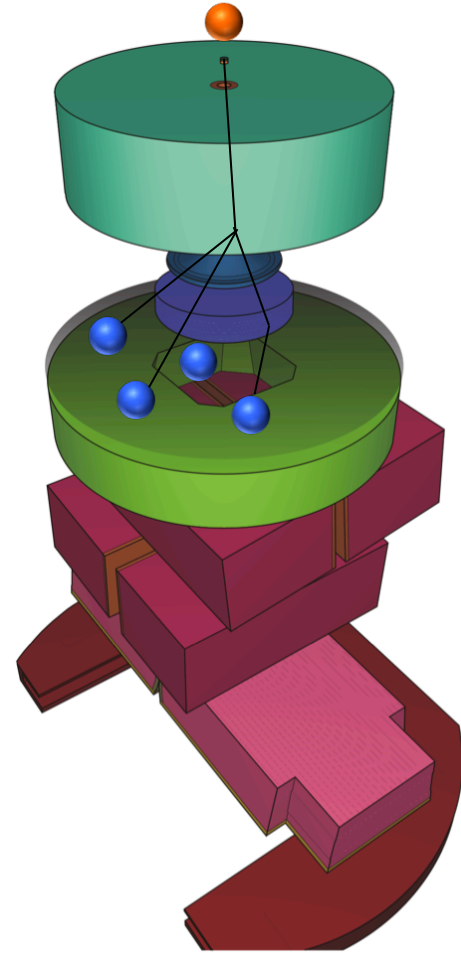
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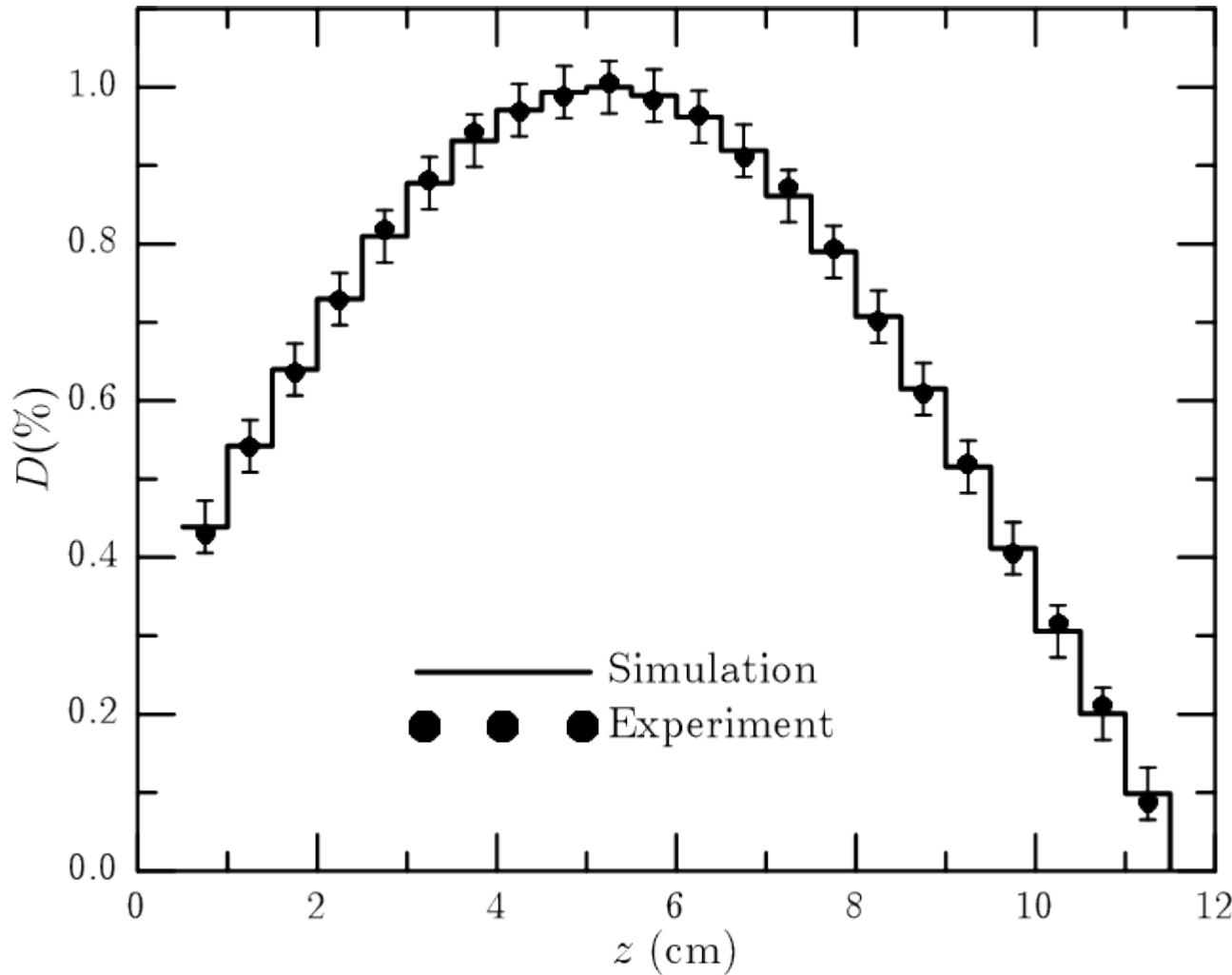
Incremental shower number

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2	2	1.00973E+05	4.65926E+00	-6.32448E+00	6.68000E+01	7.44427E-02	-8.18501E-02	9.93861E-01	5.91716E-05	2 2 1 4 0 0
3	2	1.00973E+05	4.42096E+00	-6.49329E+00	6.68000E+01	7.13488E-02	-8.45605E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
4	2	1.00973E+05	4.17654E+00	-6.65313E+00	6.68000E+01	6.81564E-02	-8.71541E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
5	2	1.00973E+05	3.92636E+00	-6.80378E+00	6.68000E+01	6.48698E-02	-8.96273E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
6	2	1.00973E+05	3.67075E+00	-6.94502E+00	6.68000E+01	6.14935E-02	-9.19766E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
7	2	1.00973E+05	3.41007E+00	-7.07666E+00	6.68000E+01	5.80323E-02	-9.41987E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
8	2	1.00973E+05	3.14467E+00	-7.19853E+00	6.68000E+01	5.44908E-02	-9.62907E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
9	2	1.00973E+05	2.87493E+00	-7.31044E+00	6.68000E+01	5.08740E-02	-9.82496E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
10	2	1.00973E+05	2.60121E+00	-7.41225E+00	6.68000E+01	4.71869E-02	-1.00073E-01	9.93861E-01	5.91716E-05	0 2 1 4 0 0
11	2	2.06650E+05	4.51939E+00	-8.11293E+00	6.68000E+01	6.62699E-02	-1.19732E-01	9.90592E-01	5.91716E-07	1 4 1 4 0 0
12	2	2.06650E+05	4.21471E+00	-8.27531E+00	6.68000E+01	6.17737E-02	-1.22112E-01	9.90592E-01	5.91716E-07	0 4 1 4 0 0
13	2	2.06650E+05	3.90420E+00	-8.42625E+00	6.68000E+01	5.71921E-02	-1.24324E-01	9.90592E-01	5.91716E-07	0 4 1 4 0 0
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21	2	5.86523E+05	2.76987E+00	-8.12644E+00	6.68000E+01	4.11735E-02	-1.20733E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
22	2	5.86523E+05	2.46589E+00	-8.22378E+00	6.68000E+01	3.66574E-02	-1.22180E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
23	2	5.86523E+05	2.15851E+00	-8.30975E+00	6.68000E+01	3.20906E-02	-1.23458E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
24	2	5.86523E+05	1.84815E+00	-8.38424E+00	6.68000E+01	2.74795E-02	-1.24566E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
25	2	5.86523E+05	1.53523E+00	-8.44714E+00	6.68000E+01	2.28304E-02	-1.25501E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
26	2	8.44930E+05	4.05506E+00	-8.52581E+00	6.68000E+01	6.12662E-02	-1.47708E-01	9.87132E-01	5.91716E-05	0 2 1 4 0 0
27	2	8.44930E+05	3.43546E+00	-6.80856E+00	6.68000E+01	5.10947E-02	-1.01287E-01	9.93544E-01	5.91716E-05	0 2 1 4 0 0
28	2	8.44930E+05	3.18001E+00	-6.93155E+00	6.68000E+01	4.72946E-02	-1.03116E-01	9.93544E-01	5.91716E-05	0 2 1 4 0 0
29	2	8.44930E+05	2.92016E+00	-7.04496E+00	6.68000E+01	4.34291E-02	-1.04803E-01	9.93544E-01	5.91716E-05	0 2 1 4 0 0
30	2	8.44930E+05	2.65629E+00	-7.14864E+00	6.68000E+01	3.95035E-02	-1.06345E-01	9.93544E-01	5.91716E-05	0 2 1 4 0 0
31	2	8.44930E+05	2.38873E+00	-7.24243E+00	6.68000E+01	3.55234E-02	-1.07739E-01	9.93544E-01	5.91716E-05	0 2 1 4 0 0
32	2	8.44930E+05	2.11788E+00	-7.32622E+00	6.68000E+01	3.14942E-02	-1.08985E-01	9.93544E-01	5.91716E-05	0 2 1 4 0 0
33	2	8.44930E+05	1.84410E+00	-7.39987E+00	6.68000E+01	2.74214E-02	-1.10081E-01	9.93544E-01	5.91716E-05	0 2 1 4 0 0
34	2	8.44930E+05	1.56778E+00	-7.46331E+00	6.68000E+01	2.33108E-02	-1.11024E-01	9.93544E-01	5.91716E-05	0 2 1 4 0 0



Key concepts: statistical uncertainty



Simulation unc.
coverage factor
 $k=1$

if $k=1$ then $\sim 68.3\%$
if $k=2$ then $\sim 95.4\%$
if $k=3$ then $\sim 99.7\%$



Key concepts: statistical uncertainty

Monte Carlo results mean NOTHING without the associated statistical uncertainty



Key concepts: variance-reduction techniques

Variance-reduction techniques are aimed at improving the simulation efficiency

$$\epsilon = \frac{1}{T\sigma^2}$$

with T the simulation time and σ the relative standard deviation of the mean, while keeping the simulation unbiased.



Key concepts: variance-reduction techniques

- Movable skins¹
- Standard splitting
- Rotational splitting^{2,3}
- Fan splitting²
- Splitting roulette⁴
- Russian roulette
- Interaction forcing

1

IOP PUBLISHING
Phys. Med. Biol. 54 (2009) 4131–4149

PHYSICS IN MEDICINE AND BIOLOGY
doi:10.1088/0031-9155/54/13/011

Efficient Monte Carlo simulation of multileaf collimators using geometry-related variance-reduction techniques

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³ Karolinska University Hospital, Sjukhusfysik P8.02, 171 76 Stockholm, Sweden

2

A PENELOPE-based system for the automated Monte Carlo simulation of clinics and voxelized geometries—application to far-from-axis fields

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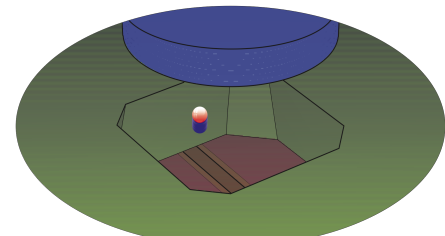
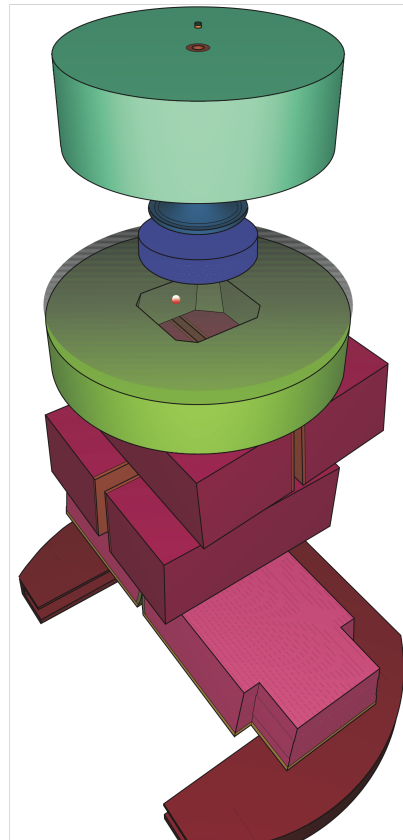
Andreu Badal

