Generic Studies of Radioactivity Induced by High Energy Beams in Different Absorber Materials

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Motivation

- A rigorous campaign of **benchmark measurements** for materials typically used at accelerators has shown the **high accuracy of FLUKA calculations** for **isotope production** and **residual dose rates**

- Residual dose rate estimates are an important information during **all phases of an accelerator**, *i.e.,* design, operation and decommissioning

- A detailed implementation of geometries and accurate consideration of loss assumptions allows **optimizing the layout of components and performing intervention planning** already during the design phase *(e.g., LHC collimation region, dumps, TDIs, CNGS,…)*

- Recent design modifications have shown the need to derive scaling coefficients in order to quickly asses how estimated results can be roughly scaled for different used: **materials; beam energies and particles; loss conditions, cooling times and beam impacts**

- Aiming to provide **quick and effective estimates** in the order of a factor of two

Residual Dose Rate Calculations with FLUKA

- **Exact analytical solution of the Bateman equations** describing activity build-up and decay during irradiation and cooling down, for arbitrary irradiation conditions

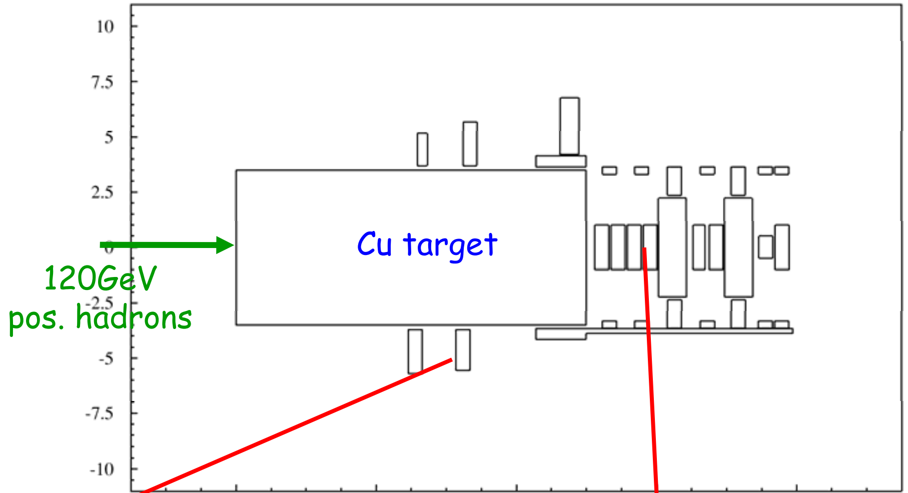
- **Generation and transport of decay radiation** (limited to gamma, beta-, and beta+ emissions for the time being) is possible **during the same simulation which produces the radio-nuclides**
  - *Up to 4 different decay branchings for each isotope/isomer*
  - *All gamma lines down to 0.1% branching*
  - *All beta emission spectra down to 0.1% branching: the sampling of the beta+/- spectra is for the time being still without Coulomb corrections*

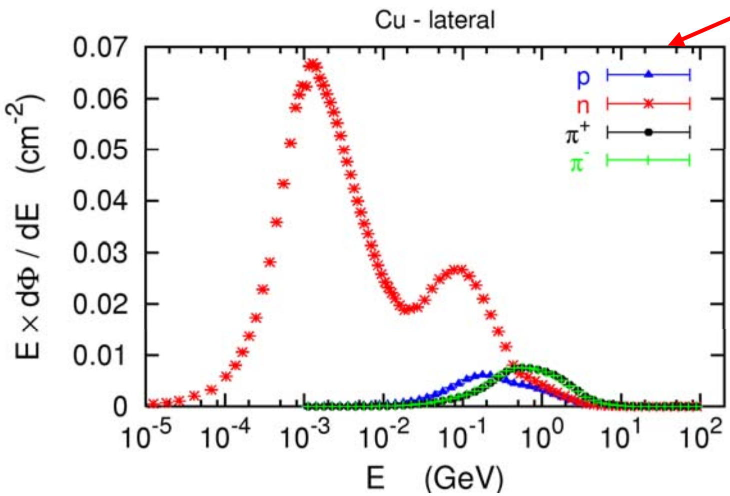
- **Isomers**: the present models do not distinguish among ground state and isomeric states (it would require spin/parity dependent calculations during evaporation). A rough estimate (**equal sharing among states**) of isomer production can be activated.

- **Different transport thresholds can be set for the prompt and decay radiation parts**, as well as some (limited) biasing differentiation

Benchmark Experiments

Irradiation of samples of different materials to the stray radiation field created by the interaction of a 120 GeV positively charged hadron beam in a copper target





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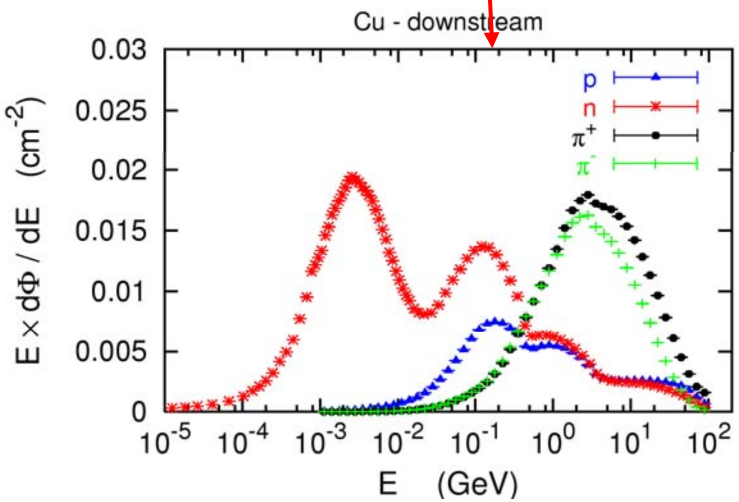


