National Physical Laboratory

Monte Carlo simulations for a prototype calorimeter for HDR brachytherapy sources

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Overview

- Motivation: Ionometry and calorimetry
- MC calculations for calorimeter design parameters (build-up curves, overall dimensions for full scatter, dose distributions)
- MC calculated correction factors (vacuum gap, inhomogeneity, volume averaging)
- Summary

Current calibration method: air kerma based approach (Ionometry)

- Reference air kerma rate (RAKR) of brachytherapy photon source measured with primary standard cavity chamber
- Source strength in terms of Gy/s at 1 m
- Conversion from RAKR to absorbed dose to water using AAPM TG-43 protocol

Calibration set-up

Nucletron micro-Selectron source

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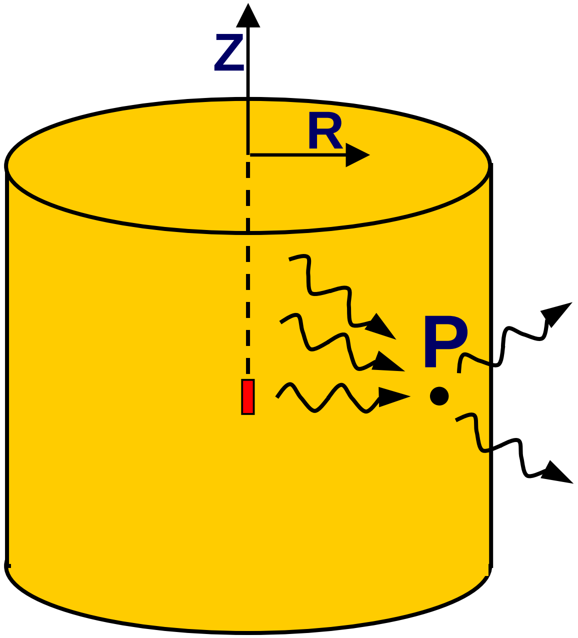
Alternative measurement method: absorbed dose based approach (Calorimetry)

- Objective: avoid conversion of RAKR to absorbed dose
- Overall standard uncertainty in conversion using TG-43 is estimated to be 5% (clinically significant)
- Development of a prototype calorimeter for HDR brachytherapy sources
- Direct measurement of absorbed dose

$$D_{\text{point}} = \frac{E_{rad}}{m} = c_p \Delta T$$



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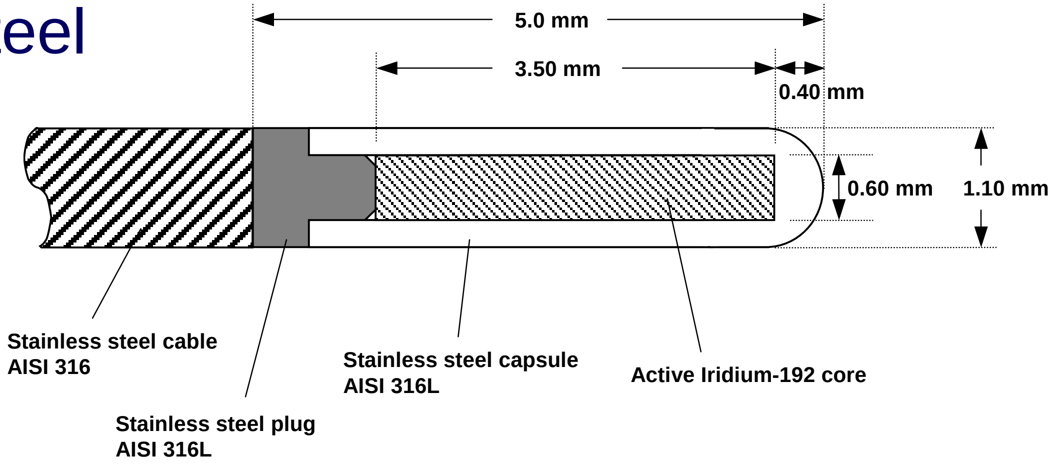
EGSnrc Monte Carlo simulations

- Various aspects of calorimeter modelled with DOSRZnrc
  - Default settings used (incl. PRESTA-II)
  - ECUT = 10 keV, PCUT = 5 keV
  - All calculations to ≤0.1% standard uncertainty
- Source (Nucletron microSelectron Classic):
  - Bare ^{192}Ir spectrum used for ^{192}Ir cylinder
  - Source encapsulation and steel cable: AISI 316L stainless steel



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MC geometrical inputs
DOSRZnrc model for calorimeter

EGS file name: **TS0031**

Source centred.
z = 7 cm

Core height Z: 0.5 cm, core thickness: 0.2 cm
Centre-to-centre source-to-core: 2.5 cm

Geometrical inputs

radii (cm)	**R**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
10	**8**	58	59	60	61	62	63	64	65
2.7	**7**	50	51	52	53	54	55	56	57
2.6	**6**	42	43	44	45	46	47	48	49
2.4	**5**	34	35	36	37	38	39	40	41
2.3	**4**	26	27	28	29	30	31	32	33
1.3	**3**	18	19	20	21	22	23	24	25
0.055	**2**	10	11	12	13	14	15	16	17
0.03	**1**	2	3	4	5	6	7	8	9
0									

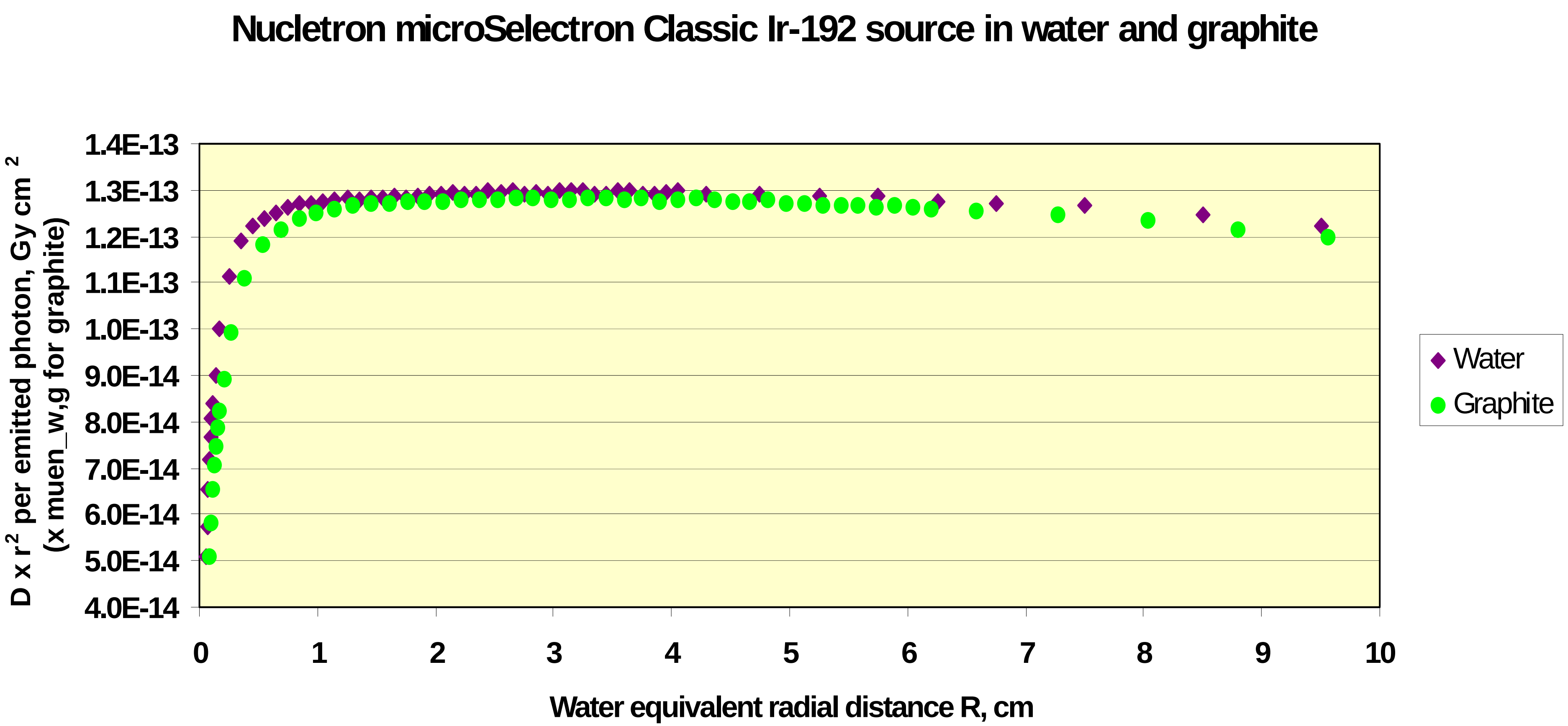
Z

depth boundaries (cm) 0 | 6.65 | 6.75 | 6.825 | 7.175 | 7.215 | 7.25 | 7.35 | 14

Legend

- (grey) = graphite
- (red) = iridium
- (yellow) = stainless steel 316L

Build-up curves in water and graphite



- $(\mu_{en}/\rho)^{w}{}_{g}$ = 1.11 for mean ^{192}Ir energy (encapsulated source: 397 keV)
- Energy dependent → calculate fluence spectrum