Division of Imaging and Applied Mathematics, OSEL, CDRH U.S. Food and Drug Administration,
10903 New Hampshire Ave, Silver Spring, Maryland 20993-0002

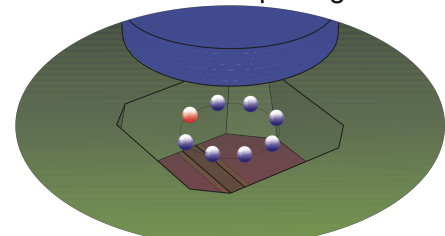
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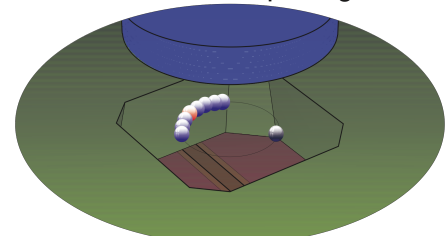
(Received 8 June 2011; revised 17 August 2011; accepted for publication 4 September 2011;
published 11 October 2011)



Standard splitting



Rotational splitting



Fan splitting

3

Radiation Physics and Chemistry 79 (2010) 929–932

Contents lists available at ScienceDirect



Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem



On the efficiency of azimuthal and rotational splitting for Monte Carlo simulation of clinical linear accelerators

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4

IOP PUBLISHING
Phys. Med. Biol. 57 (2012) 3013–3024

PHYSICS IN MEDICINE AND BIOLOGY
doi:10.1088/0031-9155/57/10/3013

A combined approach of variance-reduction techniques for the efficient Monte Carlo simulation of linacs

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Statistical weight

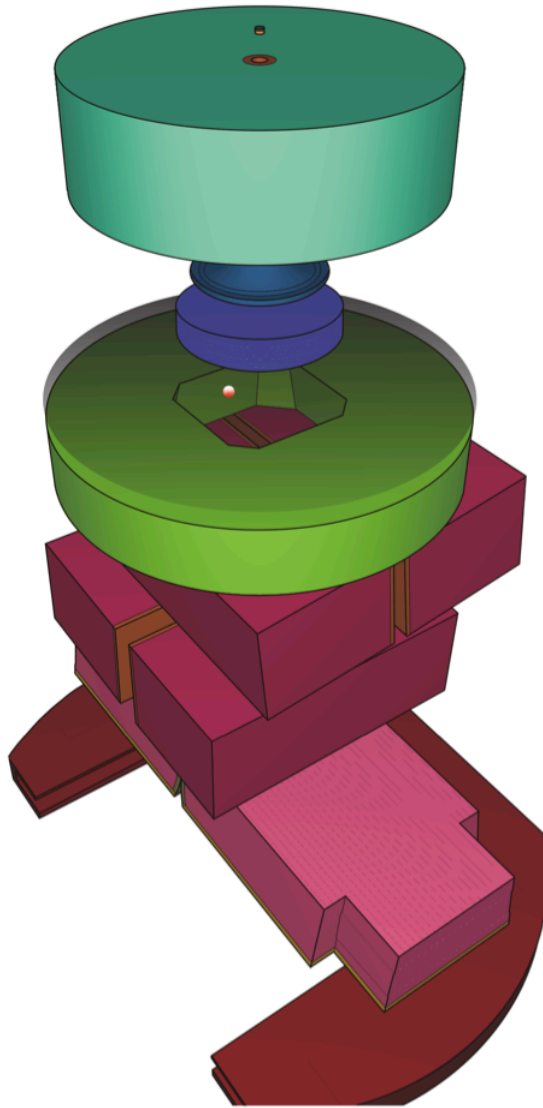
[PHASE SPACE FILE FORMAT penEasy v.2008-05-15]

#	#KPAR:	E	X	Y	Z	U	V	W	WGHT	DeltaN:ILB(1..5)
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2	2	1.00973E+05	4.65926E+00	-6.32448E+00	6.68000E+01	7.44427E-02	-8.18501E-02	9.93861E-01	5.91716E-05	2 2 1 4 0 0
3	2	1.00973E+05	4.42096E+00	-6.49329E+00	6.68000E+01	7.13488E-02	-8.45605E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
4	2	1.00973E+05	4.17654E+00	-6.65313E+00	6.68000E+01	6.81564E-02	-8.71541E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
5	2	1.00973E+05	3.92636E+00	-6.80378E+00	6.68000E+01	6.48698E-02	-8.96273E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
6	2	1.00973E+05	3.67075E+00	-6.94502E+00	6.68000E+01	6.14935E-02	-9.19766E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
7	2	1.00973E+05	3.41007E+00	-7.07666E+00	6.68000E+01	5.80323E-02	-9.41987E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
8	2	1.00973E+05	3.14467E+00	-7.19853E+00	6.68000E+01	5.44908E-02	-9.62907E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
9	2	1.00973E+05	2.87493E+00	-7.31044E+00	6.68000E+01	5.08740E-02	-9.82496E-02	9.93861E-01	5.91716E-05	0 2 1 4 0 0
10	2	1.00973E+05	2.60121E+00	-7.41225E+00	6.68000E+01	4.71869E-02	-1.00073E-01	9.93861E-01	5.91716E-05	0 2 1 4 0 0
11	2	2.06650E+05	4.51939E+00	-8.11293E+00	6.68000E+01	6.62699E-02	-1.19732E-01	9.90592E-01	5.91716E-07	1 4 1 4 0 0
12	2	2.06650E+05	4.21471E+00	-8.27531E+00	6.68000E+01	6.17737E-02	-1.22112E-01	9.90592E-01	5.91716E-07	0 4 1 4 0 0
13	2	2.06650E+05	3.90420E+00	-8.42625E+00	6.68000E+01	5.71921E-02	-1.24324E-01	9.90592E-01	5.91716E-07	0 4 1 4 0 0
14	2	2.06650E+05	3.58830E+00	-8.56555E+00	6.68000E+01	5.25314E-02	-1.26364E-01	9.90592E-01	5.91716E-07	0 4 1 4 0 0
15	2	5.86523E+05	4.49902E+00	-7.31232E+00	6.68000E+01	6.68626E-02	-1.08633E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
16	2	5.86523E+05	4.22411E+00	-7.47449E+00	6.68000E+01	6.27785E-02	-1.11043E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
17	2	5.86523E+05	3.94337E+00	-7.62634E+00	6.68000E+01	5.86077E-02	-1.13300E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
18	2	5.86523E+05	3.65717E+00	-7.76764E+00	6.68000E+01	5.43558E-02	-1.15400E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
19	2	5.86523E+05	3.36592E+00	-7.89821E+00	6.68000E+01	5.00288E-02	-1.17341E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
20	2	5.86523E+05	3.07001E+00	-8.01787E+00	6.68000E+01	4.56327E-02	-1.19119E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
21	2	5.86523E+05	2.76987E+00	-8.12644E+00	6.68000E+01	4.11735E-02	-1.20733E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
22	2	5.86523E+05	2.46589E+00	-8.22378E+00	6.68000E+01	3.66574E-02	-1.22180E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
23	2	5.86523E+05	2.15851E+00	-8.30975E+00	6.68000E+01	3.20906E-02	-1.23458E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
24	2	5.86523E+05	1.84815E+00	-8.38424E+00	6.68000E+01	2.74795E-02	-1.24566E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
25	2	5.86523E+05	1.53523E+00	-8.44714E+00	6.68000E+01	2.28304E-02	-1.25501E-01	9.91831E-01	5.91716E-05	0 2 1 4 0 0
26	2	8.44930E+05	4.05506E+00	-8.52581E+00	6.68000E+01	6.12662E-02	-1.47708E-01	9.87132E-01	5.91716E-05	0 2 1 4 0 0
27	2	8.44930E+05	3.43546E+00	-6.80856E+00	6.68000E+01	5.10947E-02	-1.01287E-01	9.93544E-01	5.91716E-05	0 2 1 4 0 0
28	2	8.44930E+05	3.18001E+00	-6.93155E+00	6.68000E+01	4.72946E-02	-1.03116E-01	9.93544E-01	5.91716E-05	0 2 1 4 0 0
29	2	8.44930E+05	2.92016E+00	-7.04496E+00	6.68000E+01	4.34291E-02	-1.04803E-01	9.93544E-01	5.91716E-05	0 2 1 4 0 0
30	2	8.44930E+05	2.65629E+00	-7.14864E+00	6.68000E+01	3.95035E-02	-1.06345E-01	9.93544E-01	5.91716E-05	0 2 1 4 0 0
31	2	8.44930E+05	2.38873E+00	-7.24243E+00	6.68000E+01	3.55234E-02	-1.07739E-01	9.93544E-01	5.91716E-05	0 2 1 4 0 0
32	2	8.44930E+05	2.11788E+00	-7.32622E+00	6.68000E+01	3.14942E-02	-1.08985E-01	9.93544E-01	5.91716E-05	0 2 1 4 0 0
33	2	8.44930E+05	1.84410E+00	-7.39987E+00	6.68000E+01	2.74214E-02	-1.10081E-01	9.93544E-01	5.91716E-05	0 2 1 4 0 0
34	2	8.44930E+05	1.56778E+00	-7.46331E+00	6.68000E+01	2.33108E-02	-1.11024E-01	9.93544E-01	5.91716E-05	0 2 1 4 0 0

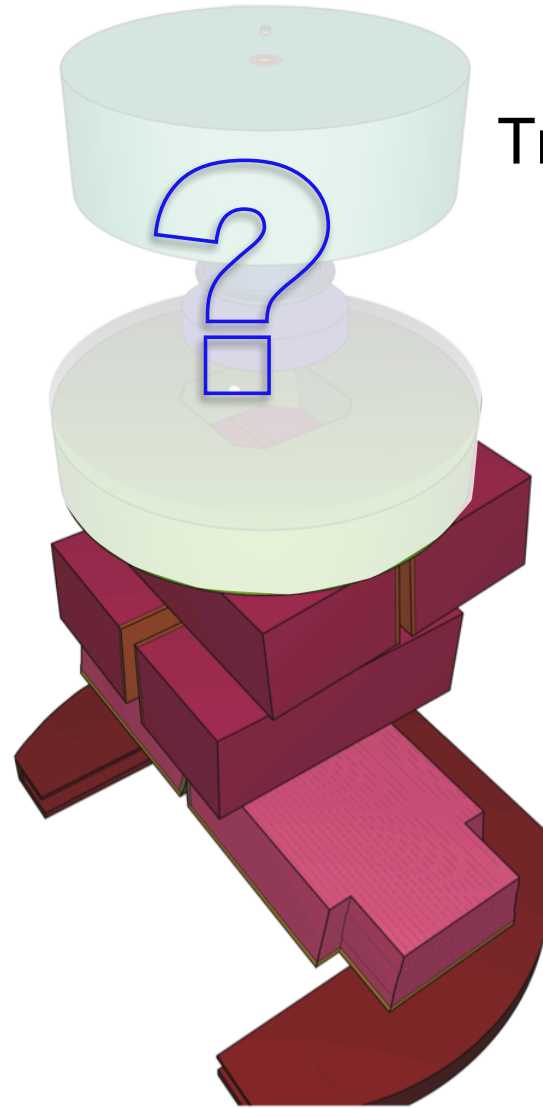


Available geometries of Varian linacs

2100 C/D



TrueBeam



FakeBeam (ungenuine geometry) vs. TrueBeam (PSF distributed by Varian)