Isotope	Copper		Iron		Titanium		Stainless Steel			Aluminum			Concrete		
^{7}Be 53.29d	1.47 ± 0.19	M	1.65 ± 0.22		1.50 ± 0.19		0.98 ± 0.24	M	C,N	0.71 ± 0.09		Al	1.17 ± 0.14		O, C
	0.84 ± 0.25		0.90 ± 0.15												
^{22}Na 2.60y	0.72 ± 0.11		0.70 ± 0.13	M	0.85 ± 0.11		—			0.76 ± 0.07		Al	0.86 ± 0.09		Ca,(Si,Mg)
^{24}Na 14.96h	0.42 ± 0.03		0.48 ± 0.02		0.63 ± 0.02		0.37 ± 0.02		Fe,(Cr,Si)	0.81 ± 0.03		Al,Mg	0.62 ± 0.02		Ca,(Si,Al)
^{27}Mg 9.46m					0.79 ± 0.14	M				1.52 ± 0.25		Al,Mg			
^{28}Mg 20.91h	0.25 ± 0.04	-	0.23 ± 0.03	-	0.31 ± 0.02	-	0.29 ± 0.10	M-	Fe,Ni,Si)				0.29 ± 0.02	-	Ca,(Si)
^{28}Al 2.24m	0.25 ± 0.03	-	0.21 ± 0.02	-	0.31 ± 0.02	-	0.29 ± 0.10	M-	Fe,Ni,Si)				0.29 ± 0.03	-	Ca,(Si)
^{29}Al 6.56m			—		0.93 ± 0.25	M									
^{38}S 2.84h	—		—		0.60 ± 0.12	-	—								
^{m34}Cl 32.00m			0.91 ± 0.19	M	1.19 ± 0.16		0.77 ± 0.15		Fe,Cr,(Mn)				1.25 ± 0.07		Ca
^{38}Cl 37.24m	—		0.61 ± 0.08		0.60 ± 0.01		0.58 ± 0.07		Fe,Cr,(Mn)						
^{39}Cl 55.60m			0.64 ± 0.11	M	0.73 ± 0.08		0.66 ± 0.12		Fe,Cr,(Mn)						
^{41}Ar 1.82h	0.39 ± 0.06		0.46 ± 0.05		0.47 ± 0.04	-	0.38 ± 0.05		Fe,Cr,(Mn)				0.98 ± 0.14		Ca
^{38}K 7.64m	—		—				—						1.76 ± 0.20	-	Ca
^{42}K 12.36h	0.66 ± 0.10		0.83 ± 0.06		0.95 ± 0.05		0.76 ± 0.09		Fe,Cr,(Mn)				1.21 ± 0.08		Ca
^{43}K 22.30h	0.81 ± 0.10	-	0.77 ± 0.05		0.85 ± 0.03		0.74 ± 0.04		Fe,Cr,(Mn)	—			1.16 ± 0.05		Ca
^{44}K 22.13m					—										
^{45}K 17.30m					—										
^{47}Ca 4.54d	0.59 ± 0.16		0.56 ± 0.17	M	0.73 ± 0.12		0.51 ± 0.15	M	Fe,Cr,(Mn)				0.79 ± 0.12		Ca
^{43}Sc 3.89h	0.40 ± 0.07	-	1.01 ± 0.14		1.28 ± 0.28	-	0.93 ± 0.15		Fe,Cr,(Mn)						
^{44}Sc 3.93h	0.89 ± 0.07		1.06 ± 0.06		0.88 ± 0.05		0.96 ± 0.08		Fe,Cr,(Mn)	—			0.83 ± 0.06		Fe,(Ti)
^{m44}Sc 58.60h	0.95 ± 0.12		1.20 ± 0.09		2.13 ± 0.12		1.24 ± 0.09		Fe,Cr,(Mn)	1.08 ± 0.17		Fe,Mn	1.67 ± 0.22		Fe,(Ti)
^{46}Sc 83.79d	0.81 ± 0.07		0.86 ± 0.07		0.93 ± 0.08		0.89 ± 0.08		Fe,Cr,(Mn)	0.79 ± 0.18		Mn,(Ti,Fe)	0.88 ± 0.10		Fe,(Ti)
^{47}Sc 80.28h	1.09 ± 0.14		1.17 ± 0.10	-	0.87 ± 0.07		1.06 ± 0.09		Fe,Cr,(Mn)	1.04 ± 0.15		Mn,(Ti,Fe)	1.00 ± 0.09		Fe,Ti,(Ca)
^{48}Sc 43.67h	1.39 ± 0.16		1.47 ± 0.10		1.10 ± 0.04		1.42 ± 0.08		Fe,Cr,(Mn)				1.36 ± 0.25		Fe,Ti,(Ca)
^{48}V 15.97d	1.16 ± 0.08		1.45 ± 0.06		1.11 ± 0.07		1.44 ± 0.11		Fe,Cr,(Mn)	1.07 ± 0.13		Fe,Mn	1.63 ± 0.16		Fe
^{48}Cr 21.56h	0.92 ± 0.14		0.97 ± 0.07				1.02 ± 0.08		Fe,(Cr)				1.06 ± 0.23	M	Fe
^{49}Cr 42.30m	1.00 ± 0.22	M	1.24 ± 0.12	-			1.06 ± 0.12		Fe,(Cr)						
^{51}Cr 27.70d	1.06 ± 0.13		1.15 ± 0.12		0.64 ± 0.24	M	1.24 ± 0.16		Fe,Cr	0.86 ± 0.16		Fe,Mn	1.33 ± 0.22		Fe
^{52}Mn 5.59d	0.68 ± 0.05		1.15 ± 0.04				1.09 ± 0.03		Fe,(Mn)	0.88 ± 0.07		Fe,Mn	1.39 ± 0.07		Fe
^{m52}Mn 21.10m	1.68 ± 0.35		1.24 ± 0.09				1.12 ± 0.10		Fe,(Mn)				1.75 ± 0.79	M	Fe
^{54}Mn 312.12d	1.13 ± 0.12		1.01 ± 0.10				1.08 ± 0.11		Fe,(Mn)	0.96 ± 0.12		Mn,Fe	1.06 ± 0.13		Fe
^{56}Mn 2.58h	0.81 ± 0.06		0.99 ± 0.05				1.33 ± 0.10		Fe	1.53 ± 0.25		Mn	1.03 ± 0.25		Mn,Fe
^{52}Fe 8.28h	—		1.09 ± 0.13				0.99 ± 0.19	M	Fe,(Mn)						
^{53}Fe 8.51m			—												
^{59}Fe 44.50d	0.82 ± 0.09														
^{55}Co 17.53h	0.66 ± 0.09		0.76 ± 0.04				1.03 ± 0.05		Fe,Ni				—		
			1.13 ± 0.10												
^{56}Co 77.27d	1.04 ± 0.08		1.15 ± 0.10				1.37 ± 0.11		Fe,Ni	—			0.80 ± 0.20	M	Fe
			1.79 ± 0.15												
^{57}Co 271.79d	0.85 ± 0.09		0.38 ± 0.09	M			1.16 ± 0.13		Ni	0.66 ± 0.24	M	Cu,Zn,Ni			
^{58}Co 70.82d	0.91 ± 0.09		0.31 ± 0.08	M			0.98 ± 0.10		Ni	0.82 ± 0.19		Cu,Zn,Ni	—		
^{60}Co 5.27y	0.90 ± 0.08														
^{61}Co 99.00m	0.68 ± 0.08														
^{62}Co 90.00s	—														
^{57}Ni 35.60h	0.76 ± 0.11		—				1.44 ± 0.07		Ni				—		
^{65}Ni 2.52h	1.46 ± 0.29														
^{60}Cu 23.70m	0.78 ± 0.08														
^{61}Cu 3.33h	0.87 ± 0.25														
^{64}Cu 12.70h	0.63 ± 0.10														
^{62}Zn 9.19h	1.05 ± 0.23														
^{63}Zn 38.47m	—														
^{65}Zn 244.26d	0.62 ± 0.08														
	0.97 ± 0.20														

R = Ratio FLUKA/Exp

$0.8 < R < 1.2$

$0.8 < R \pm Error < 1.2$

$Exp/MDA < 1$

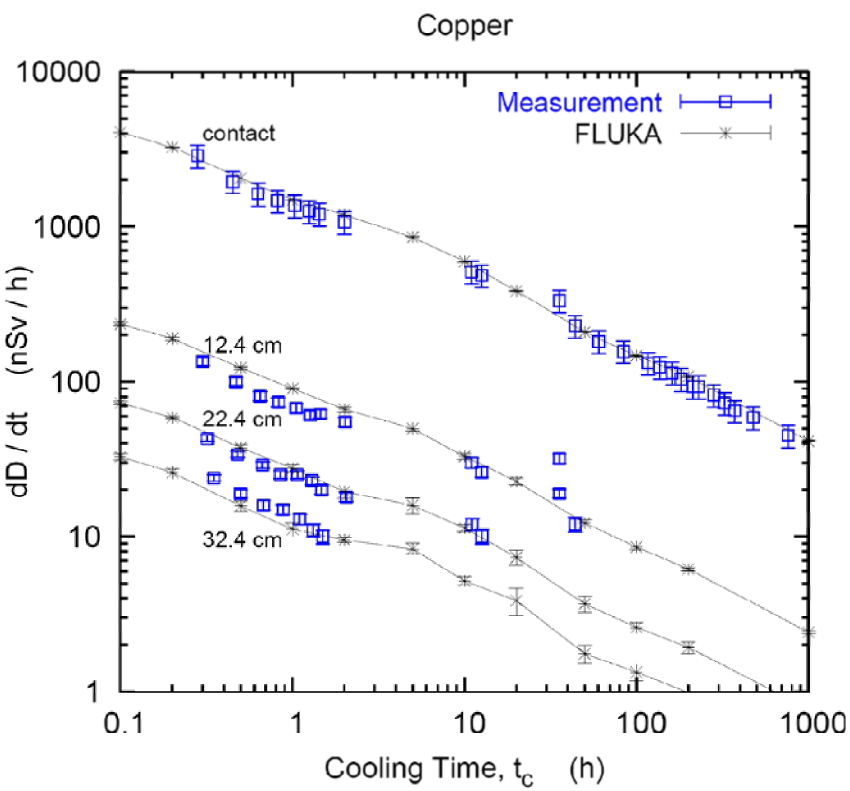
$R + Error < 0.8$ or
$R - Error > 1.2$

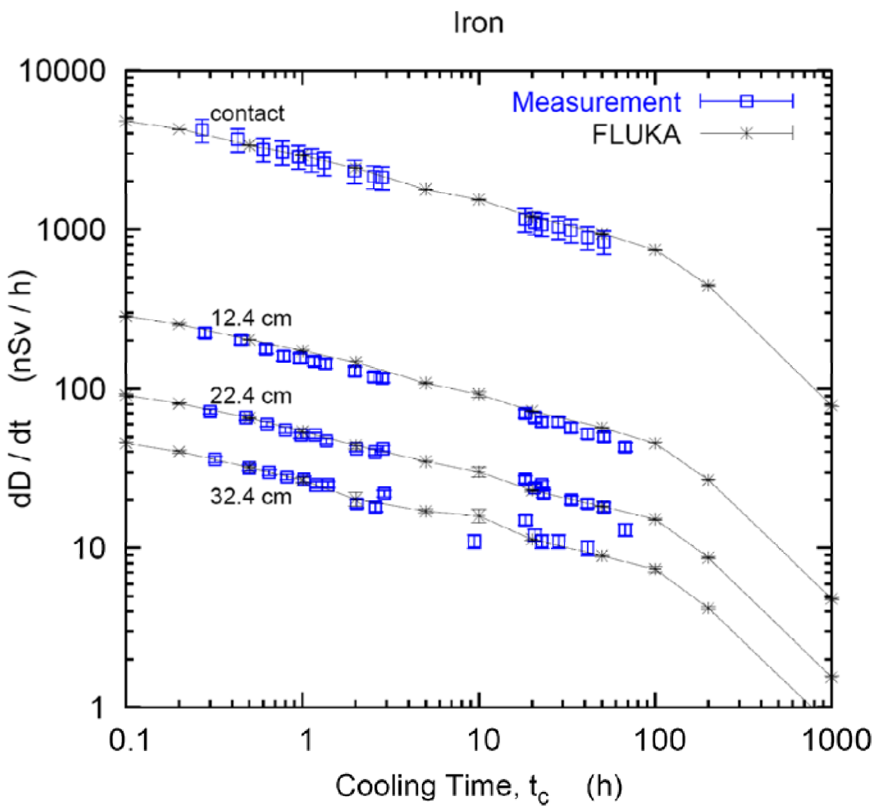
Reference:
M. Brugger, *et al.*, Nuclear Instruments and Methods A 562 (2006) 814-818