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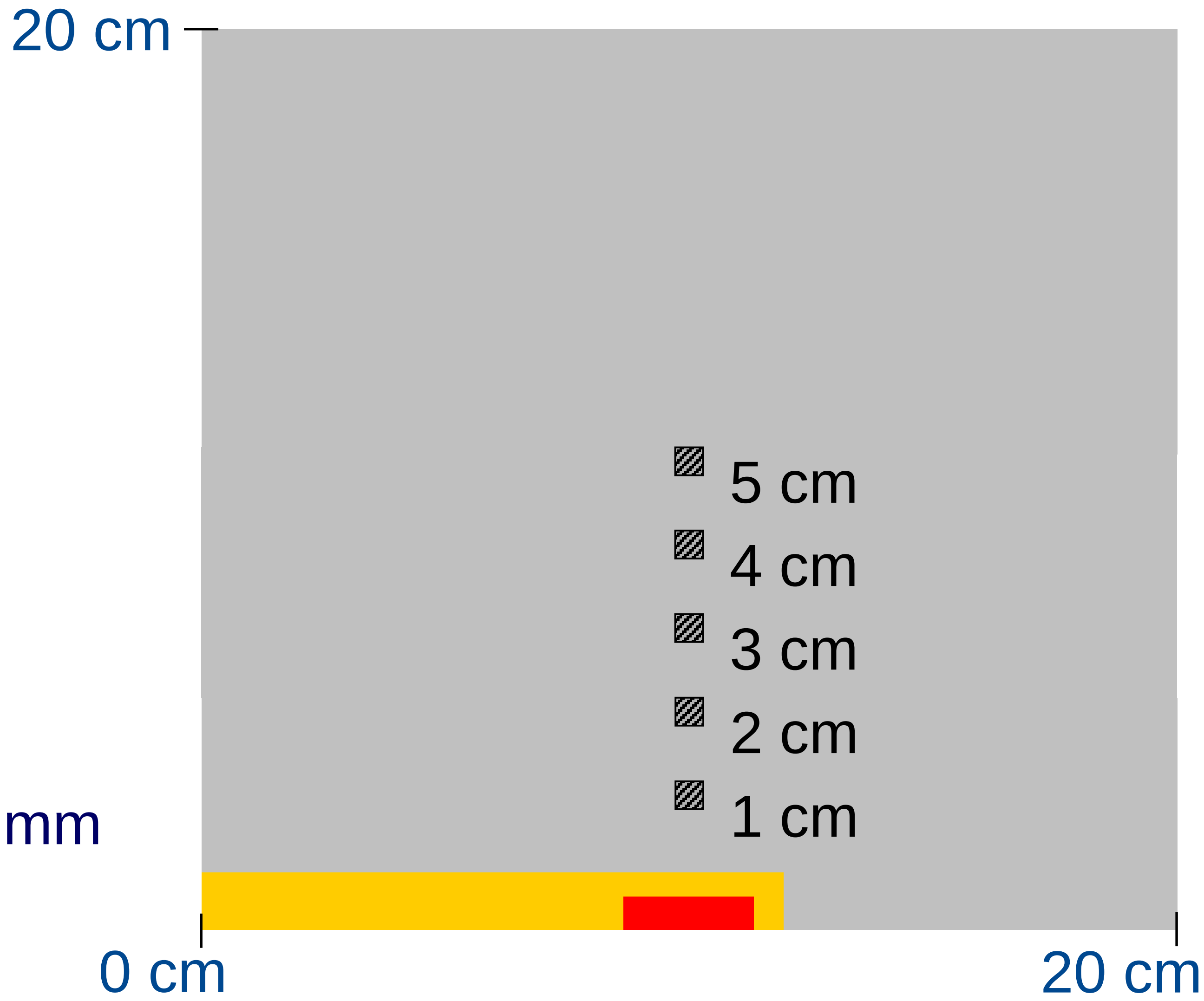
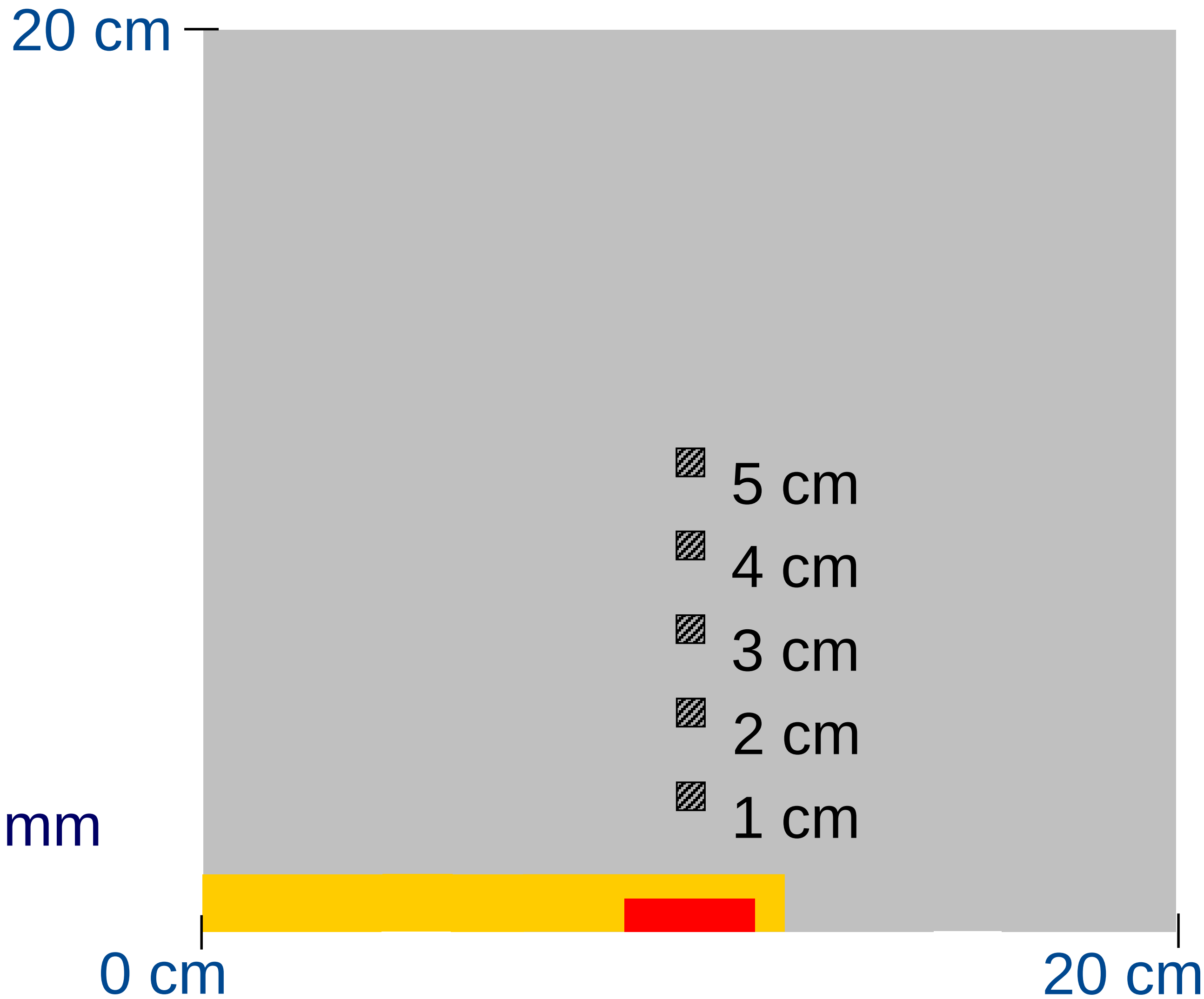
Scatter build-up along R-axis



ROI = 1 mm x 1 mm

Scatter build-up along Z-axis



ROI = 1 mm x 1 mm

Scatter build-up in graphite (1)

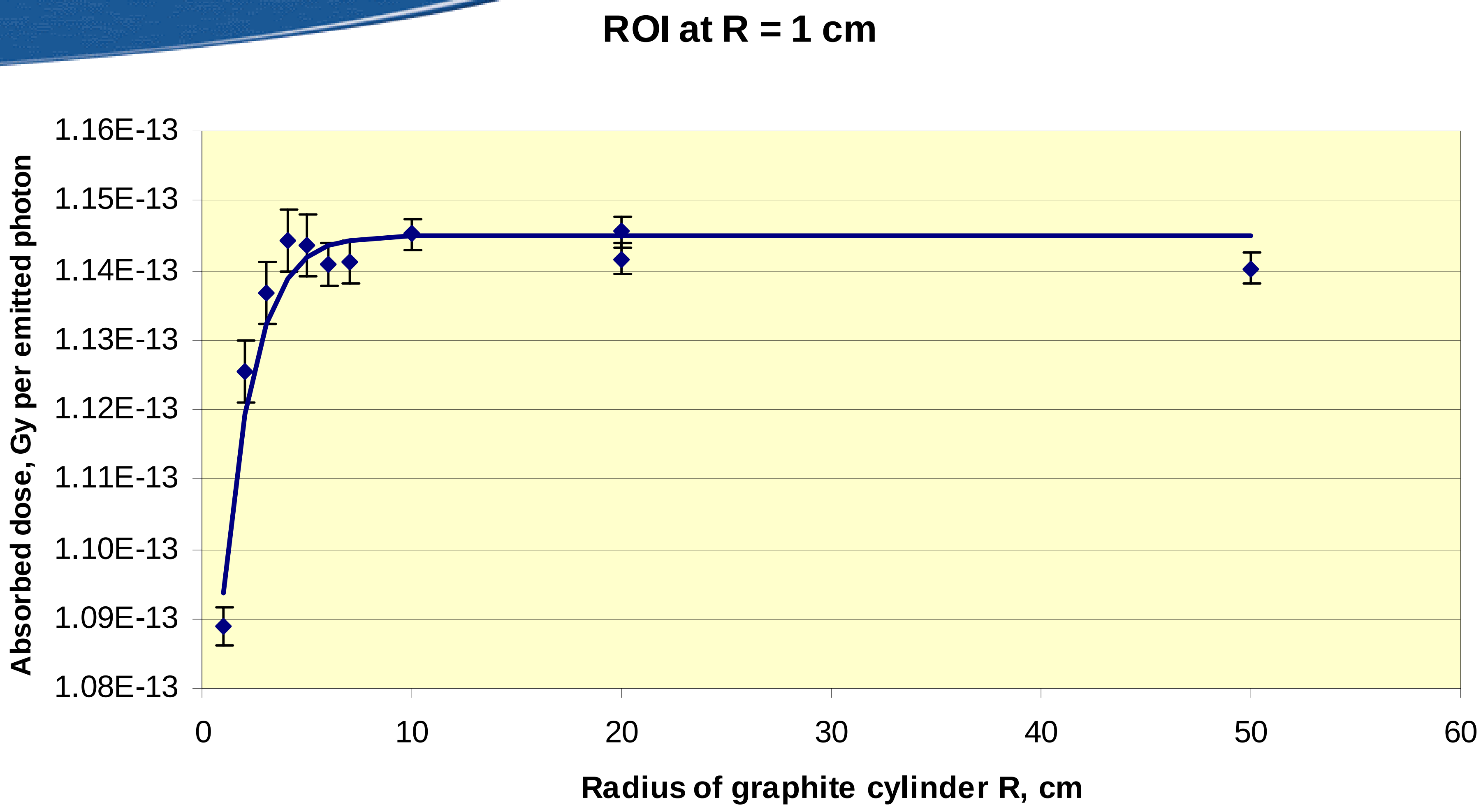
- R = 20 cm and Z = ±10 cm from centre of source

→ absorbed dose in all 5 ROIs (1…5 cm)