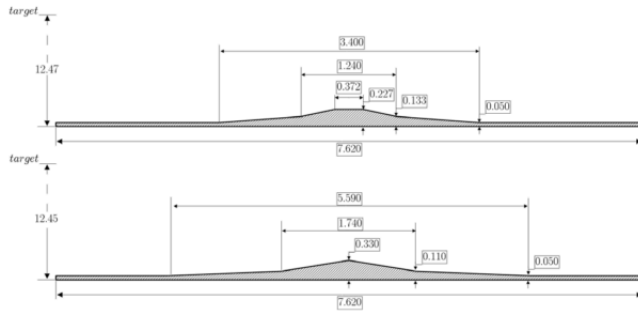
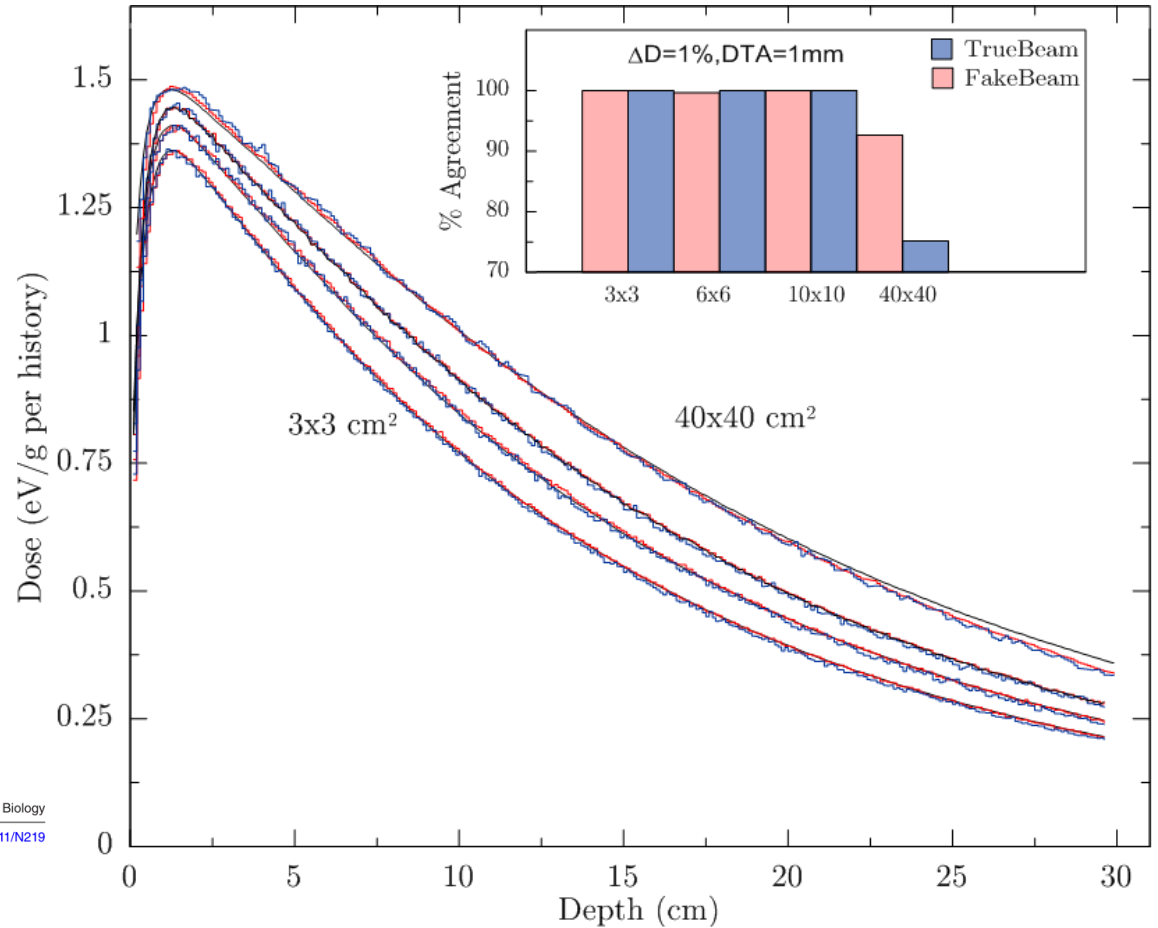


Figure 1. Cross-section of the *ad hoc* 6-FFF (above) and 10-FFF (below) filters. The materials are bronze and tantalum, respectively. Cylindrical symmetry applies. All dimensions are given in centimeters.

Note

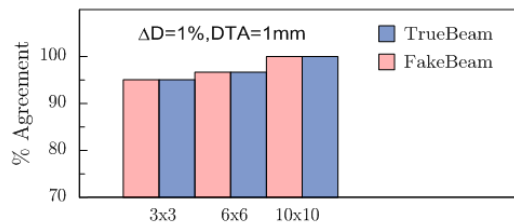
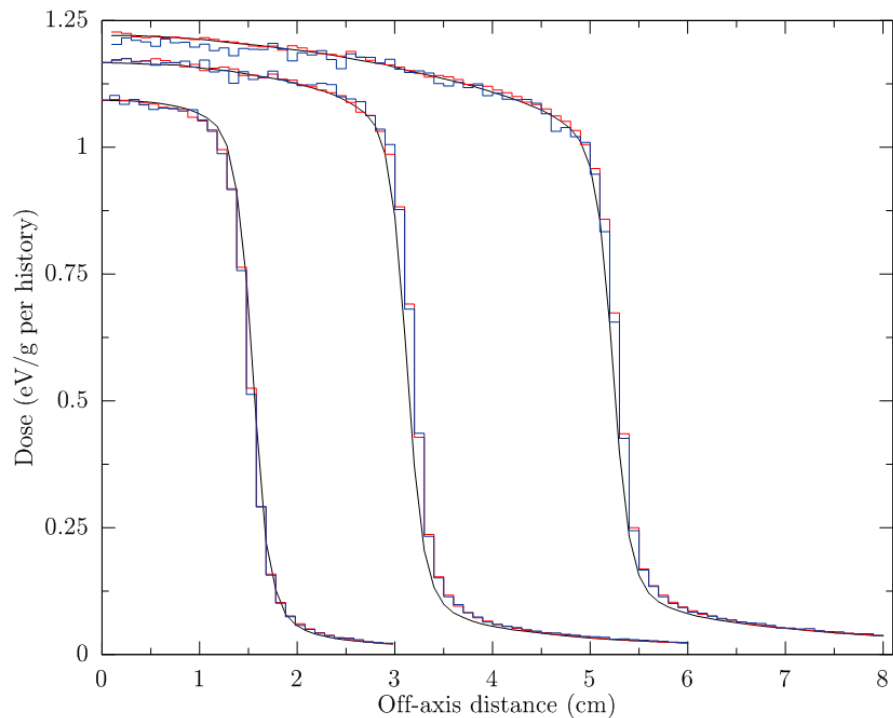
A geometrical model for the Monte Carlo simulation of the TrueBeam linac

M Rodriguez¹, J Sempau¹, A Fogliata², L Cozzi²,
 W Sauerwein³ and L Brualla³

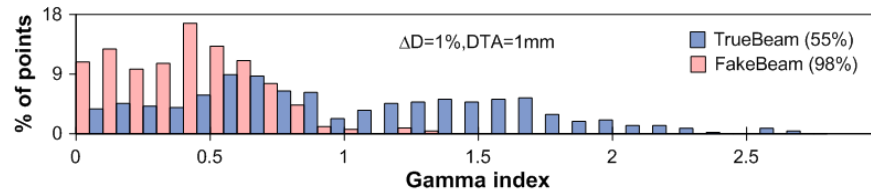
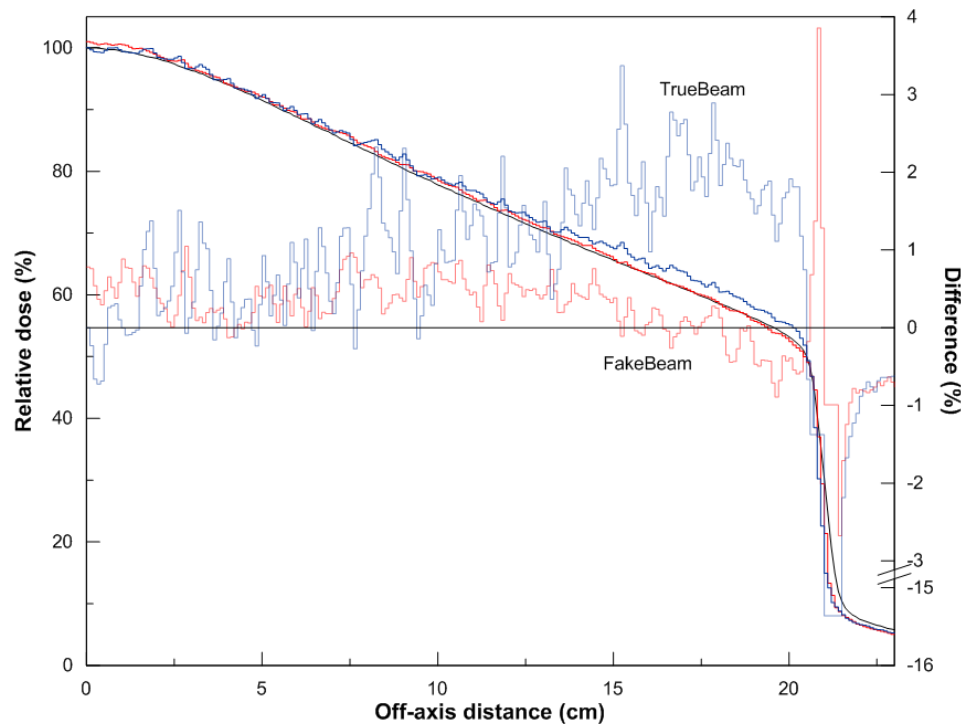


Depth dose curves for a 6MV FFF beam and filters of 3x3 cm², 6x6 cm², 10x10 cm² and 40x40 cm². Black lines: experimental data. Red lines: MC estimated results from Varian's TrueBeam PSF. Blue line: MC estimated results using FakeBeam geometry. Gamma analysis appears in the inset.

FakeBeam (ungenuine geometry) vs. TrueBeam (PSF distributed by Varian)




Lateral crossplane profiles for a 6 MV FFF beam and fields of 3X3, 6x6 and 10x10 cm² at 5 cm depth. Black Line: experimental Golden Beam Data; Blue line: MC estimated results from Varian's TrueBeam PSF; Red line: MC estimated results using FakeBeam geometry. Gamma analysis appears in the lower panel.



Lateral crossplane profile (left ordinate axis) from a 6 MV FFF beam of a 40X40 cm² field at 5 cm depth. Black Line: experimental Golden Beam Data; Blue line: MC estimated results from Varian's TrueBeam PSF. Red line: MC estimated results using FakeBeam geometry. Relative difference curves respect to the maximum experimental dose are plotted using the right ordinate axis. Notice that this axis is broken. Gamma analysis appears in the lower panel.

REVIEW ARTICLE

Monte Carlo systems used for treatment planning and dose verification

Lorenzo Brualla¹  · Miguel Rodriguez² · Antonio M. Lallena³

Received: 4 May 2016 / Accepted: 25 October 2016 / Published online: 25 November 2016
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Ultra-accurate Monte Carlo based dose calculation algorithm.
(Webpage of the product)

Similar accuracy to and faster calculation times than Monte Carlo.
(Brochure of the product)

[It] calculates a fraction of the total stopping power stochastically using a specially constructed energy straggling cross section.
(Algorithm's technical manual)



Types of MC codes for radiation transport

General-purpose

- Wide range of energy (~1 keV up to ~1 GeV)
- Any material. Any geometry
- Examples: PENELOPE, EGSnrc, Geant, MCNP

Fast

- Only energies with clinical interest (~MeV)
- Only low Z materials. Only binned geometries
- Examples: DPM, XVMC, VMC, PENFAST

Pre-computed

- Use pre-calculated data
- Only energies with clinical interest (~MeV)
- Only low Z materials
- Examples: MMC, eMC, SMC