Benchmark Experiment - *Residual Dose Rates*

<u>Reference:</u> M. Brugger *et al.,* Radiat. Prot. Dosim. 116 (2005) 12-15

Dose rate as function of cooling time
for different distances between sample and detector





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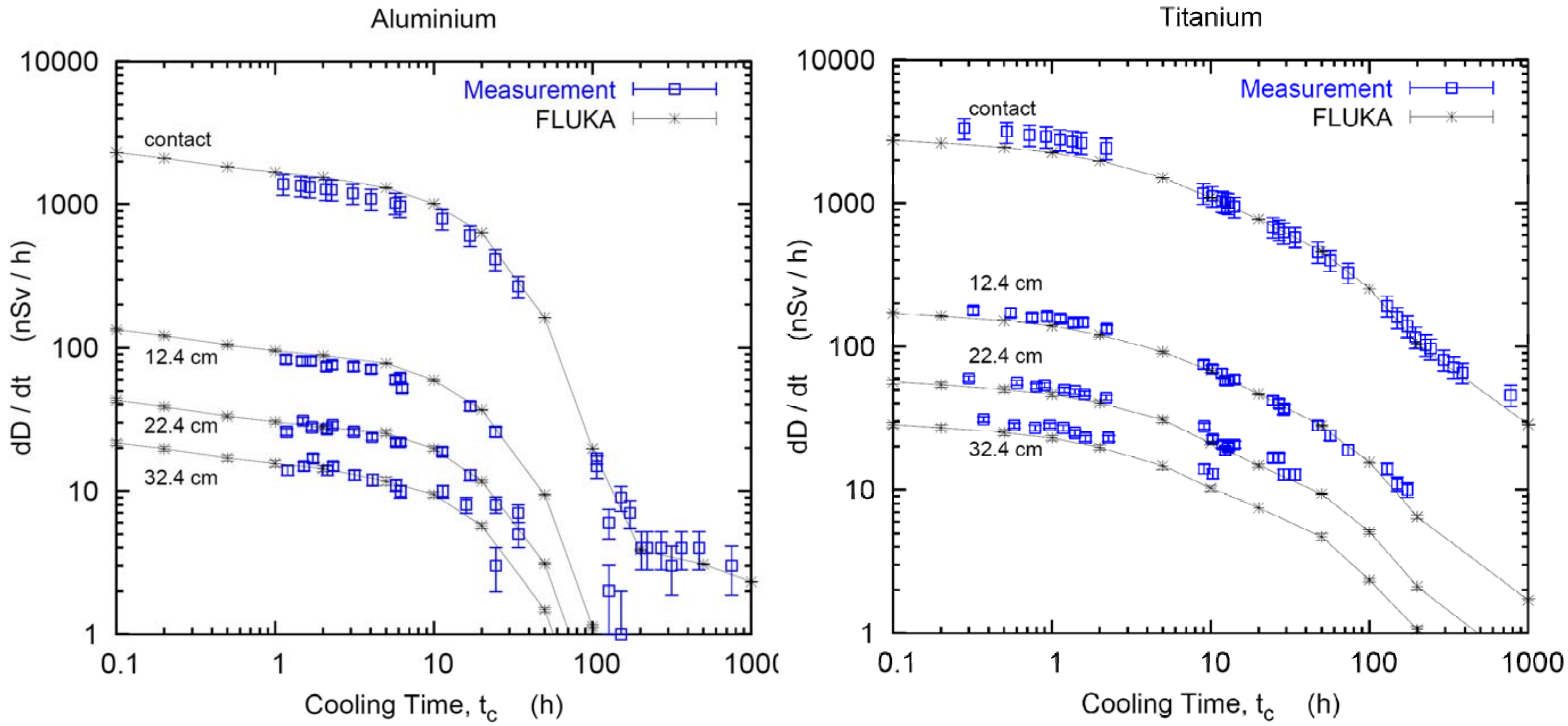

Benchmark Experiment - *Residual Dose Rates*

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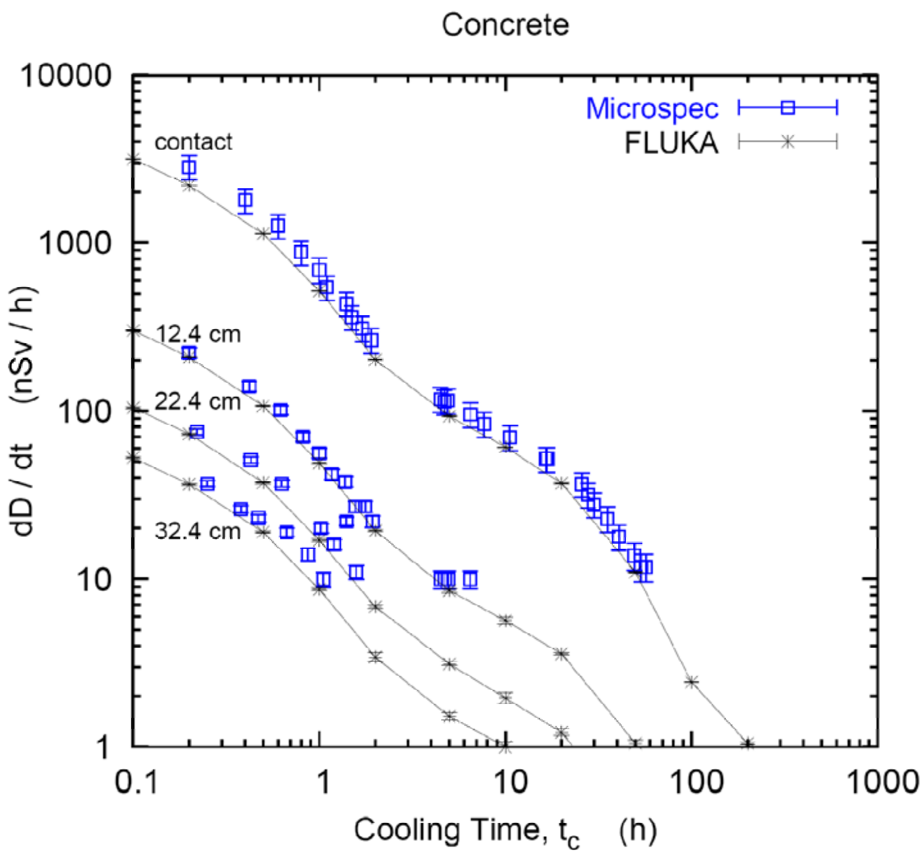
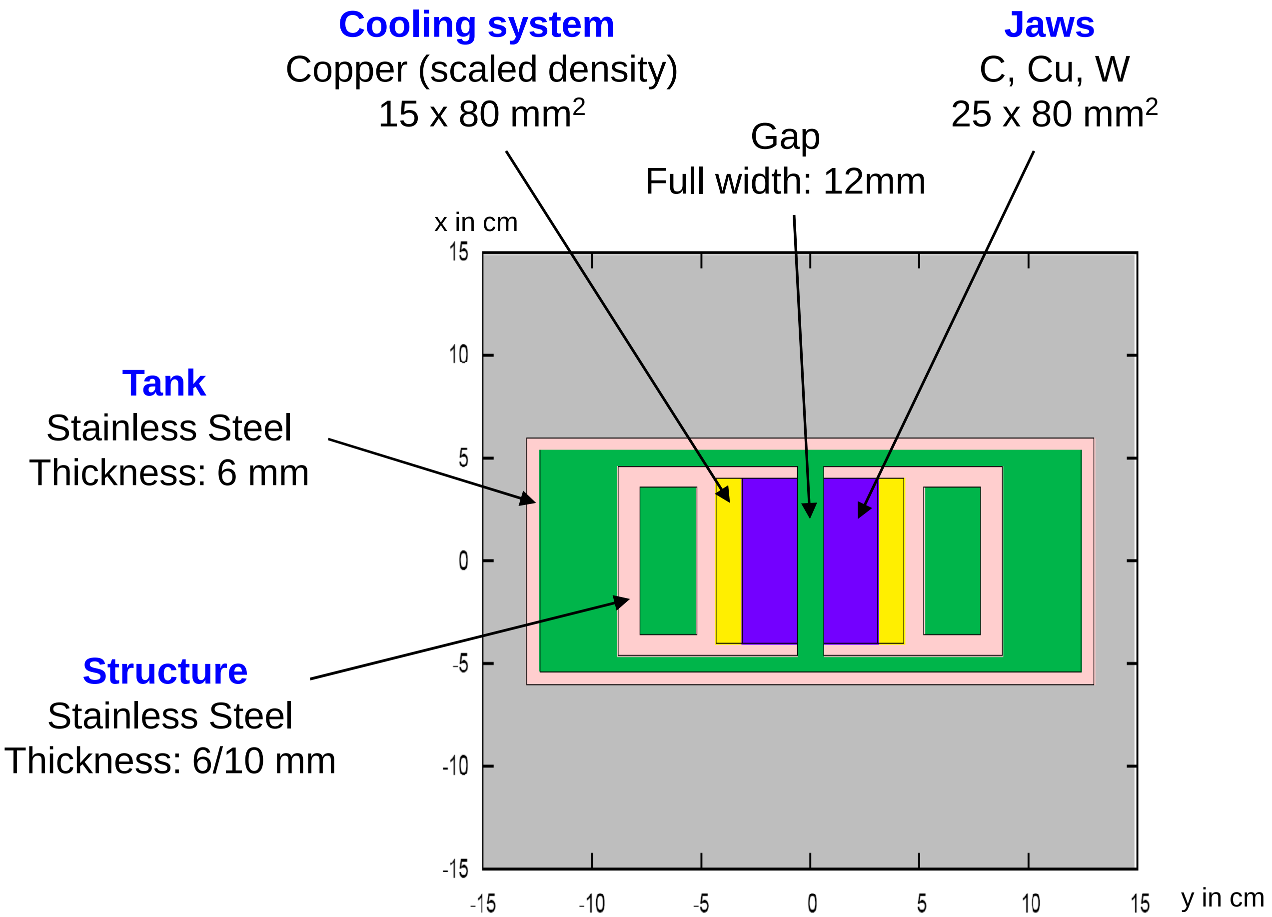