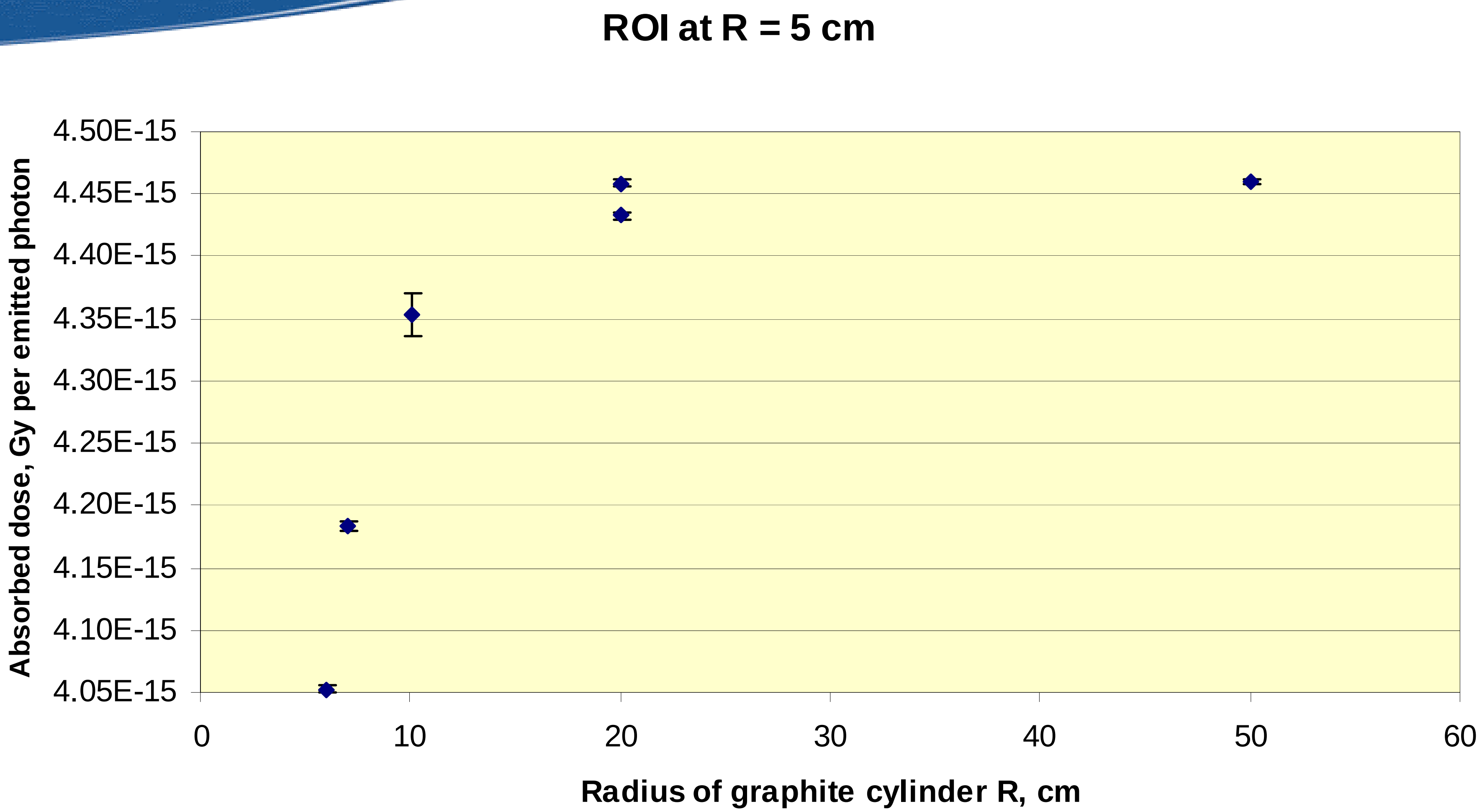
>99.5% of $D_{full\ scatter}$

- $D_{full\ scatter}$ calculated using R = 50 cm and Z = ±50 cm

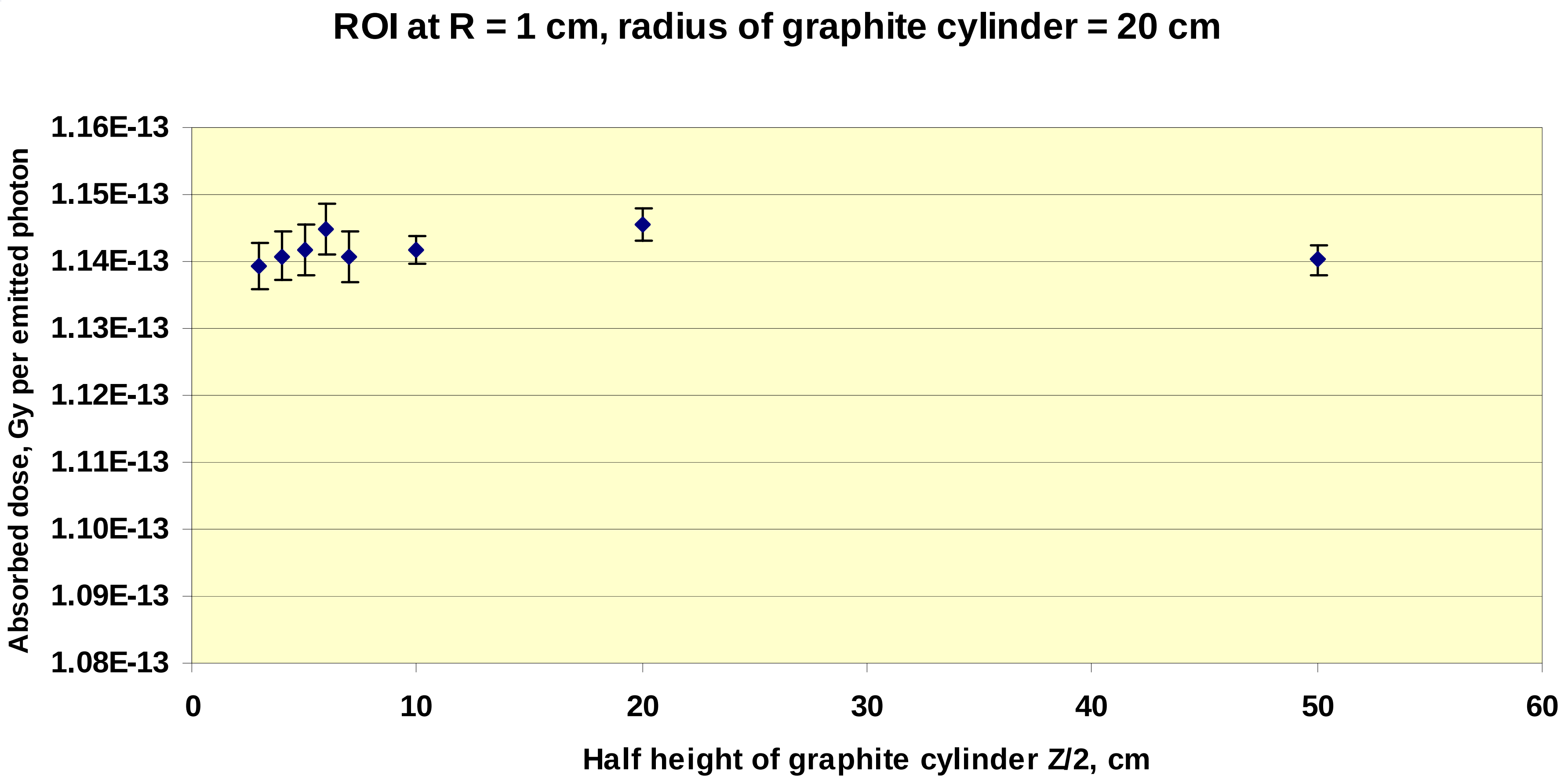
Scatter build-up in graphite (2)



Scatter build-up in graphite (3)



Scatter build-up in graphite (4)