Accuracy

Speed



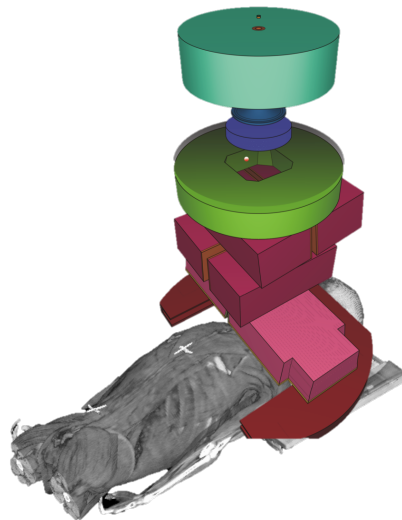
Classification criteria

Purpose

Treatment
planning

Reach

Full



Algorithm

General
purpose

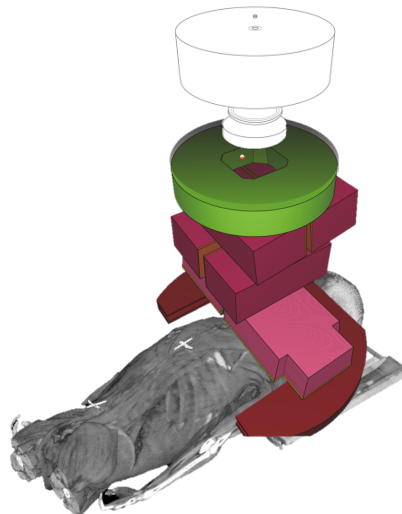
Self-contained

Yes

Fast

Dose
verification

Virtual source



Pre-
computed

No

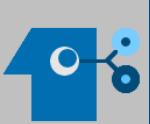


MC systems according criteria

System	Purpose	Reach	Algorithm linac	Algorithm patient	Self-contained	Distributed
CARMEN	tp	full	gp (EGSnrc)	gp (EGSnrc)	no	no
CERR	dv	-	-	fast (VMC++)	no	free
Corvus	tp	vsm	-	fast (PEREGRINE)	yes	no
Eclipse	tp	vsm	-	pc (MMC)	yes	pay
eIMRT	dv	full	gp (EGSnrc)	gp (EGSnrc)	yes	free
iPlan	tp	vsm	-	fast (XVMC)	yes	pay
ISOgray	tp	full	gp (PENELOPE)	fast (PENFAST)	yes	no
MCDE	tp	full	gp (EGSnrc)	gp (EGSnrc)	no	no
MCDOSE	tp	vsm	-	gp (EGS4)	no	no
MCV	dv	full	gp (EGS4)	gp (EGS4)	no	no
MCVS	dv	full	gp (EGSnrc)	gp (EGSnrc)	no	no
MMCTP	dv	full	gp (EGSnrc)	gp (EGSnrc)	no	free
Monaco	tp	vsm	-	fast (XVMC)	yes	pay
MSKCC	dv	vsm	-	gp (EGS4)	yes	no
Oncentra	tp	vsm	-	fast (VMC++)	yes	pay
Pinnacle	tp	-	-	fast (DPM)	yes	no
PLanUNC	dv	full	gp (EGSnrc)	gp (EGSnrc)	no	free
PRIMO	dv	full	gp (PENELOPE)	gp (PENELOPE)/fast (DPM)	yes	free
RTGrid	tp	full	gp (EGSnrc)	gp (EGSnrc)	no	no
SMCP	tp	vsm	-	gp (EGSnrc)/fast (VMC++)	no	no
VIMC	dv	full	gp (EGSnrc)	gp (EGSnrc)/fast (VMC++)	no	no
XiO	tp	vsm	-	fast (XVMC)	yes	pay

MC systems according criteria

System	Purpose	Reach	Algorithm linac	Algorithm patient	Self-contained	Distributed
CERR	dv	-	-	fast (VMC++)	no	free
Eclipse	tp	vsm	-	pc (MMC)	yes	pay
eIMRT	dv	full	gp (EGSnrc)	gp (EGSnrc)	yes	free
iPlan	tp	vsm	-	fast (XVMC)	yes	pay
MMCTP	dv	full	gp (EGSnrc)	gp (EGSnrc)	no	free
Monaco	tp	vsm	-	fast (XVMC)	yes	pay
Oncentra	tp	vsm	-	fast (VMC++)	yes	pay
PLanUNC	dv	full	gp (EGSnrc)	gp (EGSnrc)	no	free
PRIMO	dv	full	gp (PENELOPE)	gp (PENELOPE)/fast (DPM)	yes	free
XiO	tp	vsm	-	fast (XVMC)	yes	pay



MC systems according criteria

System	Purpose	Reach	Algorithm linac	Algorithm patient	Self-contained	Distributed
Eclipse	tp	vsm	-	pc (MMC)	yes	pay
eIMRT	dv	full	gp (EGSnrc)	gp (EGSnrc)	yes	free
iPlan	tp	vsm	-	fast (XVMC)	yes	pay
Monaco	tp	vsm	-	fast (XVMC)	yes	pay
Oncentra	tp	vsm	-	fast (VMC++)	yes	pay
PRIMO	dv	full	gp (PENELOPE)	gp (PENELOPE)/fast (DPM)	yes	free
XiO	tp	vsm	-	fast (XVMC)	yes	pay

Features of distributed MC systems

		Eclipse	eIMRT	iPlan	Monaco	Oncentra	PRIMO	XiO
Algorithm	Linac upper	vsm	gp (BEAMnrc)	vsm	vsm	vsm	gp (PENELOPE)	vsm
	Linac lower	vsm	gp (BEAMnrc)	fast	transmission filter	vsm	gp (PENELOPE) fast (DPM)	pc
	Dose	pc (MMC)	gp (DOSXYZnrc)	fast (XVMC)	fast (XVMC)	fast (VMC++)	gp (PENELOPE) fast (DPM)	fast (XVMC)
Beams	Electrons	yes	no	no	no	yes	yes	yes
	Photons	no	yes	yes	yes	no	yes	no
Beam QA tools in water		yes	no	no	yes (optional)	yes	yes	yes
Modalities	3D-CRT	n/a	yes	yes	yes	n/a	yes	n/a
	IMRT	n/a	yes	yes	yes	n/a	yes	n/a
	VMAT	n/a	no	no	yes	n/a	yes	n/a
Linacs	Varian	C-Series	C-Series	600, C-Series, Novalis	600, C-Series	C-Series	600, Unique, C,TrueBeam	C-Series
	Elekta	-	-	MLCi, MLCi2	MLCi, MLCi2	SLi, MLCi, MLCi2	SLi, MLCi	SLi, MLCi, MLCi2
	Siemens	-	Primus, Oncor	Meva, Primus, Oncor, Artiste	-	Mevatron, Primus, Oncor	-	Mevatron, Primus, Oncor
Inverse TP optimization		n/a	no	pbc	pbc	n/a	no	n/a
Dose referred to		water	water	medium/water	medium/water	water	medium	medium/water
Beam configuration		auto	auto	manufacturer	manufacturer	manufacturer	manual	manufacturer
Operating system		Windows	Linux	Windows	Windows	Windows	Windows	Linux
FDA approval		yes	no	yes	yes	yes	no	yes

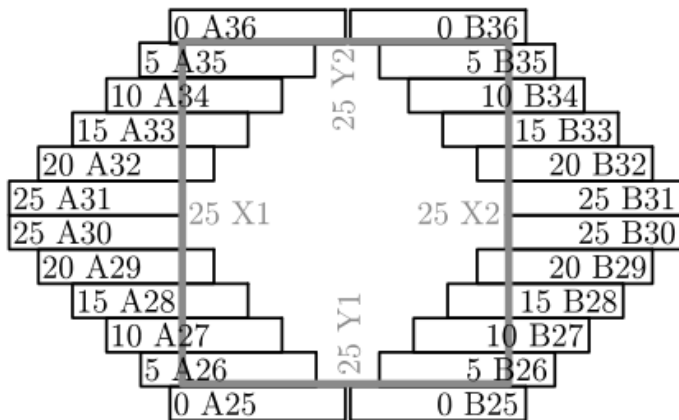
Benchmarks

Field 1 (photons)

- 6 MV
- water phantom
- voxel $3 \times 3 \times 3 \text{ mm}^3$
- uncertainty 2% ($k=1$)
- field $10 \times 10 \text{ cm}^2$

Field 2 (photons)

- field $5 \times 5 \text{ cm}^2$



Field 3 (electrons)

- 6 MeV
- water phantom
- voxel $3 \times 3 \times 3 \text{ mm}^3$
- uncert 2% ($k=1$)
- field $10 \times 10 \text{ cm}^2$

Field 4 (electrons)

- 16 MeV
- water phantom
- voxel $3 \times 3 \times 3 \text{ mm}^3$
- uncert 2% ($k=1$)
- field $10 \times 10 \text{ cm}^2$



Benchmarks

Simulation time in minutes

	Eclipse	eIMRT	iPlan	Monaco	Oncentra	PRIMO (DPM)	PRIMO (PENELOPE)	XiO
Field 1 (10x10)	-	372 (57)	0.5	0.4	-	5	30	-
Field 2 (MLC)	-	361 (17)	0.2	0.5	-	3	24	-
Field 3 (6 MeV e ⁻)	0.1	-	-	-	0.5	-	21	0.1
Field 4 (16 MeV e ⁻)	0.2	-	-	-	0.9	-	31	0.2





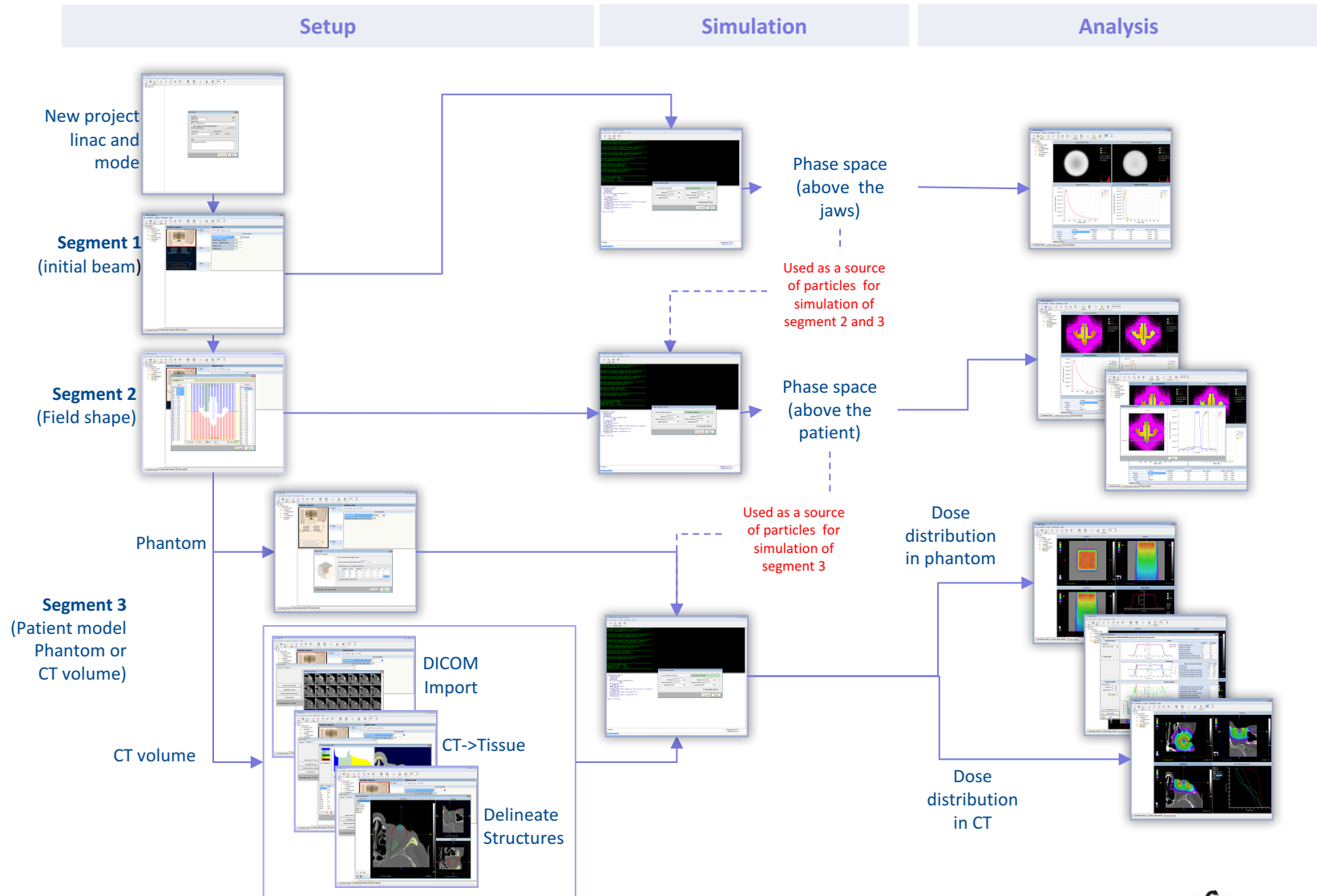
PRIMO is a computer software that simulates linacs and dose distributions in water phantoms and computerized tomographies. It combines a graphical user interface and a computation engine based on the Monte Carlo code PENELOPE.

www.primoproject.net





Workflow of PRIMO





Main tool bar

Structure tree
structure selection

Plan and dose

Import & review

Dose evaluation

(dose comparison)

PRIMO 0.3.1.1529 (LUNG-DPM)