Generic FLUKA Simulations – *Geometry and Materials*

Collimator length (or similar object): 120 cm



Stainless steel:

Fe	64.895%
Cr	15.0%
Ni	14.0%
Mn	2.0%
Mo	3.0%
Si	1.0%
P	0.045%
C	0.03%
S	0.03%

Generic FLUKA Simulations – *Configurations*

Jaw Material	Beam Particle: Type / Energy			
	proton			lead
	450 GeV	7 TeV	2.6 TeV	2.6 TeV/n
Carbon	x	x	x	x
Copper	x	x	x	x
Tungsten	x	x	x	-
			in order to scale to LHC lead beam	

LHC proton beam
injection / top energy

LHC lead beam
top energy

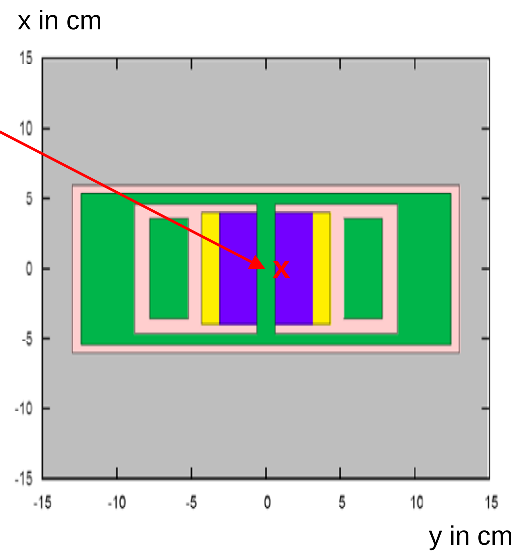
Generic FLUKA Simulations – *Irradiation Conditions*

Irradiation time: 180 days (one operational LHC year)

Beam intensity: 2.96×10^{7} beam particles / second (arbitrary, can be scaled)
Annual intensity: 4.6×10^{14} beam particles (arbitrary, can be scaled)

Cooling times: 1 hour, 12 hours, 1 day, 1 week, 1 month, 4 months

Beam impact: x = 0, y = 1 cm (*i.e.,* 4 mm from edge of jaw)
[x = 0, y = 0.61 cm (*i.e.,* 100µm)]



Transport thresholds:

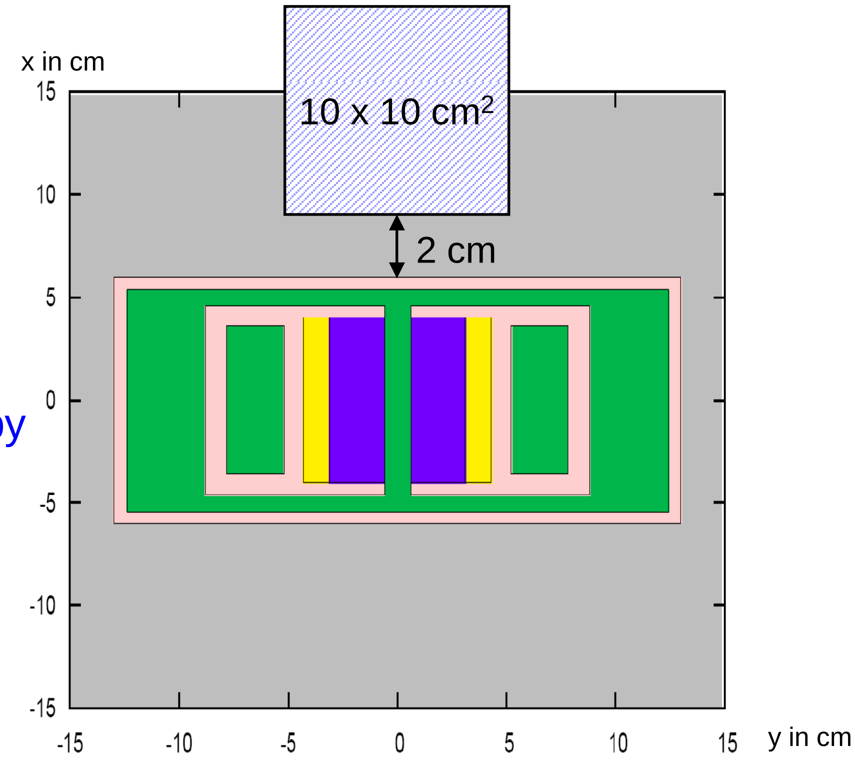
hadrons - until stopped
$e^{\pm}$ (residual radiation) - 100 keV
photons (residual radiation) - 10 keV

FLUKA Simulations – *Scoring*

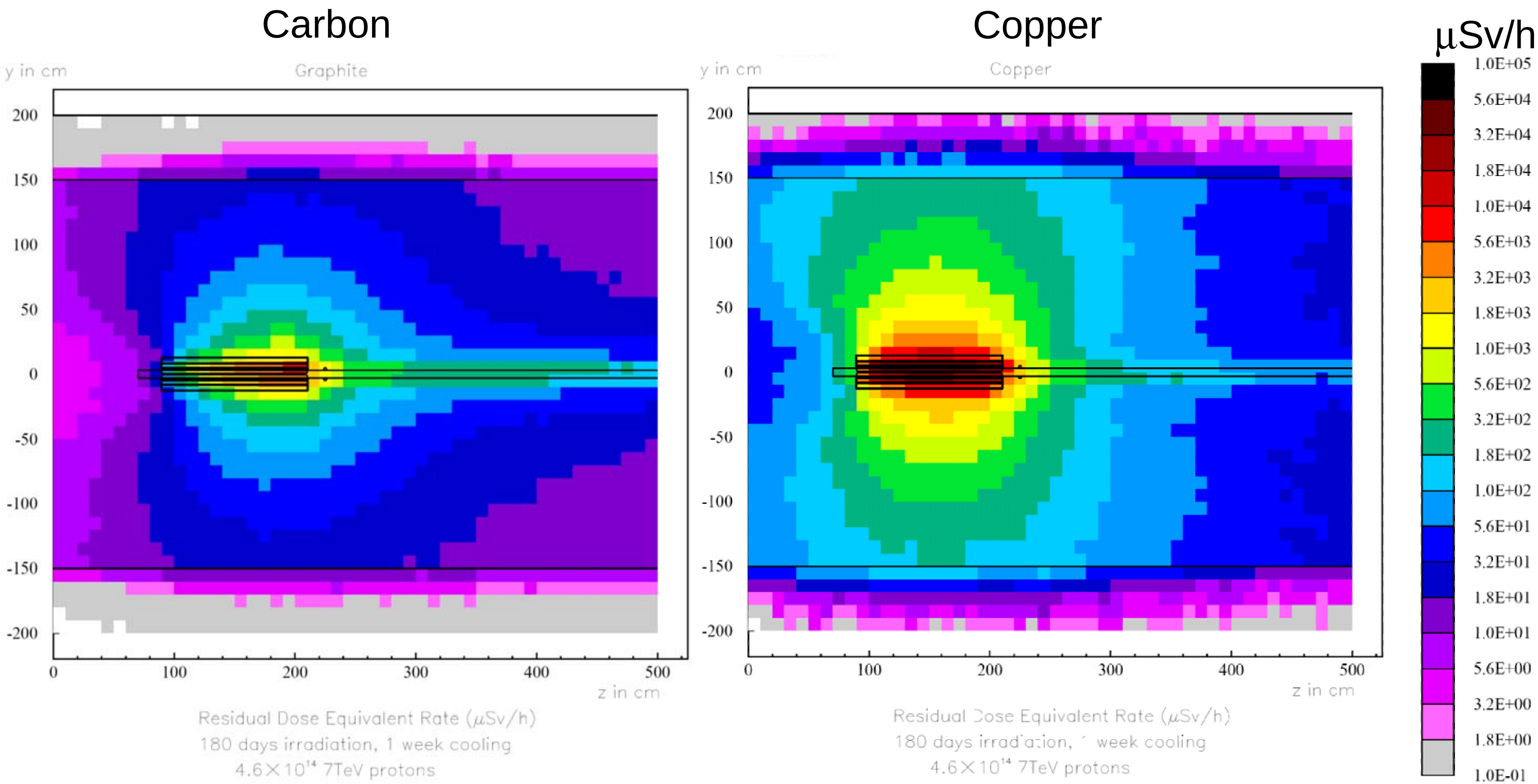
- Scoring of residual ambient dose equivalent rate in