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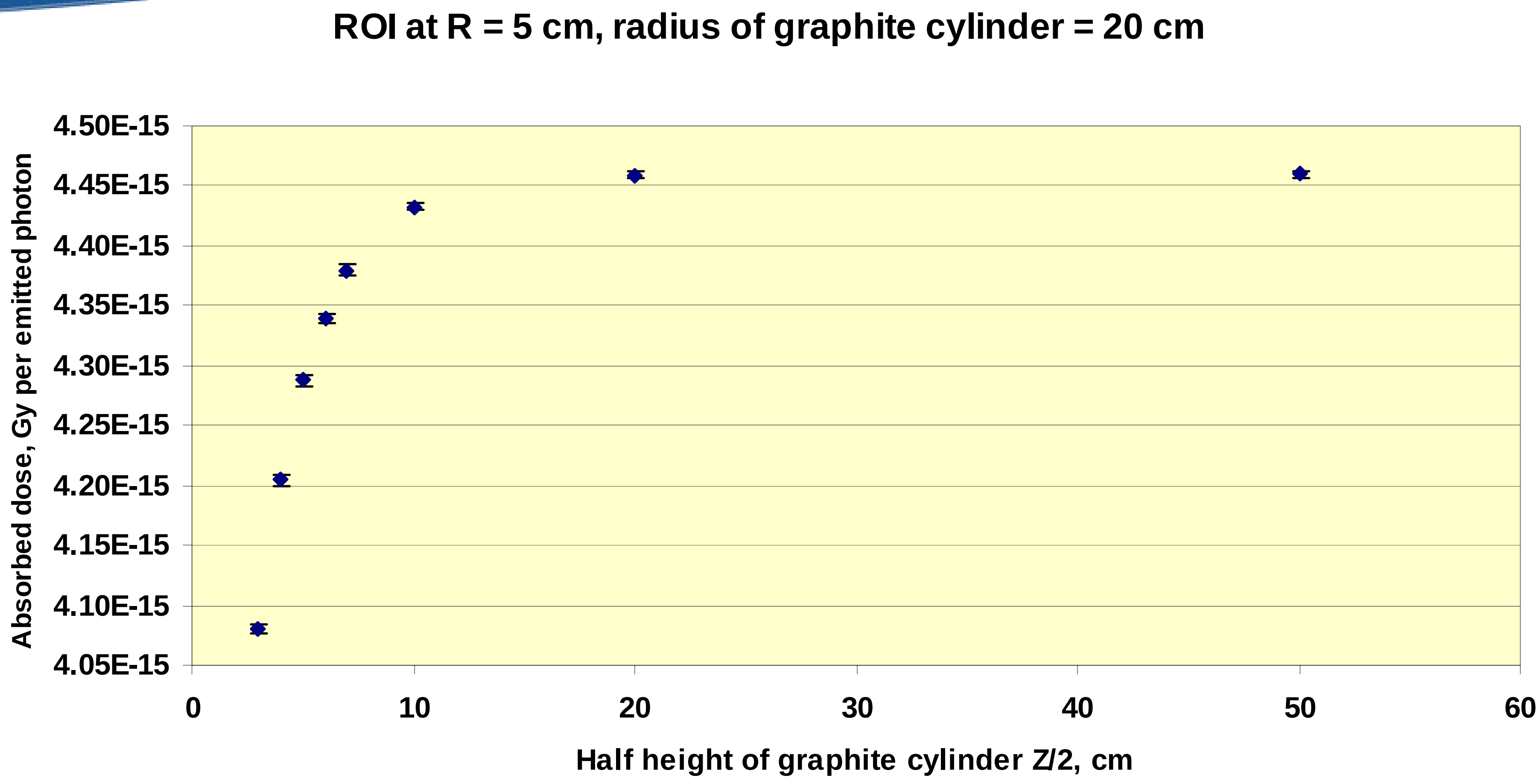
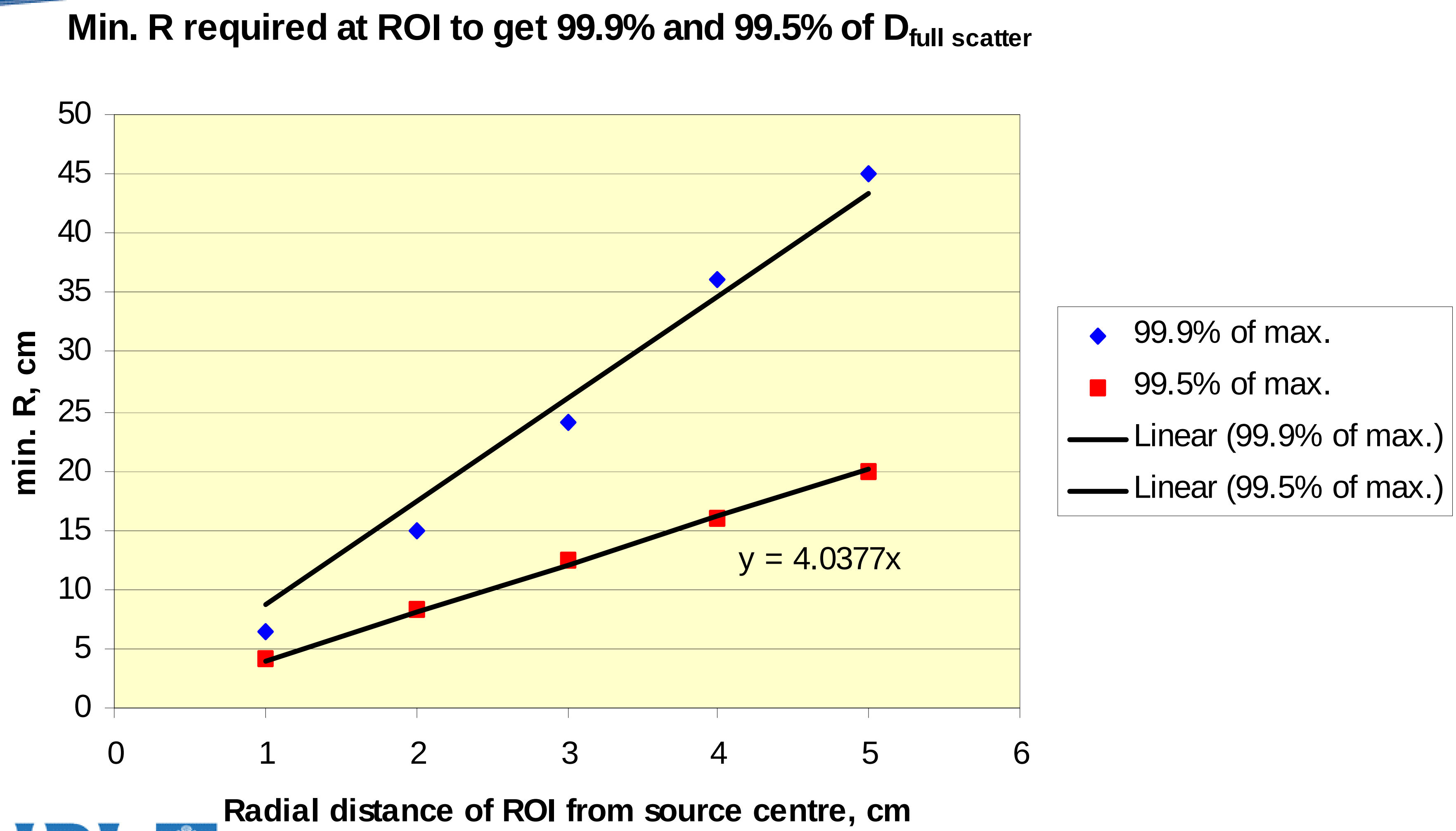
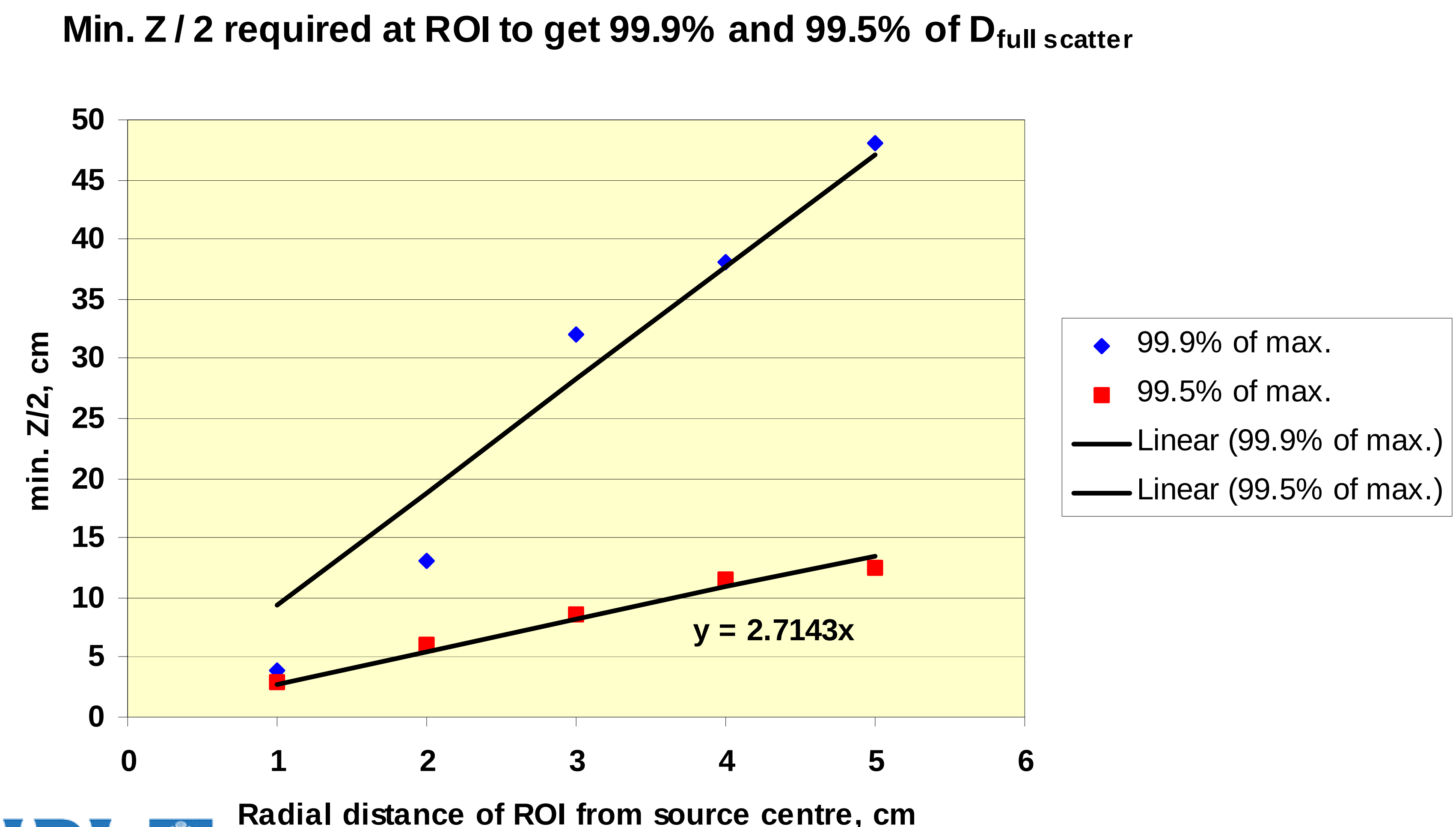
Scatter build-up in graphite (5)



Scatter build-up in graphite (6)



Scatter build-up in graphite (7)



Dose distribution parallel to long source axis (1)

EGS file name: **TS0029**

Source centred.
z = 30.175 cm

Geometrical inputs

R	radii (cm)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
32	30	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980	981	982	983	984	985	986	987	988	989	990	991	992	993
31	4.31	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960	961	962
30	4.05	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920	921	922	923	924	925	926	927	928	929	930	931
29	4.02	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900
28	3.98	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869
27	3.95	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838
26	3.69	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800	801	802	803	804	805	806	807
25	3.31	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776
24	3.05	715	716	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740	741	742	743	744	745
23	3.02	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	712	713	714
22	2.98	653	654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683
21	2.95	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652
20	2.69	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621
19	2.31	560	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589	590
18	2.05	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559
17	2.02	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528
16	1.98	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497
15	1.95	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466
14	1.69	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435
13	1.05	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404
12	1.02	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373
11	0.98	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342
10	0.95	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311
9	0.55	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280
8	0.53	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249
7	0.51	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218
6	0.49	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187
5	0.47	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156
4	0.45	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125
3	0.19	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94
2	0.055	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63
1	0.03	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
	0																															
depth boundaries (cm)		0	28.7	29	29.1	29.2	29.3	29.4	29.5	29.6	29.7	29.8	29.9	30	30	30.03	30.13	30.23	30.33	30.4	30.4	30.5	30.6	30.7	30.8	30.9	31	31.1	31.2	31.3	31.39	31.65
				29	29.1	29.2	29.3	29.4	29.5	29.6	29.7	29.8	29.9	30	30	30.08	30.18	30.28	30.34	30.4	30.4	30.5	30.6	30.7	30.8	30.9	31	31.1	31.2	31.3		