File Setup Simulation Analysis Help

Simulation Segments

Segment Setup

Primary Beam Fields Patient model

Apply Defaults

Nominal Energy (MV): 6

Initial energy (MeV): 5.400

Energy FWHM (MeV): 0.000

Focal spot FWHM (cm): 0.000

Beam divergence (deg): 0.000

s3.log

```

Simulation Log File
PRIMO version 0.3.1.1510
Project Id : LUNG-DPM
Project Name :
-----
CPU
- Architecture: x86
- Processor Type: Pentium
- Number of Processors: 32
- Speed (Ghz): 2.34
-----
Simulation engine: Dose Planning Method (DPM)
Simulation started 18.08.2017 at 16:01:14
-----
*.in files deleted in path: C:\PRIMO\DPM\Materials
*.out files deleted in path: C:\PRIMO\DPM\Materials
PRIMOPreDPM*. * Files deleted in path: C:\PRIMO\DPM\Materials
*** preDPM input file ***
HEADER section: Input file for PREDPM, 2001-04-23
File prefix Title (12 characters max):
PRIMOPreDPM
[Emin,Pr,Emax] (eV): energy interval in which data is to be generated:
49.e3 199.e3 21.e6
Wcc & Wcb (eV), cutoffs energies for collision and bremsstrahlung respectively:
200.e3 50.e3
Step length parameters shigh(cm),slow(cm),ecross(eV):
0.5 0.5 5.065
No of materials in this file:
29
Names of materials:
Air.mat
Tungsten.mat
Air.mat
Air.mat
Air.mat
Air.mat
Air.mat
Air.mat
Water.mat
Air.mat
Tungsten.mat
Tungsten.mat
Air.mat
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Tungsten.mat
Air.mat
Tungsten.mat
Air.mat
Air.mat

```

Simulation Setup Plan and Dose Dose Evaluation Phase Space Analysis





Segment Setup

Primary Beam Fields Patient model

+ Field -Field Edit Field

Field	Linac	Technique	Weight	Gantry start (deg)	Gantry end (deg)	Collimator (deg)	Couch (deg)	X1 (cm)	X2 (cm)	Aperture X (cm)	Y1 (cm)	Y2 (cm)	Aperture Y (cm)	MLC	Applicator	Isocenter X (cm)	Isocenter Y (cm)	Isocenter Z (cm)
1	Elekta SL	STATIC	1.0000	0.0	0.0	0.0	0.0	5.0	5.0	10.0	5.0	5.0	10.0	None	None	0.00	0.00	0.00

Segment Setup

Primary Beam Fields Patient model

	Size (cm)	Minimum (cm)	Maximum (cm)	Bin size (cm)	Size (bins)
Sagittal	40.50	-20.25	20.25	0.50	81
Axial	40.50	-20.25	20.25	0.50	81
Coronal	40.00	0.00	40.00	0.50	80

It is not editable

- An homogeneous (water) CT volume is created by default for the project
- A slab phantom can be created or a CT can be imported in DICOM format





New project
Open project
Save project

Import a phase-space file (copy)

Link a phase-space file (no copy)

Import a CT (DICOM)

Import contours (DICOM)

Create a slab phantom

Create simulation geometry (segmentation)



Analyze the source phase-space

The screenshot displays the PRIMO 0.3.1.1531 (PHANTOM) software interface. The main window is divided into several panels:

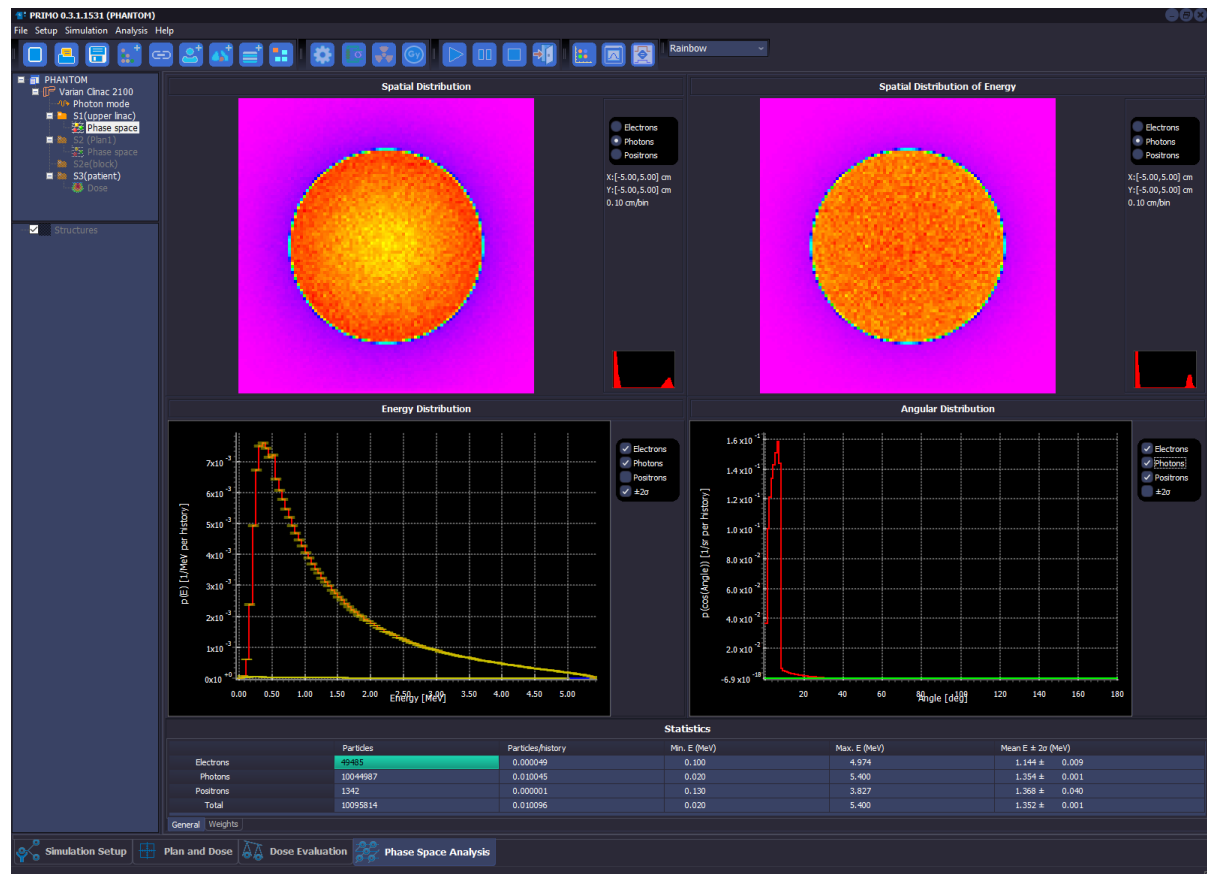
- Simulation Segments:** Shows a 3D schematic of the Varian Clinac 2100 with segments S1 (Upper linac), S2 (Plan1), and S3 (patient). A green 'Analyze' button is overlaid on the S1 segment.
- Segment Setup:** Contains parameters for the primary beam:
 - Nominal Energy (MV): 6
 - Initial energy (MeV): 5.400
 - Energy FWHM (MeV): 0.000
 - Focal spot FWHM (cm): 0.000
 - Beam divergence (deg): 0.000
- Phase Space Analysis Setup:** A dialog box with the following sections:
 - Plane dimensions:** X1: 6.00 cm, Y1: 6.00 cm, X2: 6.00 cm, Y2: 6.00 cm.
 - Rings:** Analyze in rings (checked), Maximum Radius: 1.00 cm, Radial Increment: 0.50 cm.
 - Angular interval:** Azimuthal (Phi 1: 0.00 deg, Phi 2: 360.00 deg), Polar (Theta 1: 0.00 deg, Theta 2: 180.00 deg).
 - Energy interval:** Auto (checked), E1: 0.00 MeV, E2: 30.00 MeV.
 - Bin sizes:** Spatial: 0.25 cm, Energy: 0.05 MeV, Angle: 1.00 deg.
 - Material:** A list of materials with checkboxes, including 'Source (primary particles)', 'Mylar-Mirror', 'W-Jaws-skin', 'Be-Window', 'Ta-18x18-Filter-Insert', 'Al-screen', 'Kapton-Ion-Chamber', 'Air', 'Cu-Flattening-filter', 'Water-Phantom', 'Fe-18x-Flattening-Filter', 'W-MLC-lower-skin', 'W-MLC-frontal-skin', 'W-Primary-coll-non-skin', 'W-Jaws-non-skin', 'W-18x18-Filter-Insert', 'W-MLC-non-skin', 'W-target', 'Cu-target', 'Air-absorber', and 'Air-rotation'. The 'Al-screen' and 'W-Jaws-skin' entries are highlighted with blue boxes.





Analyze the source phase-space

- Toggle among electrons, photons or positrons.
- View maps in as a 3D graph
- Zoom curves in/out
- Explore the contextual menus





Simulation setup

- Activate segments S2 and S3
- On the simulation config dialog chose:
 - DPM as simulation engine
 - Press the dice to change the RNG seeds

The screenshot displays the PRIMO 6.3.3.1.531 (PHANTOM) software interface. The main window is divided into several panels:

- Simulation Segments:** A central panel showing a 3D visualization of the Varian Cinac 2100. Three segments are visible: S1 (upper line), S2 (Plant), and S3 (patient). Segments S2 and S3 are highlighted with a blue border, indicating they are active.
- Segment Setup:** A panel on the right showing parameters for the selected segments. The 'Simulation Configuration' dialog is open, showing the following settings:
 - Simulation Engine:** perEASY/PENELOPE
 - Dose Planning Method (DPM):** Coarse dose distribution (voxel size = 0.25 cm)
 - Simulation Seeds:** Seed 1: 918882992, Seed 2: 858672133. A dice icon is highlighted, indicating the RNG seeds are being changed.
 - Stop Condition and Report:** Histories: 1000000000 > 1000, Time: 6000000 seconds, Dose uncertainty: 1.00 % (2 sigma). The stop condition is set to Histories.
 - Simulation processes:** A section for managing simulation processes.
- PHANTOM Tree:** A tree view on the left showing the hierarchy of the simulation setup, including Varian Cinac 2100, Photon mode, S1 (upper line), Phase space, S2 (Plant), S3 (patient), and Dose.
- Structures:** A panel at the bottom left showing the anatomical structures used in the simulation.





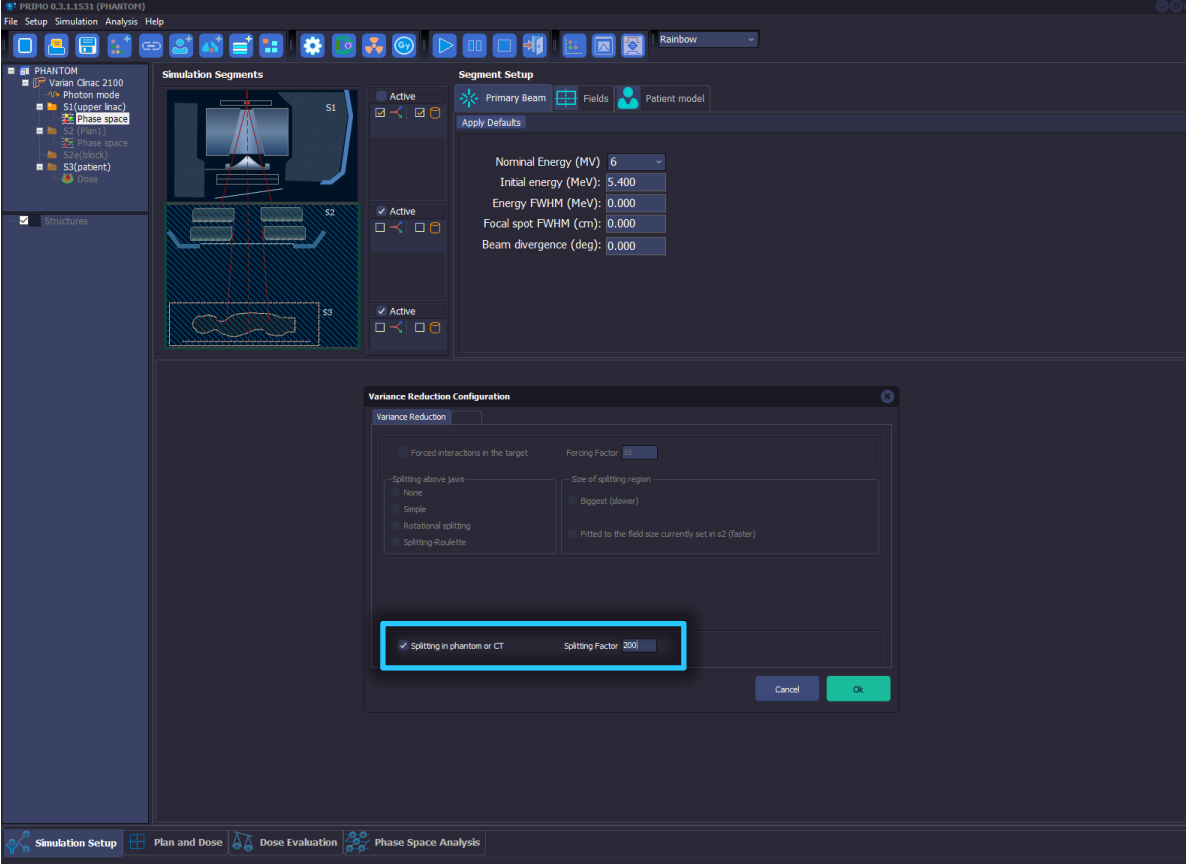
Variance-reduction technique setup

- Select 
- On the variance reduction configuration window set:

Splitting in phantom or CT

Splitting Factor

- Save the project 



The screenshot displays the PRIMO 0.3.1.1531 (PHANTOM) software interface. The main window is titled "PHANTOM" and shows a simulation setup for a Varian Clinac 2100. The "Simulation Segments" panel on the left lists segments: S1 (upper linac), S2 (phantom), S3 (block), and S3 (patient). The "Segment Setup" panel on the right shows the "Primary Beam" configuration with the following parameters:

- Nominal Energy (MV): 6
- Initial energy (MeV): 5,400
- Energy FWHM (MeV): 0,000
- Focal spot FWHM (cm): 0,000
- Beam divergence (deg): 0,000

The "Variance Reduction Configuration" window is open, showing the following settings:

- Splitting in phantom or CT
- Splitting Factor:
- Forced interactions in the target: Forcing Factor:
- Splitting above jaws: Size of splitting region: Biggest (slower) / Fitted to the field size currently set in s2 (faster)

The "Splitting in phantom or CT" checkbox and the "Splitting Factor" input field are highlighted with a red box. The bottom of the interface shows navigation buttons: Simulation Setup, Plan and Dose, Dose Evaluation, and Phase Space Analysis.

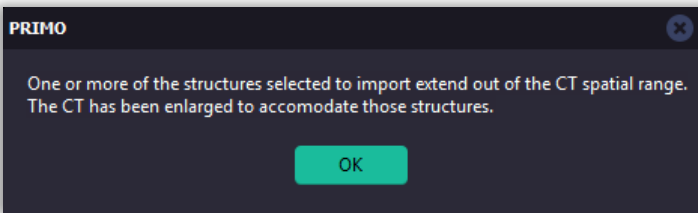




Import contours

All the voxels outside a selected contour can be set to air. To avoid accessories used in simulation that interfere with dose calculation

Support structures can be imported and its HU “written” on the CT



DICOM-RT STRUCT Import

Structure set name: CT_18/1/16Mesa

Identify body contour: **body** Set to air any CT voxel outside body contour

Select all

Import	ROI	ID	Name	Type	Modify CT	HU	Vertices
<input checked="" type="checkbox"/>	4	cap_femur_d	cap_femur_d	ORGAN	<input type="checkbox"/>	0	2742
<input checked="" type="checkbox"/>	20	CouchSurface	CouchSurface	SUPPORT	<input type="checkbox"/>	-300	194194
<input checked="" type="checkbox"/>	21	CouchInterior	CouchInterior	SUPPORT	<input type="checkbox"/>	-1000	95524
<input checked="" type="checkbox"/>	22	z_PTV57+3mm	z_PTV57+3mm		<input type="checkbox"/>	0	3710
<input checked="" type="checkbox"/>	23	z_PTV57opt	z_PTV57opt	PTV	<input type="checkbox"/>	0	1650
<input checked="" type="checkbox"/>	24	z_PTV72+3mm	z_PTV72+3mm		<input type="checkbox"/>	0	2482

Cancel Import



Plan and Dose

Default field:
 $10 \times 10 \text{ cm}^2$
 isocenter at
 (0,0,0), the
 center of the CT
 surface

Plans are
 imported from this
 window

Dynamic plans
 cannot be edited
 (only the isocenter
 can be
 repositioned)

Fields

Field	Linac	Technique	Weight	Gantry start (deg)	Gantry end (deg)	Collimator (deg)	Couch (deg)	X1 (cm)	X2 (cm)	Aperture X (cm)	Y1 (cm)	Y2 (cm)	Aperture Y (cm)	MLC	Applicator	Isocenter X (cm)	Isocenter Y (cm)	Isocenter Z (cm)	Group
1	Varian Clinac 2300	IMRT	0.2075	180.0	180.0	0.0	360.0	4.3	4.8	9.1	3.3	2.8	6.1	Millennium 120 MLC	None	0.20	3.75	22.96	✓
2	Varian Clinac 2300	IMRT	0.2287	255.0	255.0	0.0	360.0	5.0	4.3	9.3	3.3	2.8	6.1	Millennium 120 MLC	None	0.20	3.75	22.96	✓
3	Varian Clinac 2300	IMRT	0.1450	315.0	315.0	0.0	360.0	5.0	4.0	9.0	3.3	2.8	6.1	Millennium 120 MLC	None	0.20	3.75	22.96	✓
4	Varian Clinac 2300	IMRT	0.1625	45.0	45.0	0.0	360.0	4.0	4.5	8.5	3.3	2.8	6.1	Millennium 120 MLC	None	0.20	3.75	22.96	✓
5	Varian Clinac 2300	IMRT	0.2562	105.0	105.0	0.0	360.0	4.3	5.2	9.5	3.3	2.8	6.1	Millennium 120 MLC	None	0.20	3.75	22.96	✓





Simulation config

Variance reduction

Transport parameters

Dose calibration

Simulation Configuration

Setup applied to simulation of segments: (2, 3)

Simulation Engine

nenEasv/PENEL-OPF

- Dose Planning Method (DPM)
 - Coarse dose distribution (voxel side = 0.25 cm)

Simulation Seeds

Seed 1 1

Seed 2 1

Stop Condition and Report

Histories >1000

Time seconds

Dose uncertainty % (2 sigma)

Stop condition is: Histories

Refresh time: seconds

Simulation processes

Cancel Ok

DPM uses all the cores available

Dose calibration

Reference dose (measured):	1.000	[Gy]	Dose measured (e.g. with an ion-chamber) in reference conditions
Reference MU:	100	[MU]	Monitor units used to produce the measured reference dose
Reference dose (calculated):	0.500	[eV/g]	Dose estimated with a MC simulation in reference conditions

Calibration factor: 0.020 [Gy/MU g/eV]

Cancel Ok

Plan and Dose Dose Evaluation + Dose in Gy

Phys. Med. Biol. 45 (2000) 2263–2291. Printed in the UK

PII: S0031-9155(00)12211-0

DPM, a fast, accurate Monte Carlo code optimized for photon and electron radiotherapy treatment planning dose calculations

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Play simulation

DPM simulation ✕

Control Point	Elapsed time [sec]	Simulated histories	Uncertainty [%]	Progress
93/354	267.1	238985085.0	18.26	24%

Simulation status: Simulating 

[Hide Log <<](#) Close window when simulation has finished

```
*** Running DPM...

This is Dose Planing Method (parallel version 1.0)
( 8 active threads detected)

Program started on 29 Aug 2017 17:44:49

init: Reading simulation setup from STDIN;
      information from this stream follows:
No of histories:
  1.00000E+09
Allotted time; use neg values to indicate CPU time (s):
-9.000E+08
PSF filename (set to - for none):
```

[Reset](#) [Exit](#)



Plan and Dose

PRIMO 0.3.1.1529 (BRAIN-MM)

File Setup Simulation Analysis Help

Grays

BRAIN-MM

- Varian Cinac 2100
 - Photon mode
 - S1 (upper linac)
 - Phase space
 - S2 (VMA11)
 - Phase space
 - S2a (block)
 - S3 (patient)
 - Dose

Structures

- BODY
- OralCavity
- Parotid_R
- Parotid_L
- Eye_L
- Brainstem
- Mandible
- Cochlea_R
- Cochlea_L
- Brain
- Eye_R
- Lent_L
- Lent_R
- Cervical Spine
- Optic_Nerve_L
- Optic_Nerve_R
- GT_V 1
- GT_V 2
- GT_V 3
- TV 1
- CTV 1.2
- CTV 2
- CTV 3
- PT_V 45Gy/15fx
- PT_V 37.5Gy
- PT_V 33.75
- PT_V 30Gy
- Optic_System
- modgen ptv 33.75
- PT_V TOTAL
- Optic_Syst_O_PTV
- Frontal_Skin

AXIAL

Image: 51 (-2.28 cm)
256 pix x 256 pix
zoom: 1.00
X: 83 pix, Y: 177 pix
X: -5.43 cm, Y: 1.52 cm
HU: 4397
Dose: 25.263 Gy (51.2%)

SAGITTAL

Image: 128 (0.00 cm)
256 pix x 125 pix
zoom: 1.00
X: 13 pix, Y: 93 pix
X: 1.61 cm, Y: 6.06 cm
HU: 0
Dose: 0.612 Gy (1.2%)

CORONAL

Image: 88 (10.66 cm)
256 pix x 125 pix
zoom: 1.00
X: 34 pix, Y: 71 pix
X: -11.32 cm, Y: 1.70 cm
HU: 0
Dose: 0.000 Gy (0.0%)

DVHs

3D VIEW

Fields Dose

Show dose

Show dose scale

Dose inspection

Min. dose 0.000 Gy/g
± 0.000 (0.0%) eV/g

Max. dose 49.389 Gy
± 2.485 (5.0%) eV/g

Sagittal 0.000 cm
Axial -2.139 cm
Coronal 10.753 cm

Dose 41.817 Gy
± 2.186 (218.6%) eV/g

Denoise dose

Toggle isodose/color wash

Calibration

MU Fractions Dose in Gy

15

Null dose voxels with uncertainty higher than 50% Apply

Min. dose uncertainty 4.67 %
Max. dose uncertainty 30.00 %

Reload dose

Export the dose to a text file

DVHs

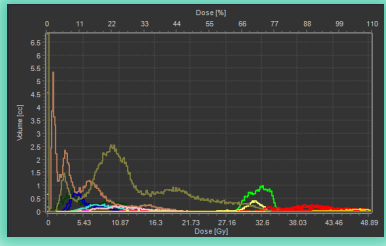
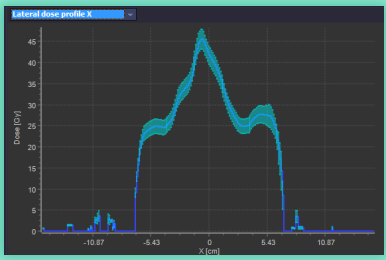
Differential DVHs