  1) 2D binning for horizontal section of ± 5cm around beam axis (for overview)
  2) 1D-binning in bins of 10 x 10 x 10 cm^3 above tank and along entire collimator length (for detailed analysis)

- Scoring of total dose rate *and* of contributions by individual radio-nuclides for 2)



Residual Dose Rates - *Overview*

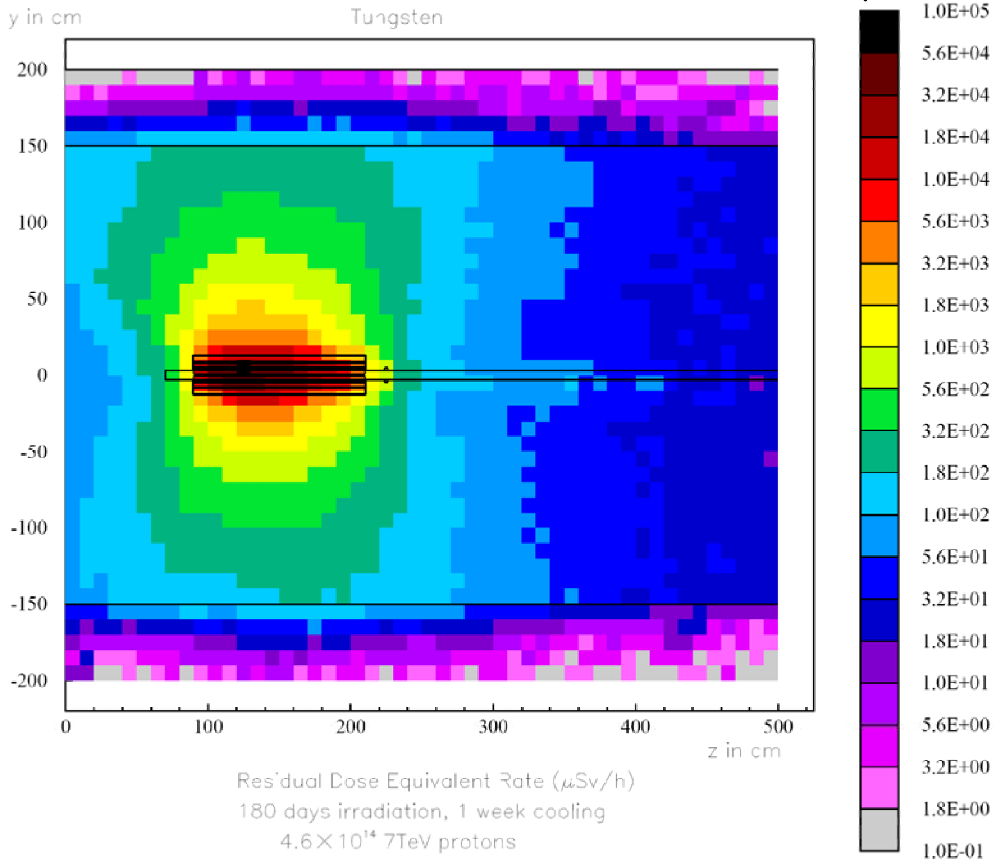


t_{cool} = 1 week

Residual Dose Rates - *Overview*

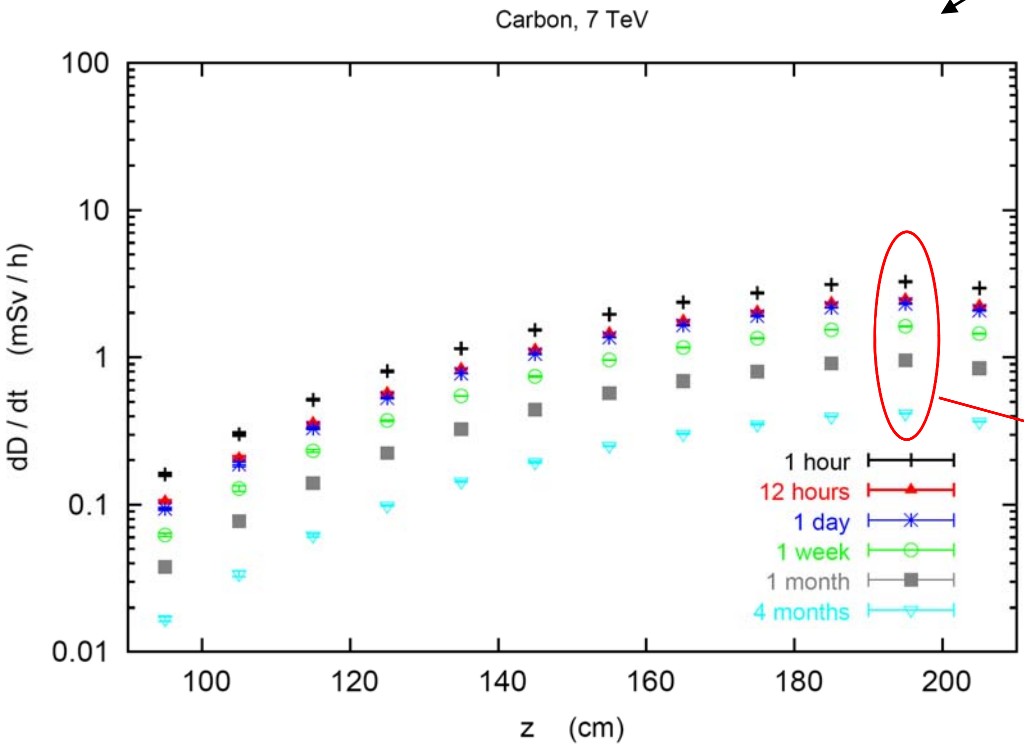
Tungsten

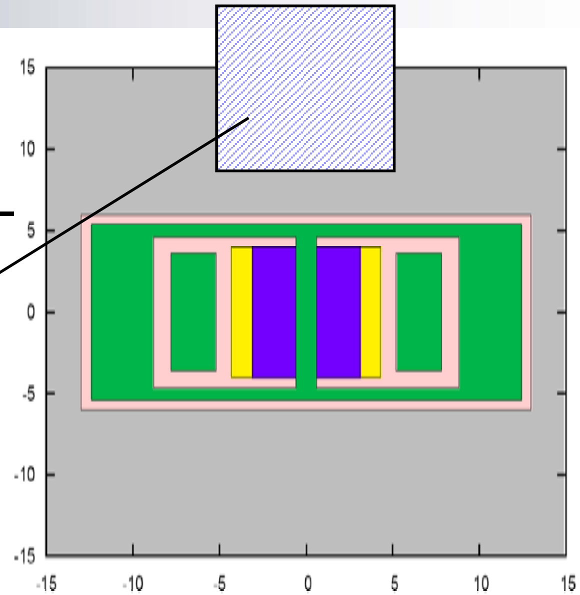
µSv/h



t_{cool} = 1 week

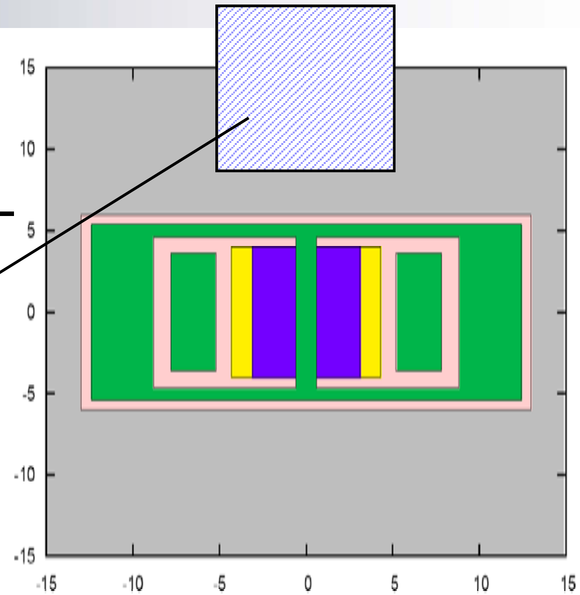
Residual Dose Rates - *Carbon*

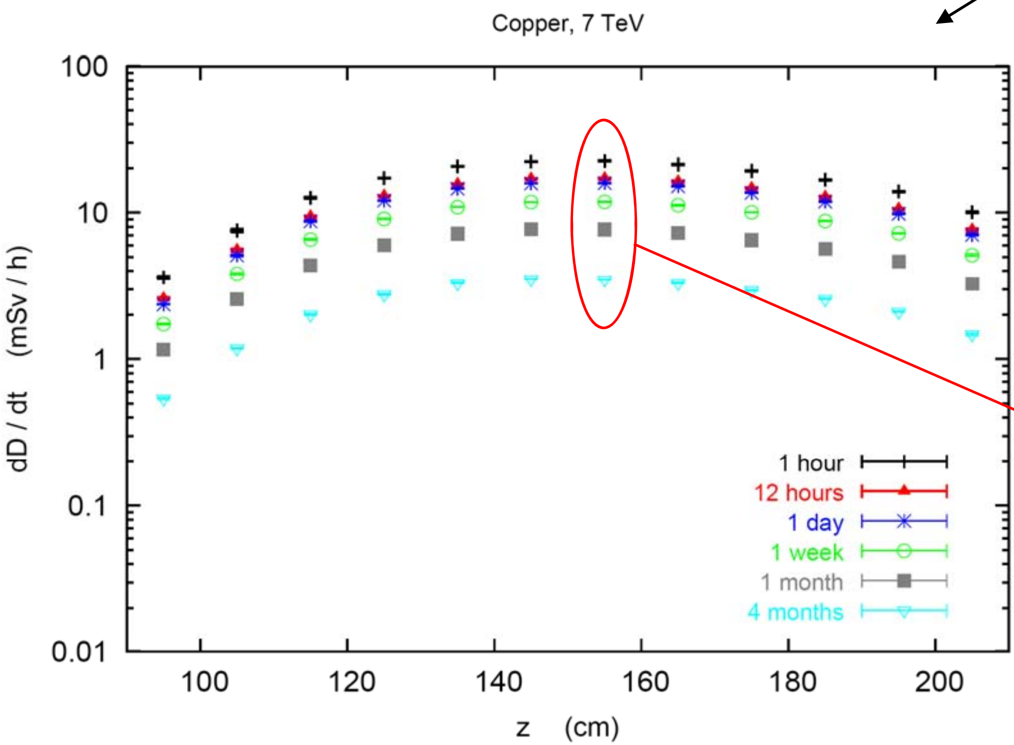




t_{cool}	(mSv/h)
1 hour	3.3
12 hours	2.5
1 day	2.3
1 week	1.6
1 month	0.96
4 months	0.42

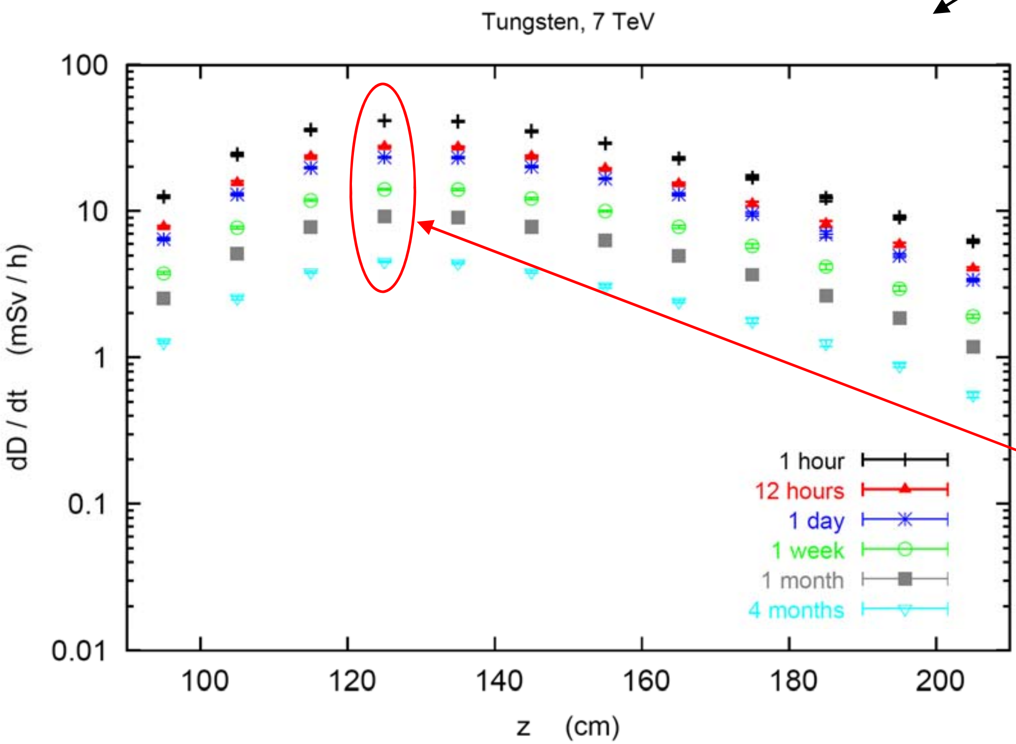
Residual Dose Rates - *Copper*

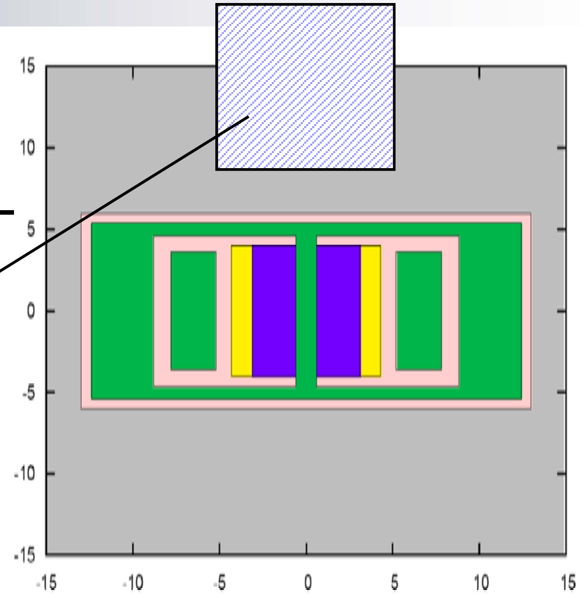




t_{cool}	(mSv/h)
1 hour	22.5
12 hours	17.2
1 day	15.9
1 week	11.8
1 month	7.7
4 months	3.5

Residual Dose Rates - *Tungsten*





t_{cool}	(mSv/h)
1 hour	41.3
12 hours	27.4
1 day	23.2
1 week	14.0
1 month	9.2
4 months	4.5

Scaling Results – *Cooling Time*

Ratios of dose rate maxima $D(t_{cool})/D(1day)$

	C 450GeV	C 7TeV	Cu 450GeV	Cu 7TeV	W 450GeV	W 7TeV
1 hour	**1.42**	**1.42**	**1.41**	**1.41**	**1.77**	**1.78**