6

Legend

- = graphite
- = iridium
- = stainless steel 316L
- = ROI
- = photon cross section enhancement in this region; minimum distance from blue line to ROI = CSDA range of 0.9 MeV electrons in graphite = 0.26 cm (ICRU report 37)

- MC simulation using NPL grid:

5,000,000,000 histories in less than 1.5 hours

Variance reduction techniques used

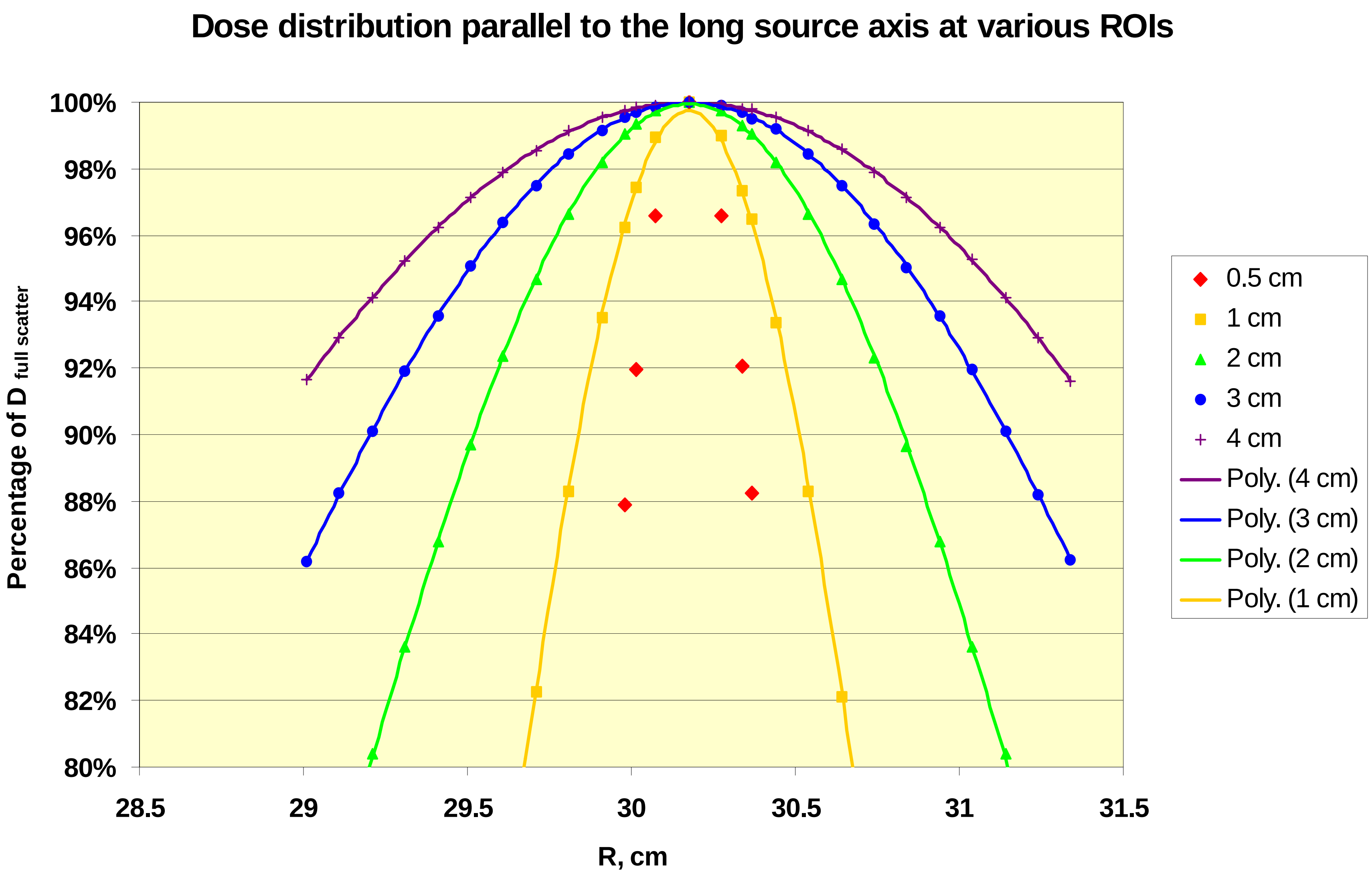
- Electron range rejection

  Here: ESAVE = 0.871 MeV

- Photon cross section enhancement

  Increase photon cross section of selected region in geometry by factor C_e → this will increase the interaction density by that factor

Dose distribution parallel to long source axis



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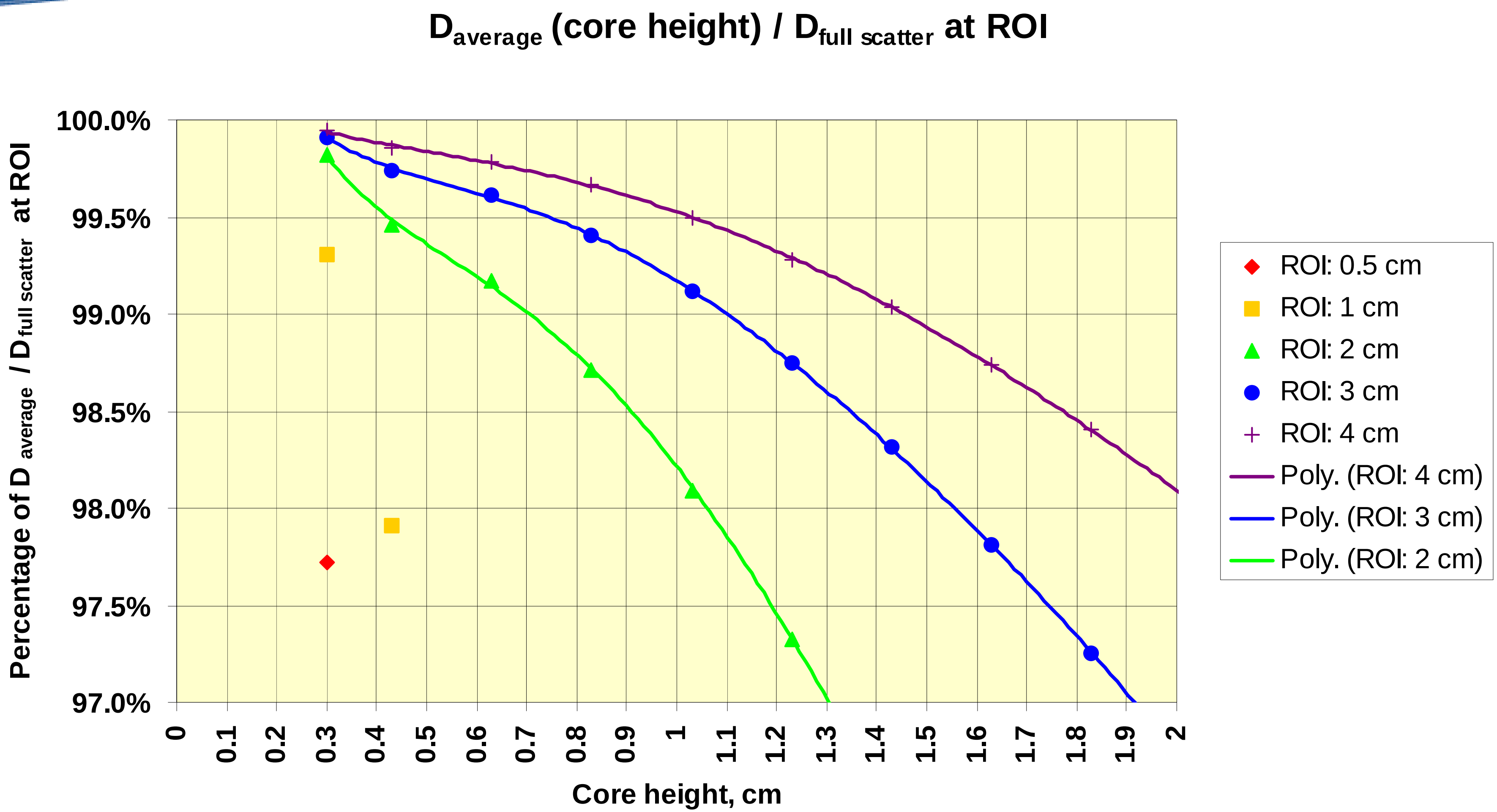
Variation of $D_{average}$ with core height