Absolute volume

Dose profiles

Fields Structures

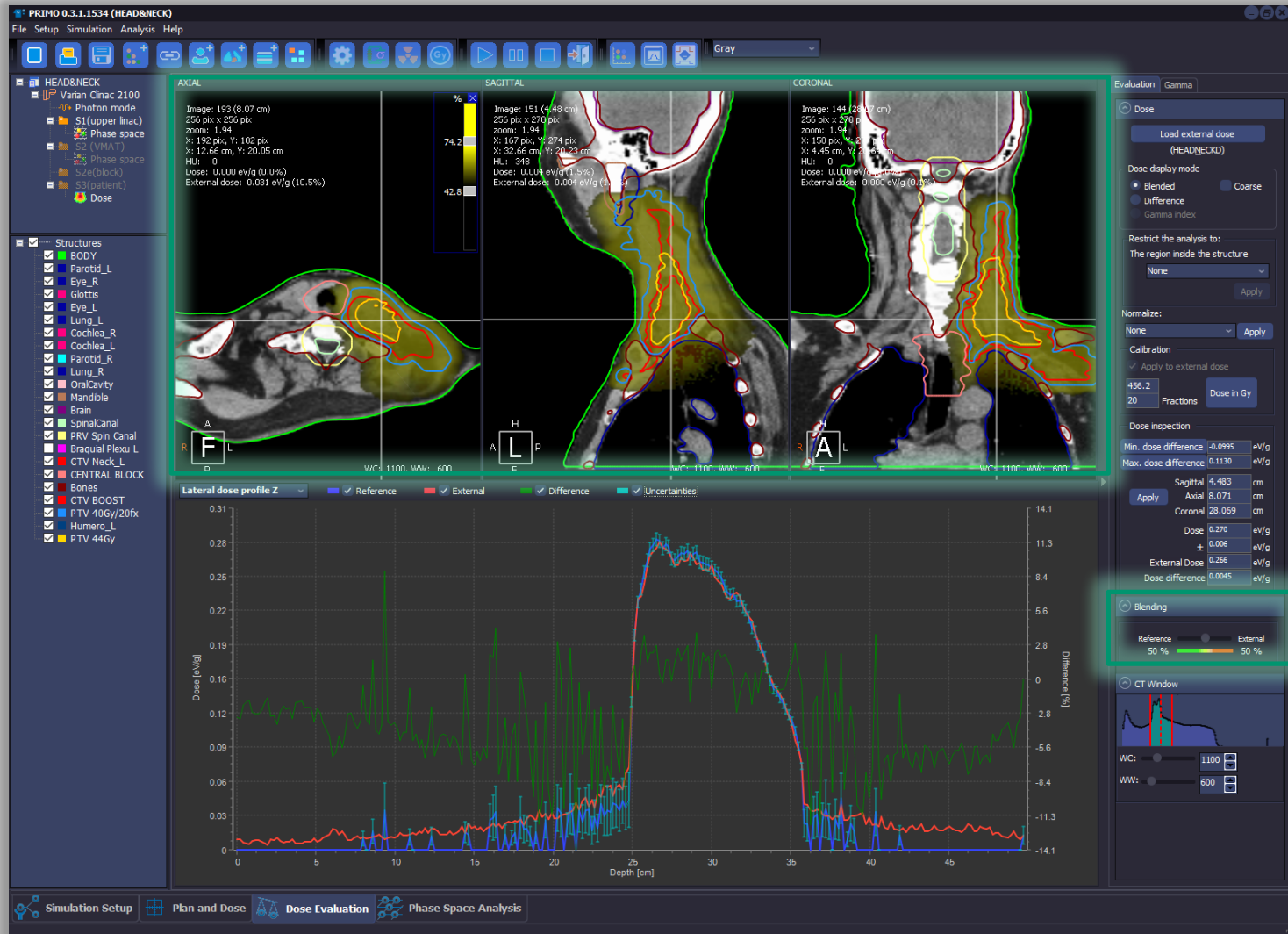
Color	Name	Volume [cm³]	Dose Coverage [%]	Dose Min. (2σ) [Gy]	Dose Max. (2σ) [Gy]	Dose Ave. (2σ) [Gy]	Dose Min. (2σ) [%]	Dose Max. (2σ) [%]	Dose Ave. (2σ) [%]
Green	BODY	4255.7	99.7	0.000 (0.000)	49.920 (2.497)	18.506 (0.019)	0.0 (0.0)	100.0 (5.0)	37.1 (0.0)
Dark Green	OralCavity	30.2	100.0	0.000 (0.000)	15.183 (1.289)	6.368 (0.072)	0.0 (0.0)	30.4 (2.6)	12.8 (0.1)
Blue	Parotid_R	15.4	100.0	0.000 (0.000)	15.449 (1.370)	5.863 (0.087)	0.0 (0.0)	30.9 (2.7)	11.7 (0.2)
Light Blue	Parotid_L	15.5	100.0	0.000 (0.000)	14.637 (1.359)	5.395 (0.080)	0.0 (0.0)	29.3 (2.7)	10.8 (0.2)
Light Blue	Eye_L	9.9	100.0	0.000 (0.000)	16.787 (1.362)	8.356 (0.150)	0.0 (0.0)	33.6 (2.7)	16.7 (0.3)
Light Blue	Brainstem	25.7	100.0	27.435 (1.780)	36.698 (1.965)	32.185 (0.343)	55.0 (3.6)	73.5 (3.9)	64.5 (0.7)
Orange	Mandible	96.0	100.0	0.000 (0.000)	21.532 (1.622)	4.814 (0.036)	0.0 (0.0)	43.1 (3.2)	9.6 (0.1)
Pink	Cochlea_R	0.9	100.0	10.604 (1.075)	21.785 (2.537)	14.698 (0.844)	21.2 (2.2)	43.6 (5.1)	29.4 (1.7)



Dose evaluation (dose comparison)

- Blending
- Difference
- Gamma

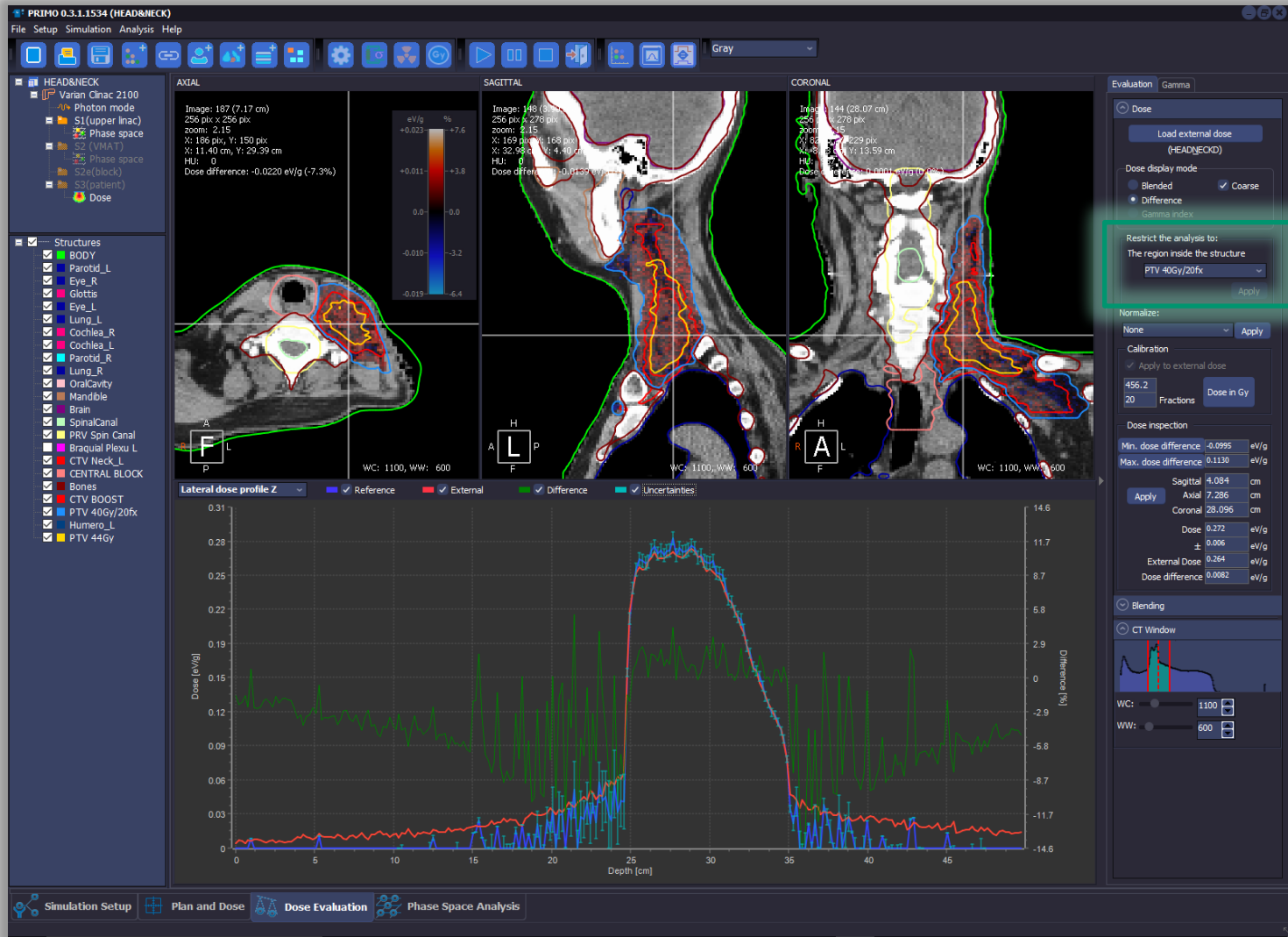
- Dose profiles w/
difference profile
- DVHs



Dose evaluation (dose comparison)

- Blending
- Difference
- Gamma

- Dose profiles w/
difference profile
- DVHs



Dose evaluation (dose comparison)

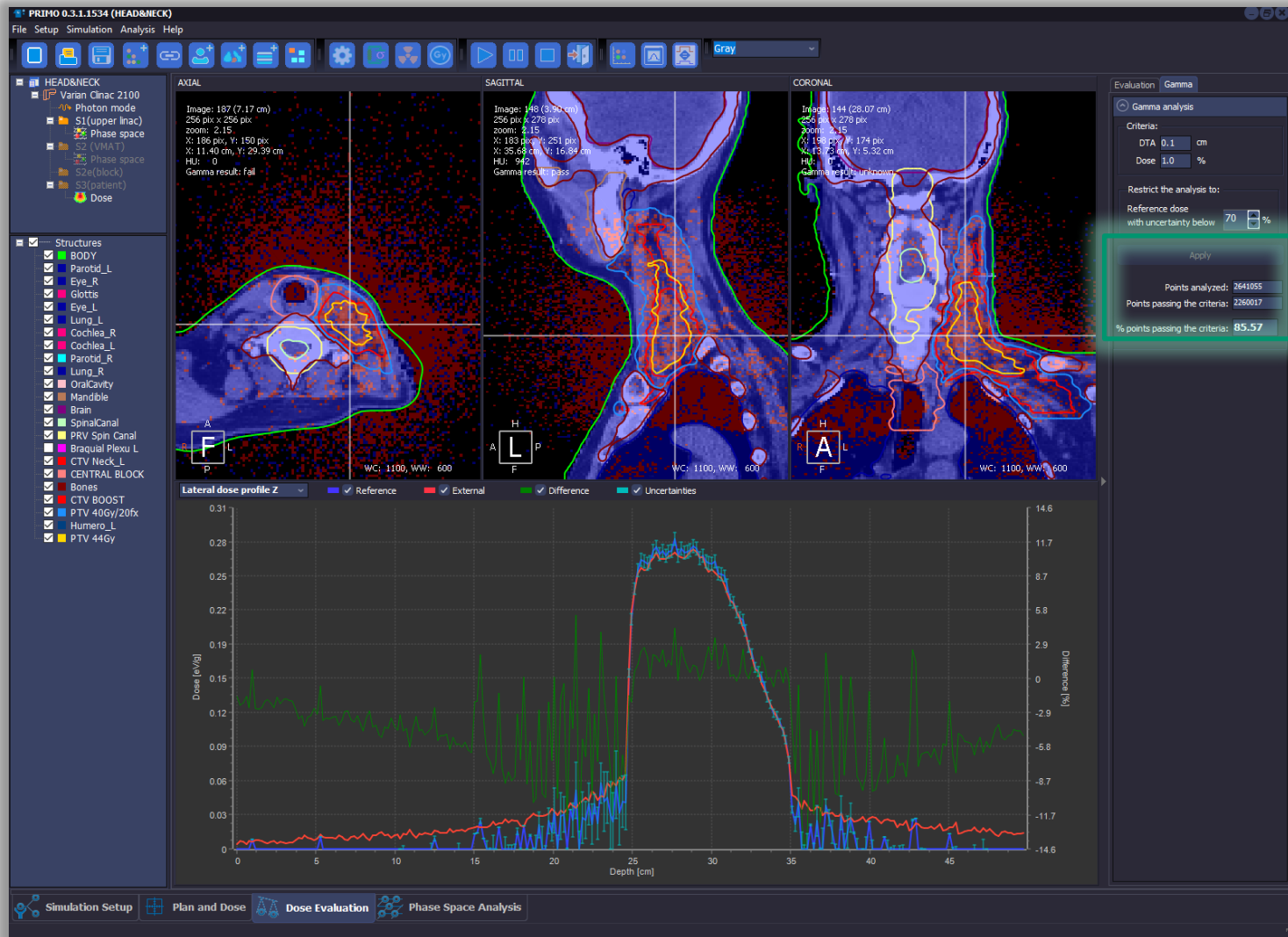
- Blending
- Difference
- **Gamma**
 $T \sim 30$ s
 18.2×10^6 voxels