12 hours	**1.07**	**1.07**	**1.08**	**1.08**	**1.18**	**1.18**
1 day	1.00	1.00	1.00	1.00	1.00	1.00
1 week	**0.71**	**0.70**	**0.74**	**0.74**	**0.60**	**0.61**
1 month	**0.42**	**0.42**	**0.49**	**0.48**	**0.39**	**0.40**
4 months	**0.18**	**0.18**	**0.22**	**0.22**	**0.19**	**0.19**

- **similar radio-nuclides contribute at cooling times larger than one day**
- **in case of W jaws, different nuclides contribute at short cooling time as compared to C or Cu jaws**

Scaling Results – *Jaw Material*

Ratios of dose rate maxima

t_{cool}	450 GeV		7 TeV	
	C/Cu	W/Cu	C/Cu	W/Cu
1 hour	0.24	1.77	0.15	1.84
12 hours	0.24	1.54	0.14	1.59
1 day	0.24	1.41	0.14	1.46
1 week	0.23	1.13	0.14	1.19
1 month	0.20	1.12	0.12	1.19
4 months	0.20	1.21	0.12	1.28

cascade not fully developed

Scaling Results – *Beam Energy*

Beam Energy: $R = (D(E_1)/D(E_2))^x$

		C	Cu	W
450GeV / 7TeV	R	0.18	0.11	0.10
	x	0.63	0.82	0.83
2.6TeV / 7TeV	R	0.55	0.52	0.52
	x	0.61	0.83	0.83

↑ cascade not fully developed

Scaling Results – *Projectile*

Beam Particle: $R = A_2/A_1$

Ratios of dose rate maxima, Protons with 2.6 TeV, ^{208}Pb with 2.6 TeV/n

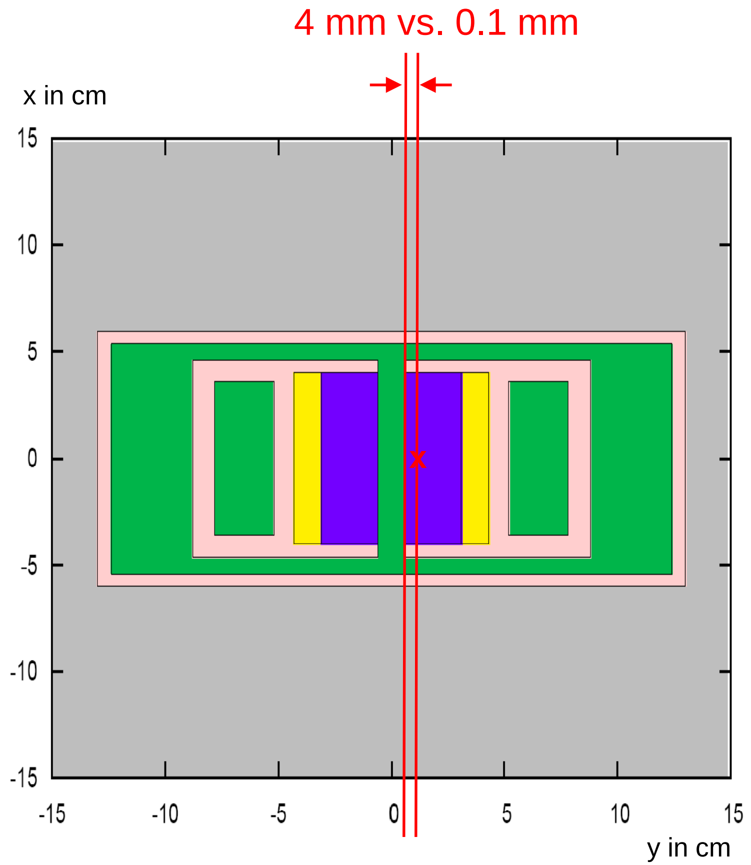
t_{cool}	Carbon Pb/p(2.6TeV)	Copper Pb/p (2.6 TeV)
1 hour	205.0	211.0
12 hours	206.4	211.6
1 day	206.5	212.1
1 week	205.1	213.6
1 month	204.5	213.5
4 months	206.1	212.4