Core height required to measure D_{total} = 99.5% of $D_{full\ scatter}$

ROI (cm)	Max. core height, cm
2	0.5
3	0.75
4	1.05

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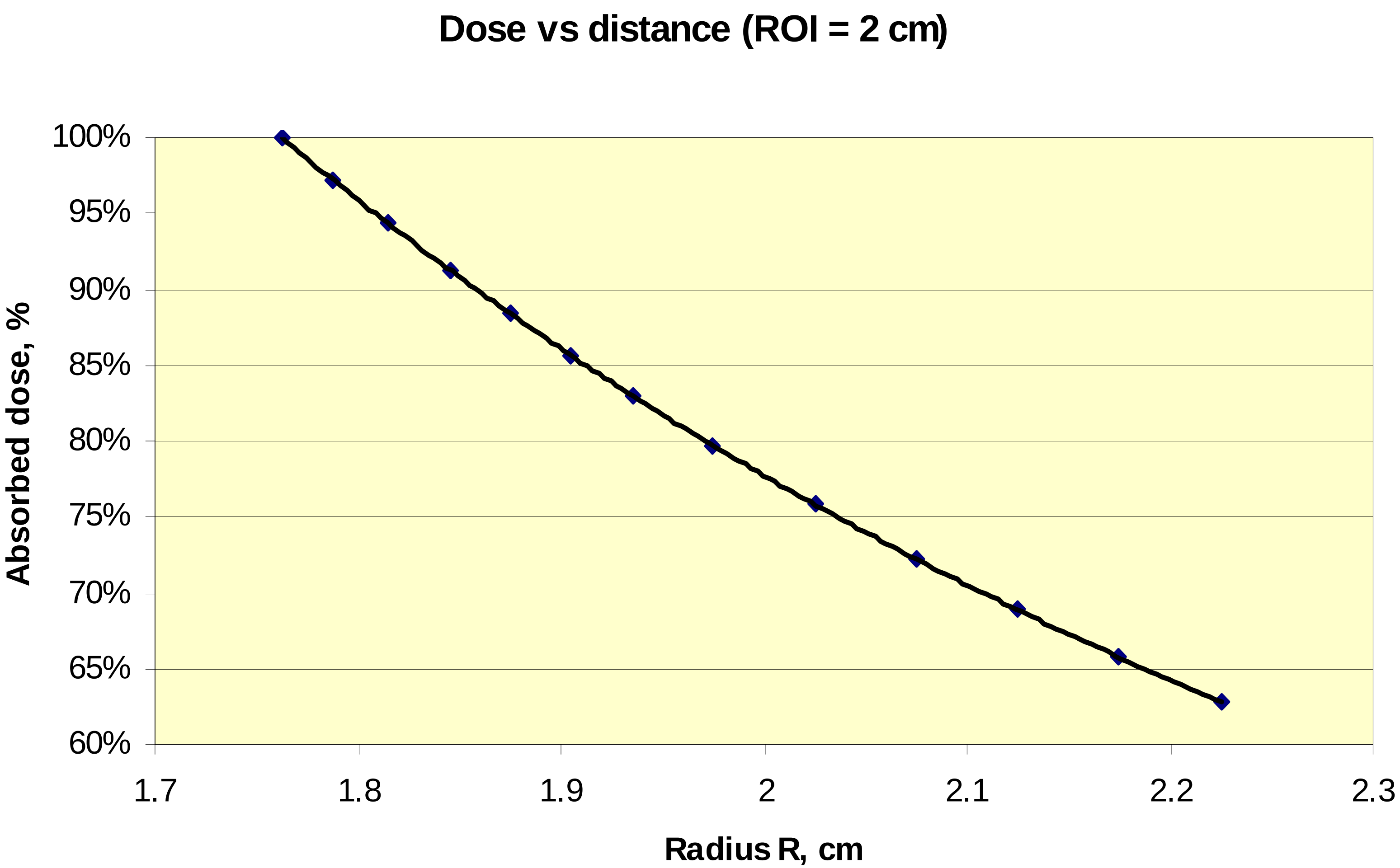
Radial dose gradient in graphite



Summary of MC simulations

Source to core, cm	Build-up	Min. R, cm	Min. Z/2, cm	Max. core height, cm	Dose gradient over 2 mm, %	Dose rate from 370 GBq source, Gy/s	ΔT in 120 s, K
1	X	✓	✓	X	X	9.99E-02	1.68E-02
2	(✓)	8.1	5.4	0.5	23	2.52E-02	4.24E-03
2.5	✓	10.1	6.8	0.6	18.5	1.60E-02	2.69E-03
3	✓	12.1	8.1	0.75	15	1.12E-02	1.88E-03
4	✓	16.2	10.9	1.05	11	6.21E-03	1.04E-03
5	✓	X	X	✓	✓	X	X

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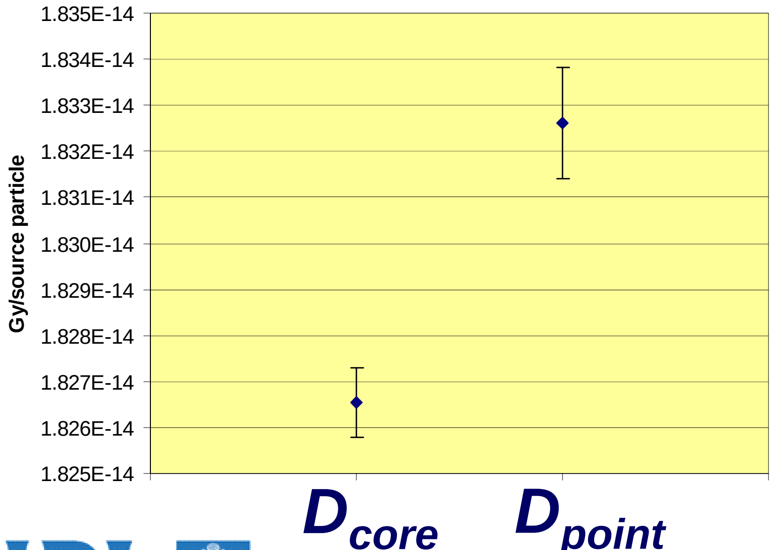
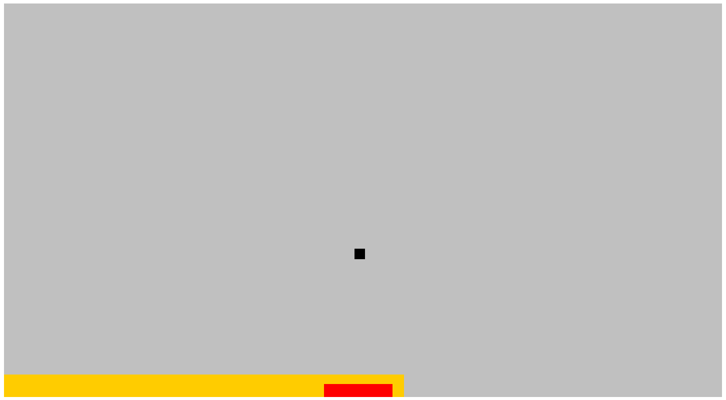
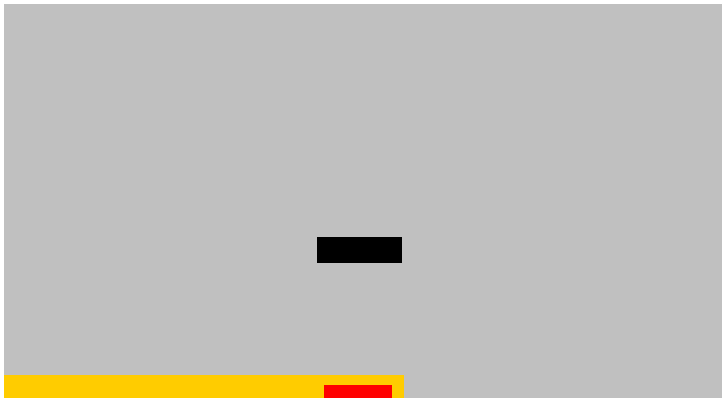
Volume averaging factor

- Centre of ROI: 25 mm from source
- Dose at a 'point', D_{point}
  size: 0.1 mm × 0.1 mm
- Dose averaged over core, D_{core}
  size: 2 mm × 5 mm



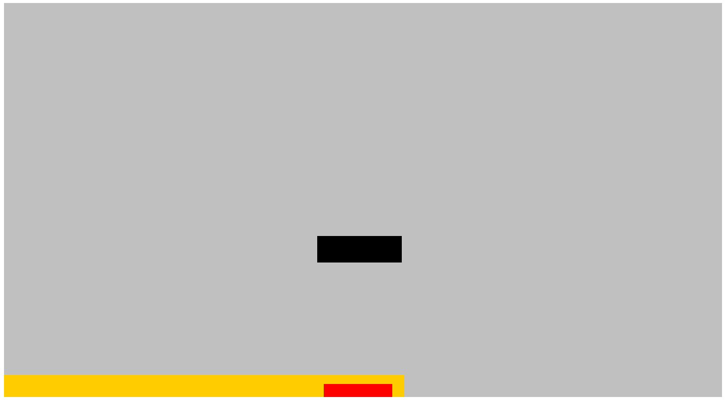


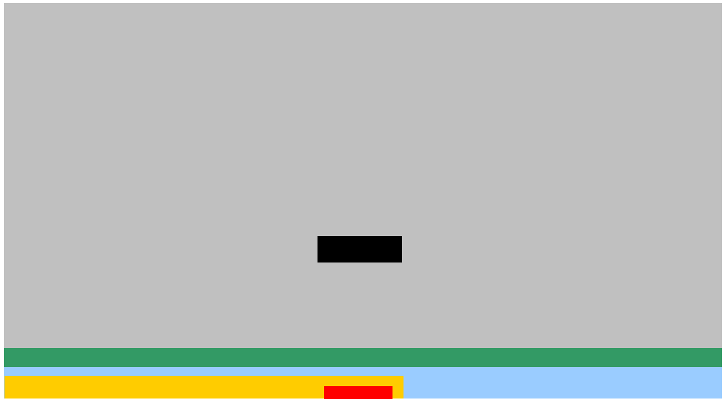


$$k_{av} = \frac{D_{point}}{D_{core}} = 1.0033$$

Inhomogeneity correction factor

- Centre of ROI: 25 mm from source
- Dose averaged over core, $\boldsymbol{D_{core}}$ size: 2 mm × 5 mm





■ = graphite

■ = air

■ = aluminium or steel

$$k_{\text{inh}} = \frac{D_{\text{core, graphite}}}{D_{\text{core, graphite+air+metal}}}$$