Restrict the analysis to:
The region inside the structure

None

Apply

- Dose profiles w/
difference profile
- DVHs



Dose evaluation (dose comparison)

- Blending
- Difference
- Gamma $T \sim 20$ s

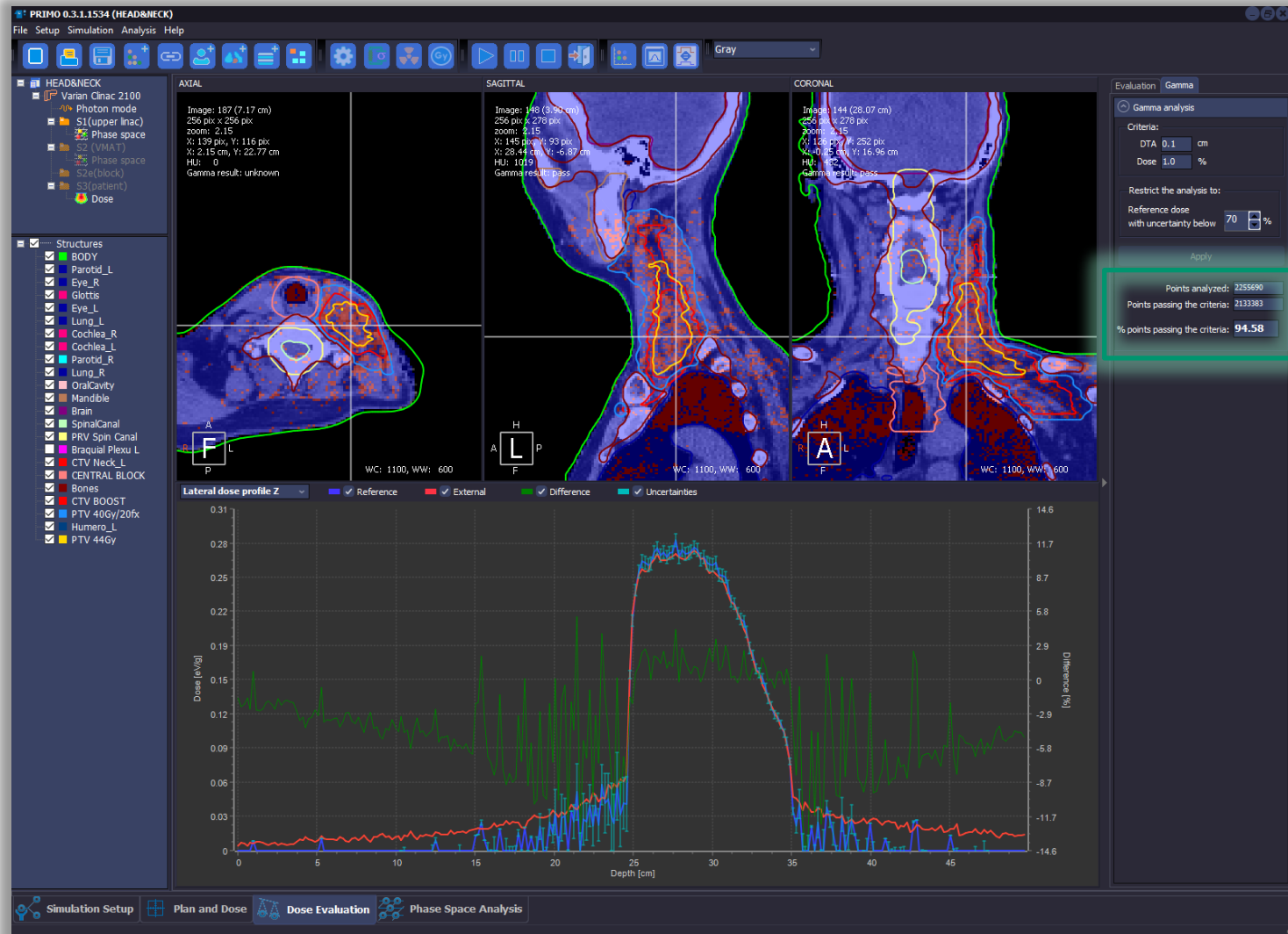
Restrict the analysis to:

The region inside the structure

BODY

Apply

- Dose profiles w/
difference profile
- DVHs



Dose evaluation (dose comparison)

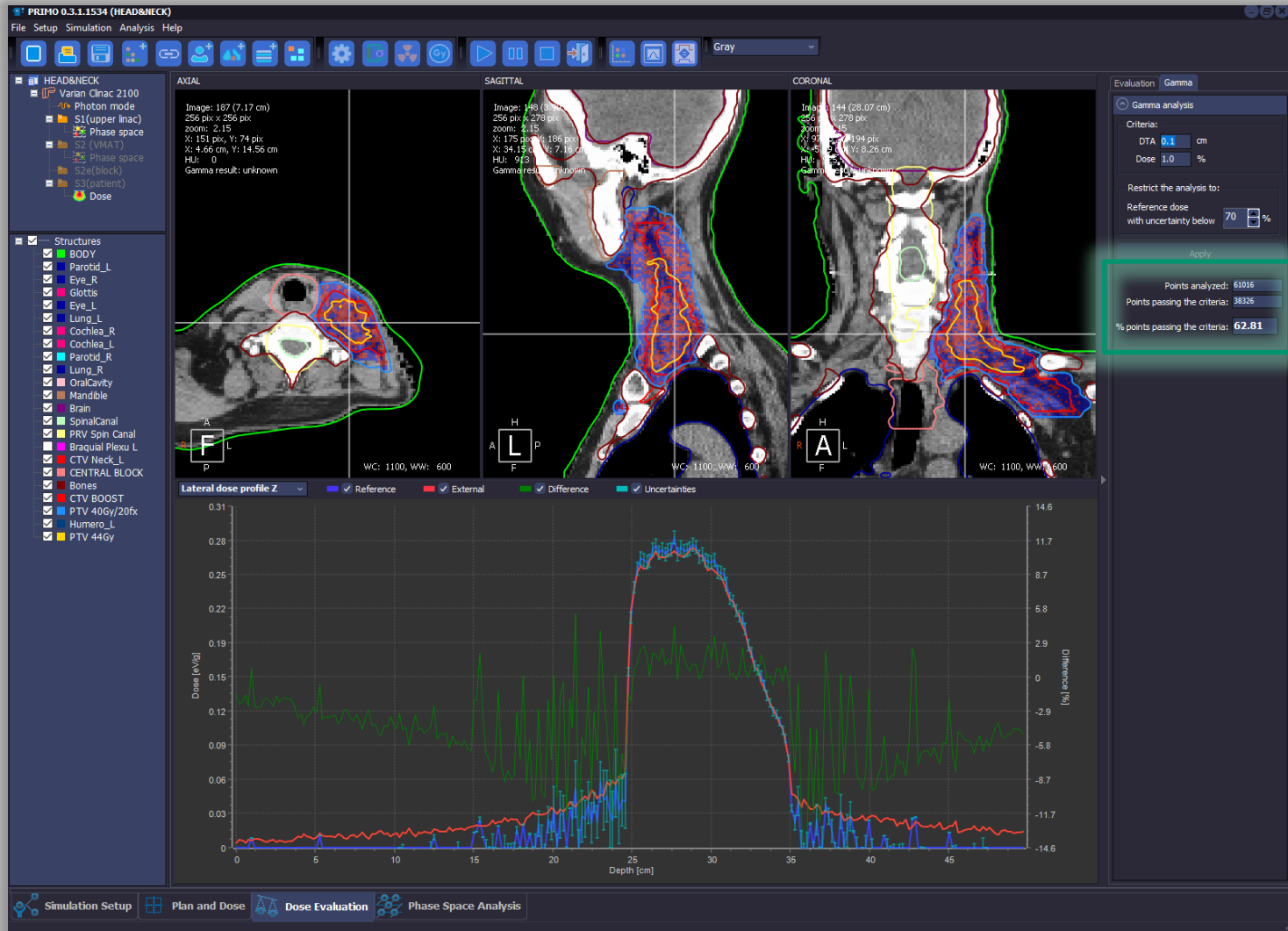
- Blending
- Difference
- $\Gamma_{\sim 3s}$

Restrict the analysis to:
The region inside the structure

PTV 40Gy/20fx

Apply

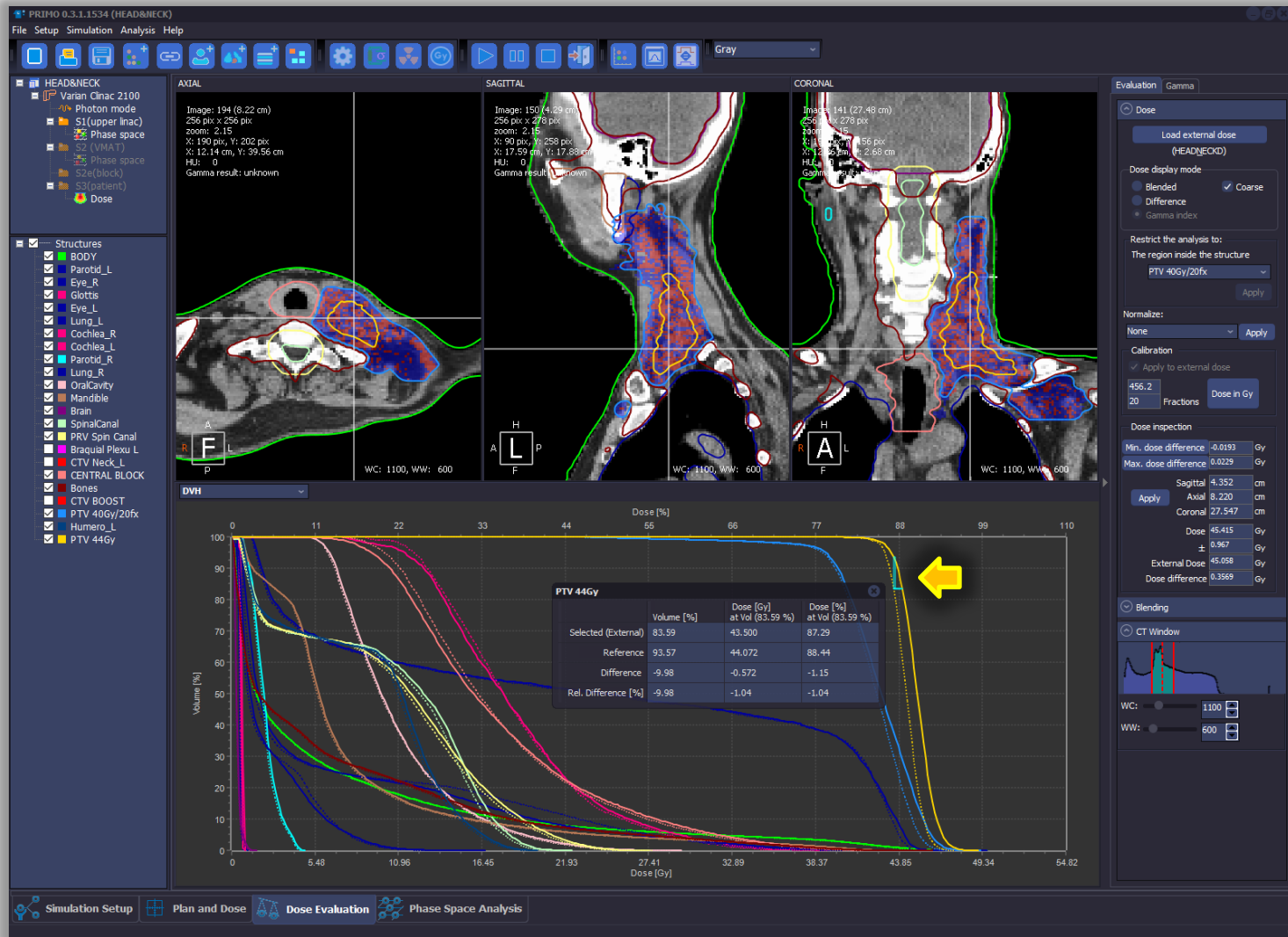
- Dose profiles w/
difference profile
- DVHs



Dose evaluation (dose comparison)

- Blending
- Difference
- Gamma

- Dose profiles w/
difference profile
- DVHs



Acknowledgement

DFG Deutsche
Forschungsgemeinschaft





MEDIZINISCHE FAKULTÄT
DER UNIVERSITÄT DUISBURG-ESSEN



Universitätsklinikum Essen