Effect of Impact Parameter (distance from jaw edge)

Ratios of dose rate maxima

D(4mm)/D(0.1mm)

1 hour	1.64
12 hours	1.64
1 day	1.64
1 week	1.64
1 month	1.63
4 months	1.63



- in case of 0.1mm impact significant contribution of secondary particles escapes through (large!) gap between jaws

Contributing Radio-Nuclides - *Carbon*

Contribution to total dose rate at maximum in percent

(only main contributors causing 90% of the total dose rate are listed)

1 hour		12 hours		1 day		1 week		1 month		4 months	
V 048	18.99	V 048	24.66	V 048	25.67	V 048	29.06	Co056	30.64	Mn054	33.41
Mn052	14.23	Mn052	17.82	Mn052	17.94	Co056	21.39	Mn054	17.88	Co056	31.20
Co056	11.61	Co056	15.28	Co056	16.56	Mn052	12.29	V 048	17.87	Co058	15.38
Co058	6.35	Co058	8.35	Co058	9.05	Co058	12.00	Co058	16.21	Sc046	10.47
Sc044	5.83	Mn054	7.48	Mn054	7.95	Mn054	11.05	Sc046	9.56	...	
Mn054	5.68	Ni057	4.88	Sc046	5.17	Sc046	7.02			*Be007	0.86
*C 011	5.36	Sc046	4.78	Ni057	4.10						
Mn056	4.71	Sc044	4.30	Sc044	3.59						
Ni057	4.68	Co055	1.58	...							
Sc046	3.76	Sc048	1.20	*Be007	0.74						
Co055	1.87										
Mn312	1.27										
Sc048	1.12										
Ti045	1.08										
Cu061	1.02										
Na024	0.92										
Cr049	0.91										
Nb090	0.88										

* contribution by jaws

Contributing Radio-Nuclides - *Carbon (iron tank and structure)*

Contribution to total dose rate at maximum in percent

(only main contributors causing 90% of the total dose rate are listed)

1 hour		12 hours		1 day		1 week		1 month		4 months	
V 048	21.88	V 048	29.71	V 048	31.34	V 048	34.59	Mn054	33.43	Mn054	59.74
Mn052	20.61	Mn052	27.33	Mn052	27.44	Mn054	18.76	V 048	23.79	Co056	16.94
Mn054	9.01	Mn054	12.62	Mn054	13.27	Mn052	18.64	Co056	17.55	Sc046	12.79
Mn056	8.32	Co056	8.14	Co056	8.55	Co056	11.39	Sc046	12.55	Co058	5.42
Sc044	6.49	Sc046	5.55	Sc046	5.94	Sc046	7.95	Co058	6.15		
C 011	6.32	Sc044	5.03	Sc044	4.20						
Co056	5.88	Co058	2.86								
Sc046	3.95										
Co058	2.03										
Mn312	1.87										
Ti045	1.32										
Co055	1.26										
Cu061	1.24										

Ratio total dose for iron vs. stainless steel tank and structure:

1 hour	12 hours	1 day	1 week	1 month	4 months
0.84	0.79	0.80	0.79	0.72	0.76

Contributing Radio-Nuclides - *Copper*

Contribution to total dose rate at maximum in percent

(only main contributors causing 90% of the total dose rate are listed)

1 hour		12 hours		1 day		1 week		1 month		4 months	
+Co056	14.46	V 048	17.96	+Co056	19.53	+Co056	24.73	+Co056	30.70	+Co056	29.80
V 048	14.07	+Co056	17.88	V 048	18.38	+Co058	22.87	+Co058	28.20	Mn054	27.08
+Co058	12.93	+Co058	16.46	+Co058	17.83	V 048	19.34	Mn054	14.94	+Co058	25.24
Mn052	12.24	Mn052	15.05	Mn052	15.31	Mn054	10.36	V 048	11.26	Sc046	7.70
Mn056	5.82	Mn054	7.27	Mn054	7.89	Mn052	10.00	Sc046	7.26	*Co060	5.39
Mn054	5.56	Sc046	4.41	Sc046	4.79	Sc046	5.87				
*Cu061	4.27	+Ni057	4.14	+Ni057	3.50						
Sc044	4.07	Sc044	3.08	Sc044	2.54						
Ni057	3.85	*Cu064	1.84	*Co060	1.21						
Sc046	3.30	Sc048	1.32								
*Cu064	2.51	+Co055	1.22								
+Co055	1.60										
Na024	1.24										
Mn312	1.08										
Sc048	1.06										
*Co060	0.88										
Ti045	0.79										
Nb090	0.79										
Jaws: 38%		37%		36%		38%		41%		41%	

* contribution by jaws
\+ partial contribution by jaws

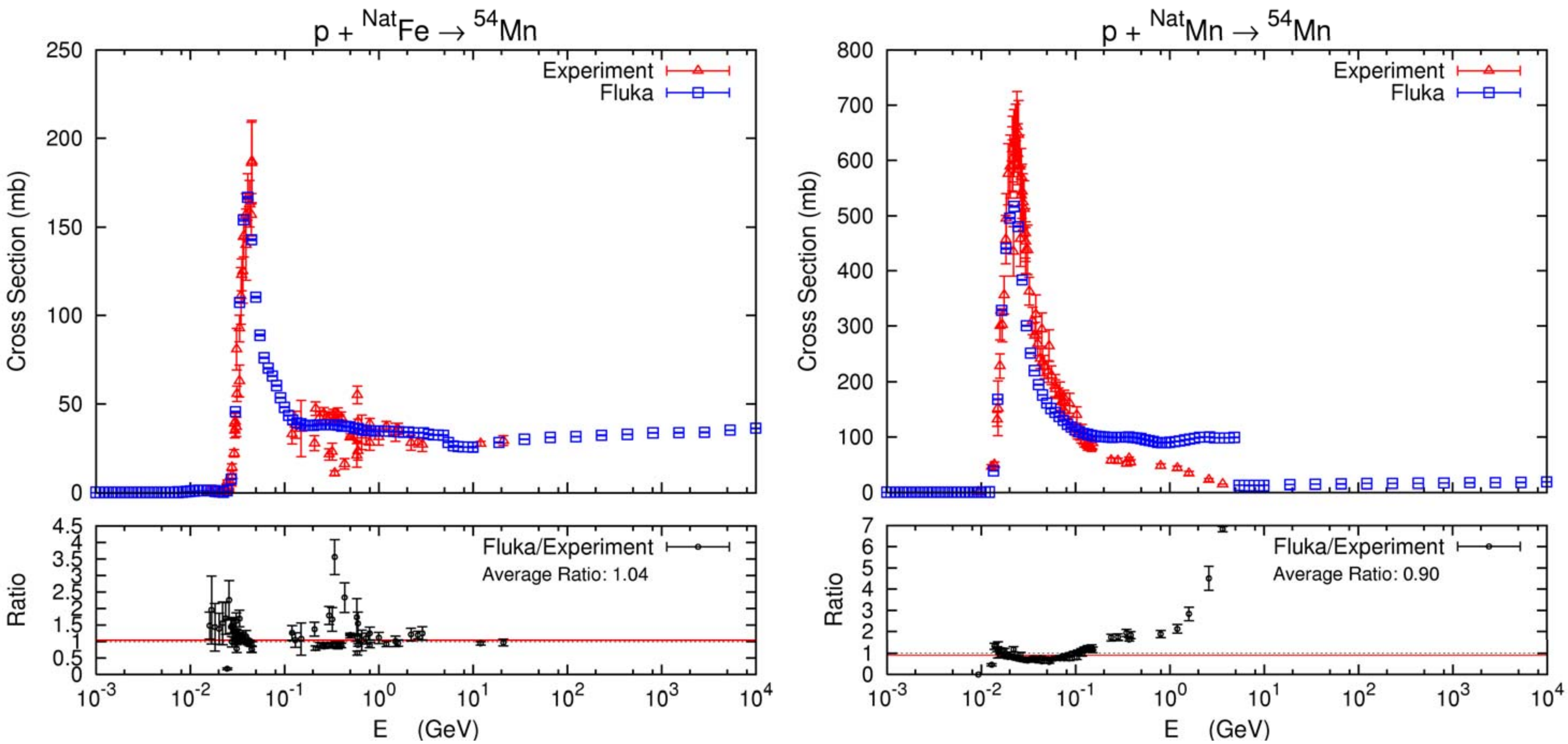
Contributing Radio-Nuclides - *Tungsten*