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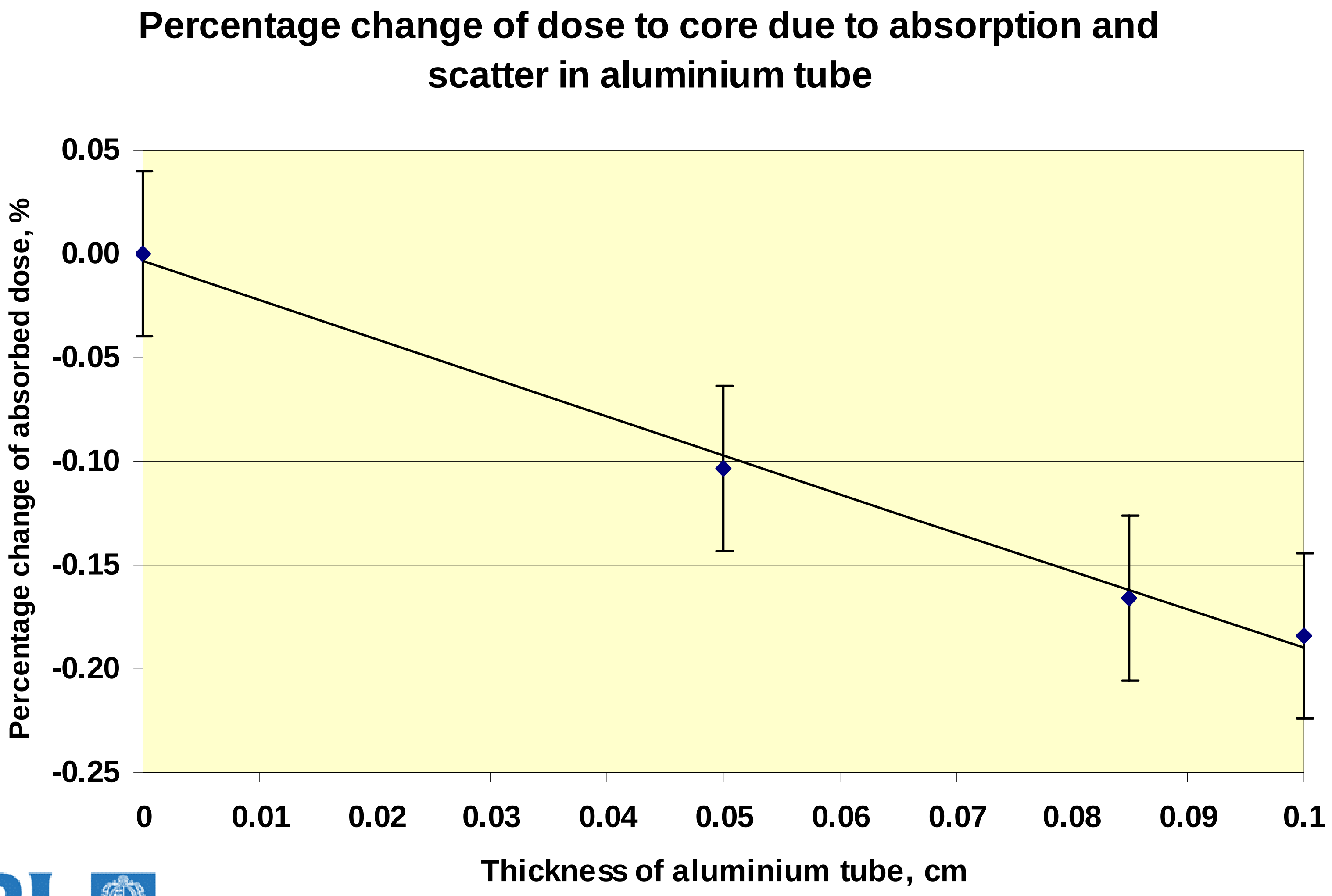
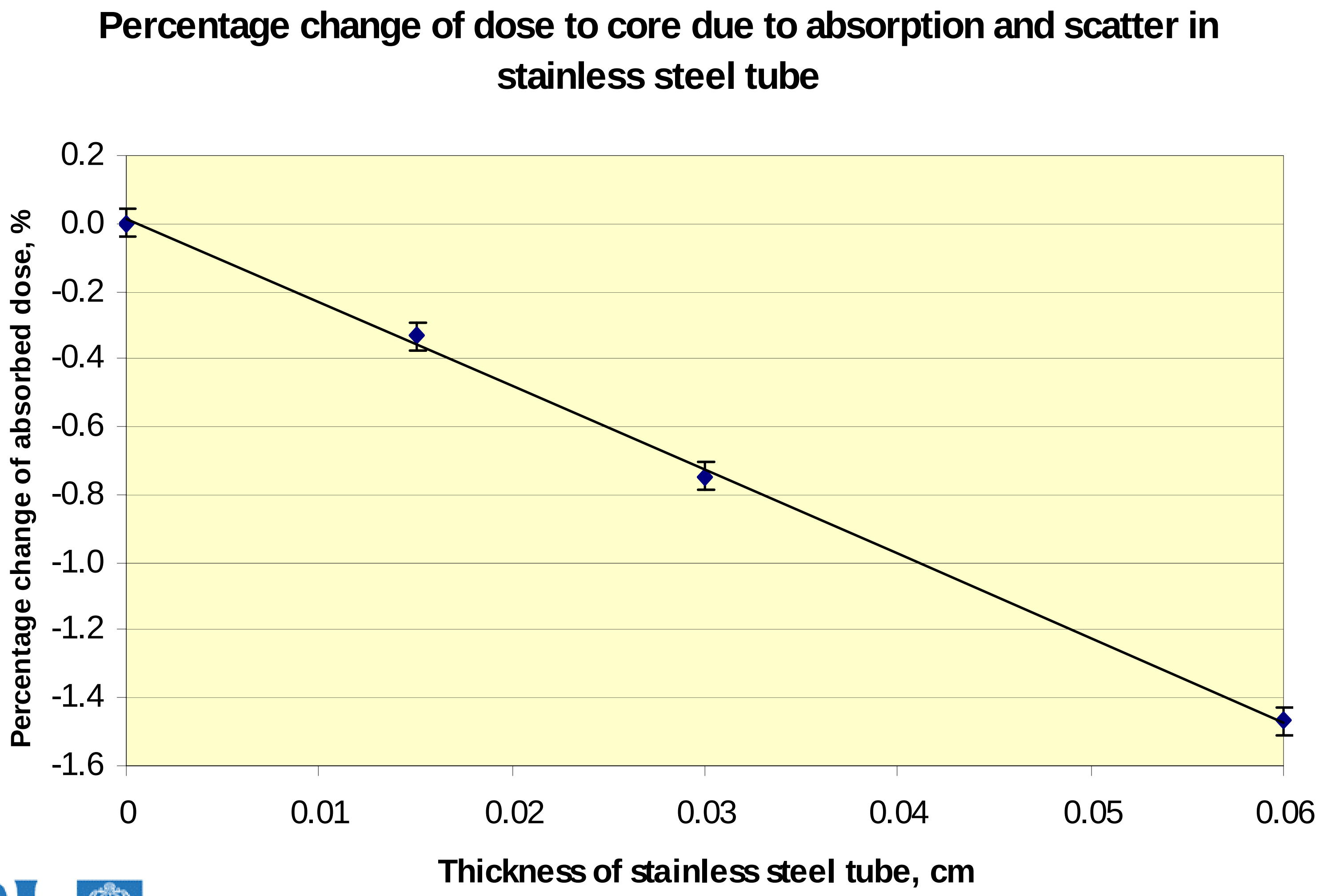
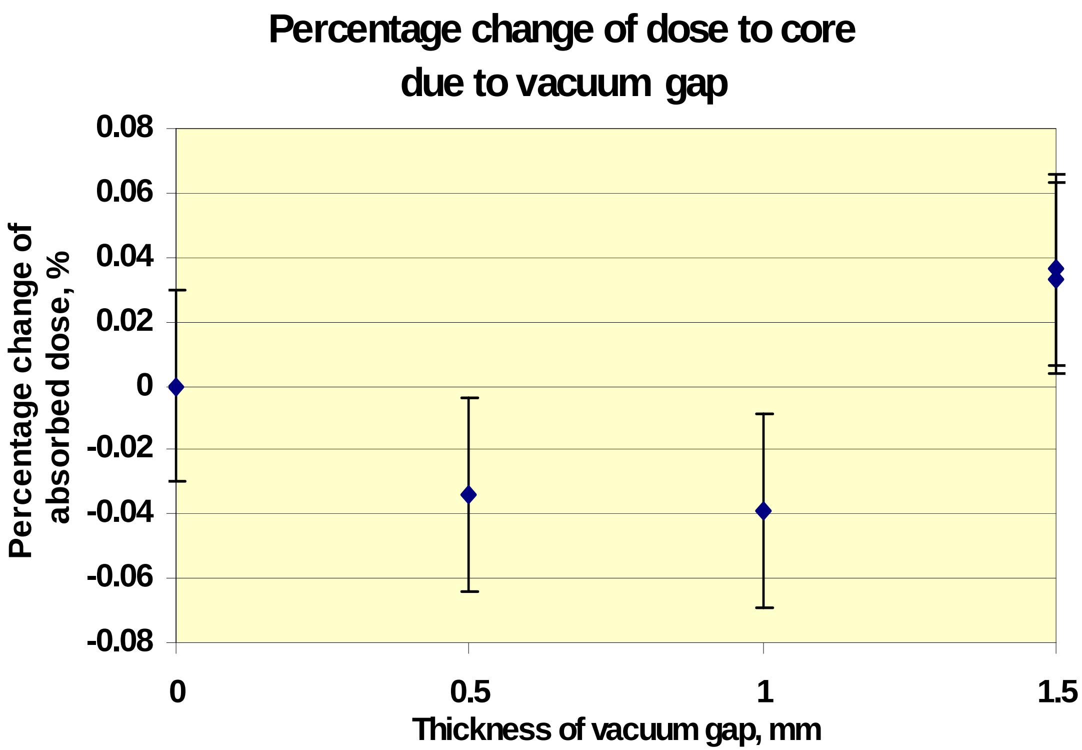
Inhomogeneity correction due to aluminium tube

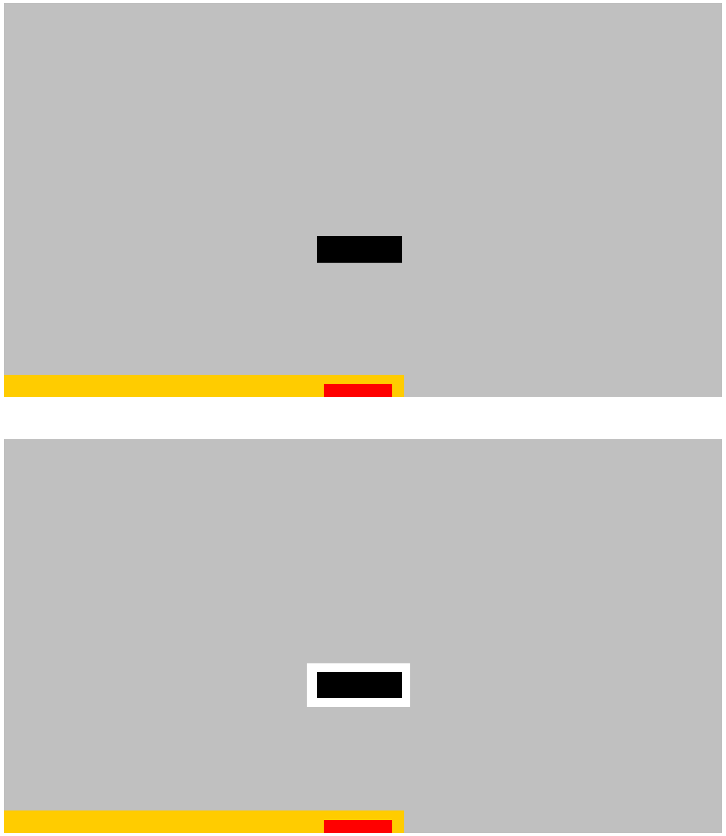


Inhomogeneity correction due to stainless steel tube



Gap correction factor





$$k_{\text{gap}} = \frac{D_{\text{core, graphite}}}{D_{\text{core, graphite+vacuum gap}}}$$

Displacement correction, Z-axis

EGS file name: **TS0034** see also TS0032

Source centred.
z = 7 cm

Core height Z: 0.5 cm, core thickness: 0.2 cm
Centre-to-centre source-to-core: 2.5 cm

Geometrical inputs

radii (cm)	R	Z 1	2	3	4	5	6	7	8	9	10	
10	11	102	103	104	105	106	107	108	109	110	111	
2.96	10	92	93	94	95	96	97	98	99	100	101	
2.7	9	82	83	84	85	86	87	88	89	90	91	
2.6	8	72	73	74	75	76	77	78	79	80	81	
2.4	7	62	63	64	65	66	67	68	69	70	71	
2.3	6	52	53	54	55	56	57	58	59	60	61	
2.04	5	42	43	44	45	46	47	48	49	50	51	
0.165	4	32	33	34	35	36	37	38	39	40	41	0.1 cm aluminium
0.065	3	22	23	24	25	26	27	28	29	30	31	
0.055	2	12	13	14	15	16	17	18	19	20	21	
0.03	1	2	3	4	5	6	7	8	9	10	11	
0												

depth boundaries (cm) 0 | 6.39 | 6.65 | 6.75 | 6.825 | 7.175 | 7.215 | 7.25 | 7.35 | 7.61 | 14

Legend

- = graphite
- = iridium
- = stainless steel 316L
- = air
- = aluminium
- = ROI
- = photon cross section enhancement in this region; minimum distance from blue line to ROI = CSDA range of 0.9 MeV electrons in graphite = 0.26 cm (ICRU report 37)

Source displaced by
±0.075 cm, ±0.175 cm and ±0.275 cm

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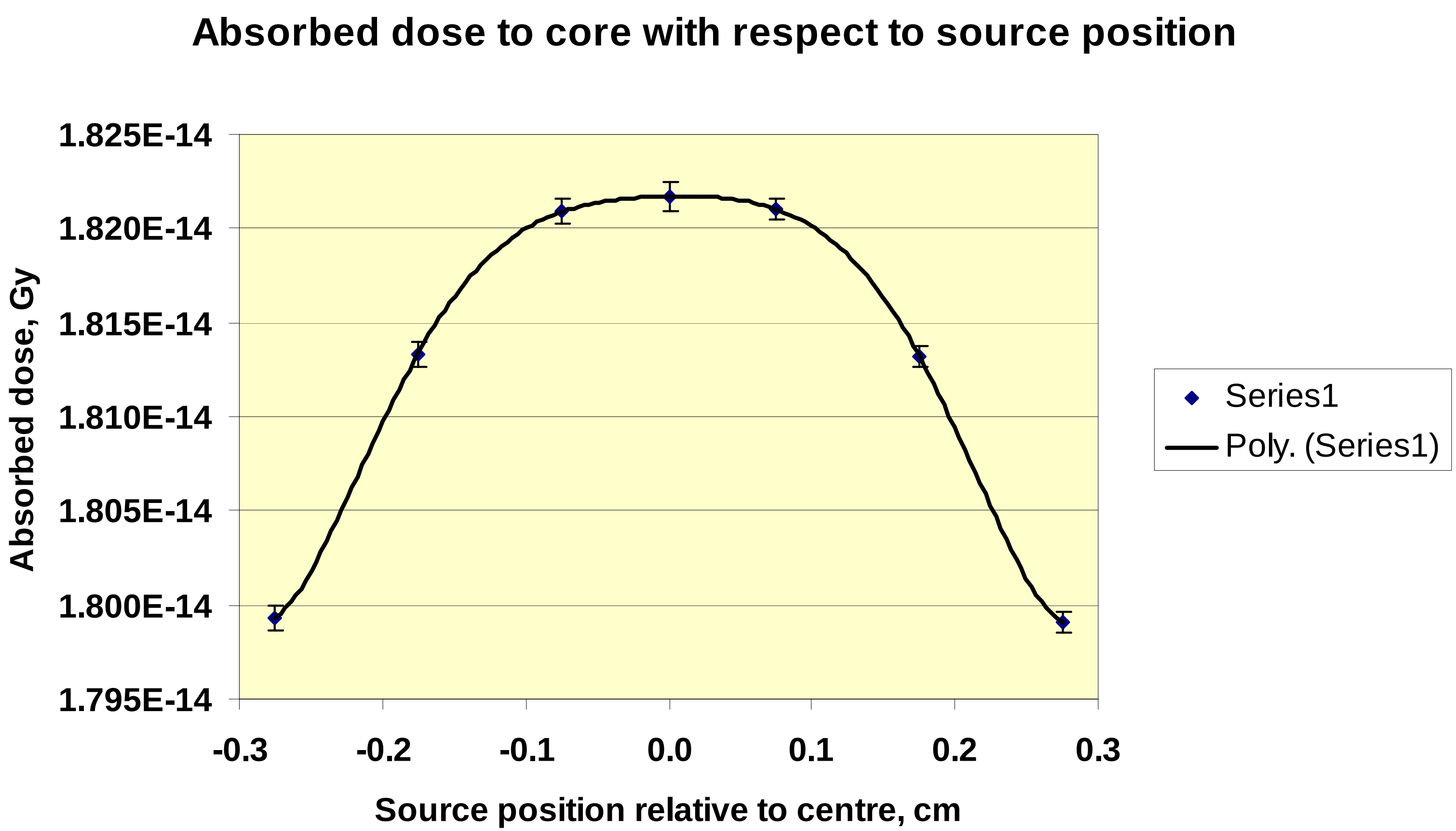
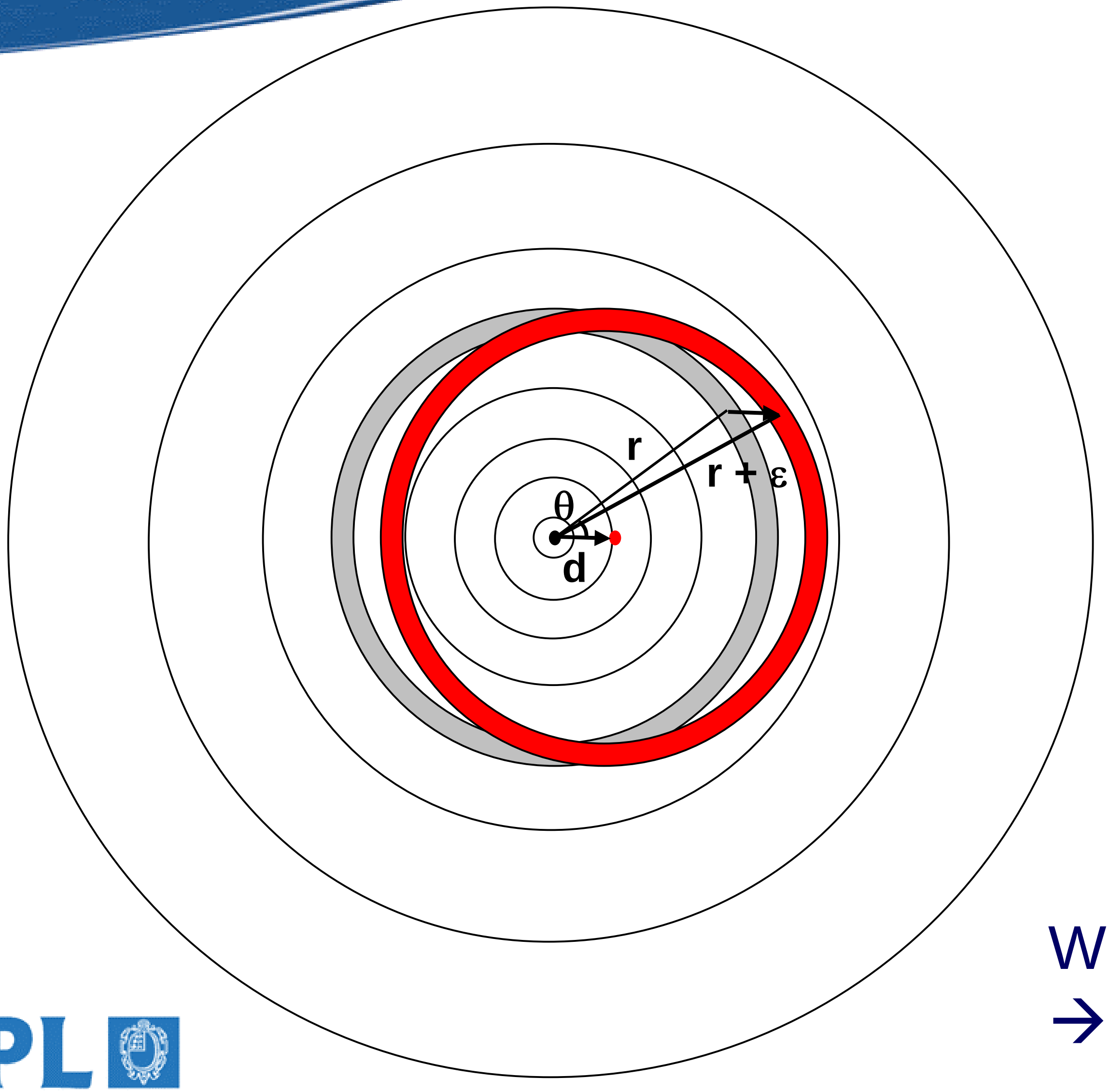
Displacement correction factor, Z-axis

$$k_{\text{disp,Z}} = \frac{D_{\text{central}}}{D_{\text{displaced, Z=0.25mm}}} = 1.0002$$



Displacement correction factor, R-axis



$$D(r) \propto \frac{1}{r^2}$$

$$D(r+\varepsilon)$$

$$\varepsilon = d\cos\theta$$

$$\iint d\theta dr D(r + d\cos\theta)$$

Taylor expansion

$$\frac{D_{\text{displaced}}}{D_{\text{symmetric}}} \approx 1 + \underbrace{\frac{3}{2}\frac{d^2}{r^2}}_{\mathbf{0.1\%}}$$

With r = 25 mm

→ ***d* = 0.64 mm**

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Summary:
Design criteria for prototype calorimeter

- Graphite cylinder (R = 10 cm, Z = 14 cm)
- Centre-to-centre source-to-core distance: 2.5 cm
- Thickness of core: 0.2 cm
- Height: 0.5 cm
- Mass: 2.67 g
- Aluminium tubing with max. 1 mm radial thickness, 0.2 mm radial clearance
- 1 mm vacuum gap around core to deal with measurement problems due to self-heating of source

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