Contribution to total dose rate at maximum in percent

1 hour		12 hours		1 day		1 week		1 month		4 months	
*Hf171	21.00	*Hf171	20.40	Co058	13.92	Co058	26.24	Co058	32.39	Mn054	30.20
*Ho158	9.71	Co058	11.20	*Hf171	12.63	V 048	13.87	Mn054	18.44	Co058	26.56
*Ta176	9.19	V 048	7.22	V 048	10.33	Co056	13.48	Co056	16.76	Co056	16.43
Co058	6.26	Mn052	6.84	Mn052	8.59	Mn054	12.96	V 048	8.56	*Ta182	8.36
Mn056	4.68	*Ta176	6.84	*Lu170	8.56	Mn052	8.18	*Ta182	7.10	*Lu172	6.54
V 048	4.53	*Lu170	6.61	Co056	7.26	*Ta182	5.48	Sc046	3.97	Sc046	4.36
Mn052	4.16	Co056	6.49	Mn054	6.64	Sc046	3.82	*Lu172	3.73		
Co056	3.75	Mn054	5.36	*Ta176	3.53	*Lu172	2.86				
*Lu170	3.69	*Tm166	2.54	*Ta182	3.13	*Lu170	2.24				
Mn054	3.04	*Ta175	2.28	*Tm166	2.88	*Lu171	1.62				
*Ta175	2.71	*Ta182	2.22	Sc046	1.89						
*Lu168	1.75	Ni057	1.94	Ni057	1.88						
Ni057	1.64	Sc046	1.65	*Lu169	1.79						
*Tm166	1.23	*Lu169	1.61	*Lu172	1.63						
*Ta182	1.18	*W 187	1.24	*Lu171	1.30						
*Lu169	1.11	*Lu172	1.23	*W 187	1.26						
*W 187	1.04	*Lu171	1.19	*Ta175	1.18						
Sc044	1.02	Sc044	0.89	Sc044	1.08						
*Ta174	0.84	*Ho158	0.67	Y 088	0.87						
*Ta172	0.75	Y 088	0.60								
Sc046	0.73	Nb090	0.53								
*Lu172	0.68	Na024	0.50								
(truncated)											
Jaws:	68%		54%		41%		18%		15%		18%

* contribution by jaws

Evaluated FLUKA Production Cross-Sections – ^{54}Mn



CERF Benchmark: 1.01, 0.90

Applications – *Intervention Planning and Optimization*

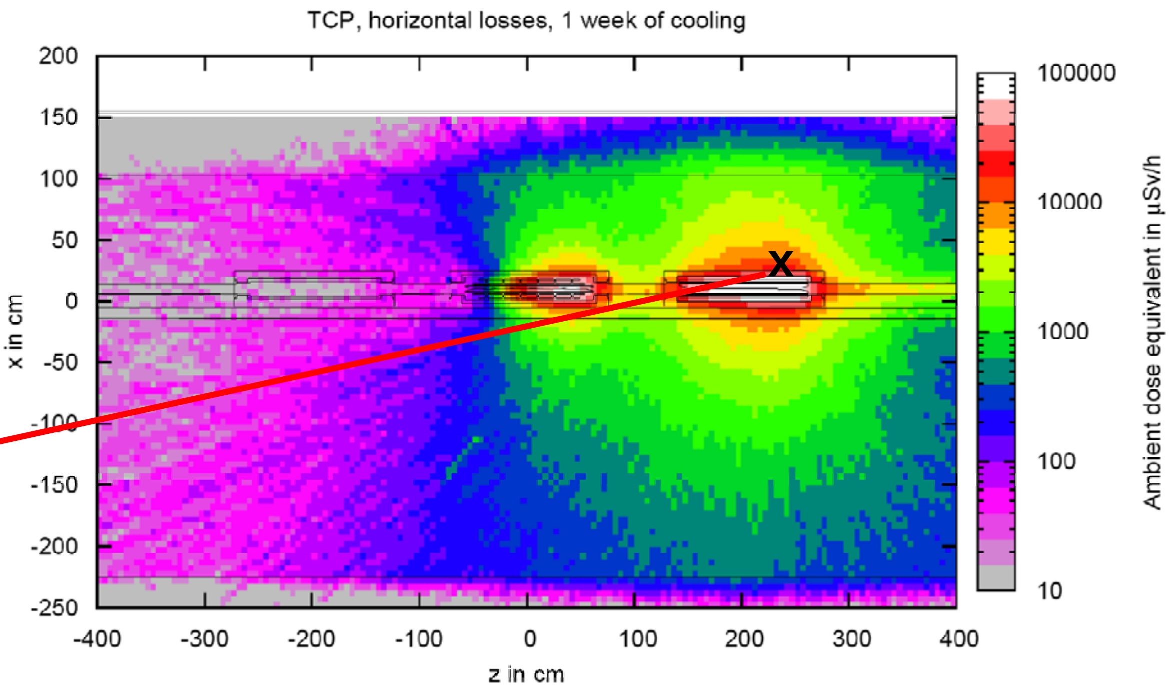
- **Detailed Geometry description** including the correct source terms (*e.g.*, primary loss distribution)
- **Monte-Carlo simulation** to calculate dose rate maps for the relevant geometry and various cooling times, including
- Compilation of **intervention scenarios** together with the corresponding groups
  - Time, location and frequency of the intervention
  - Number of persons involved
  - Typical cooling period before intervention
  - Steps of the intervention and respective time and location estimate
  - Annual frequency of the intervention
- Calculation of **individual and collective doses**
- **Iteration and optimization**
- Possible **scaling** in case of design modifications

Application Example - *Collimation Regions (IR7)*

Dedicated simulation:

Maximum residual dose rate lateral to the TCP tank

t_{cool}	(mSv/h)
1 hour	~50
12 hours	~30
1 day	~22
1 week	~10
1 month	~7
4 months	~4



Application Example - *Collimation Regions (IR7)*

t_{cool}	dedicated simulation 7TeV, C (mSv/h)	this study 7TeV, C (mSv/h)	intensity scaling (+impact) (mSv/h)
1 hour	~50	2.1	31.4
12 hours	~30	1.6	23.8
1 day	~22	1.4	21.9
1 week	~10	1.0	15.2
1 month	~7	0.5	9.1
4 months	~4	0.3	4.0

x25.0/1.64 →

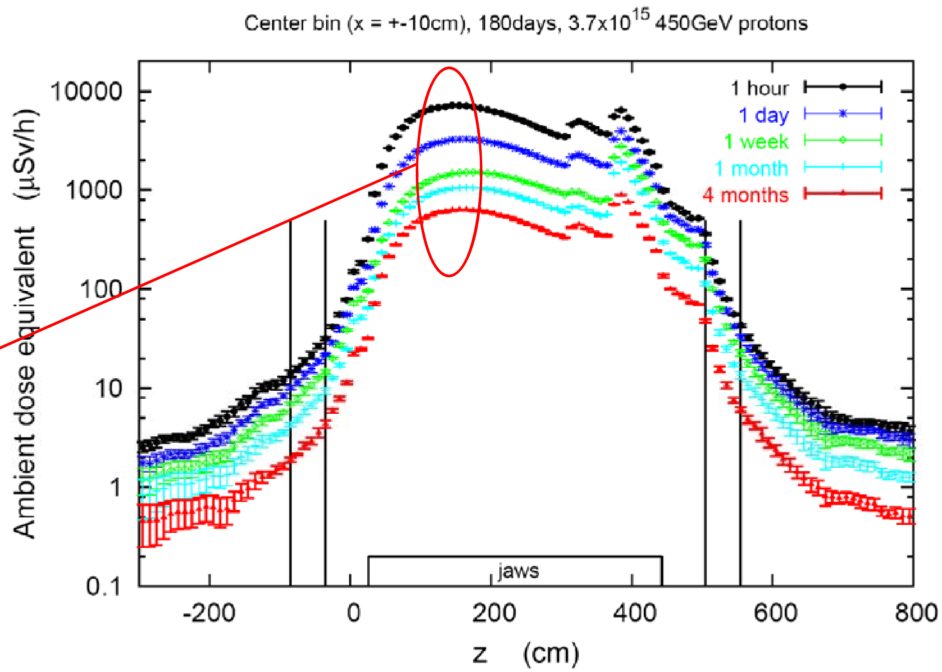
agree well within ~50%

Application Example - *TDI absorber*

Dedicated simulation:

maximum residual dose rate above Be-part of absorber

t_{cool}	(mSv/h)
1 hour	7.15
12 hours	4.36
1 day	3.27
1 week	1.51
1 month	1.06
4 months	0.63



Application - *TDI absorber*

t_{cool}	dedicated simulation 450GeV, Be (mSv/h)	this study 450GeV, C (mSv/h)		intensity scaling (mSv/h)
1 hour	7.15	0.57		4.58
12 hours	4.36	0.43		3.46
1 day	3.27	0.40	x37.0/4.6 →	3.22
1 week	1.51	0.28		2.25
1 month	1.06	0.17		1.37
4 months	0.63	0.74		0.59

agree well within ~50%

Summary

- Extensive **isotope production and residual dose rate benchmarks successfully performed with FLUKA** give us confidence in the obtained results of design and preliminary intervention calculations
- A **generic study of residual dose rates** to be expected around collimator-like objects allowed to determine scaling factors for
  - **various cooling times**
  - **different absorber materials**
  - **distinct beam energies**
  - **beam impacts and loss conditions**
- This allows for getting **quick and reliable (~50%) estimates** for residual dose rates expected close to the most activated accelerator components
- The here shown results are intended **to be extended to different loss assumptions and other generic geometries**
  - **important during LHC commissioning and early operation**