Material Choices: Radiation Constraints

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Radiation constraints

- Prompt radiation

  air and water activation

  dose to population and personnel

  damage of components

  dose to personnel during repair, downtime of accelerator due to repair

- Induced radioactivity

  residual dose rates

  dose to personnel during work, downtime of accelerator due to cooling time

  radioactive waste disposal

  dose to population, long-term costs

→ The material selection must take into account *activation and structural damage properties*.

Generic studies are most efficient to obtain order-of-magnitude and relative answers

(The following has been studied in collaboration with M.Brugger and D.Forkel-Wirth and presented at Workshop for Collimators and Beam Absorbers, CERN, Sep. 2007)

Generic FLUKA Simulations – *Geometry and Materials*

Collimator length: 120 cm

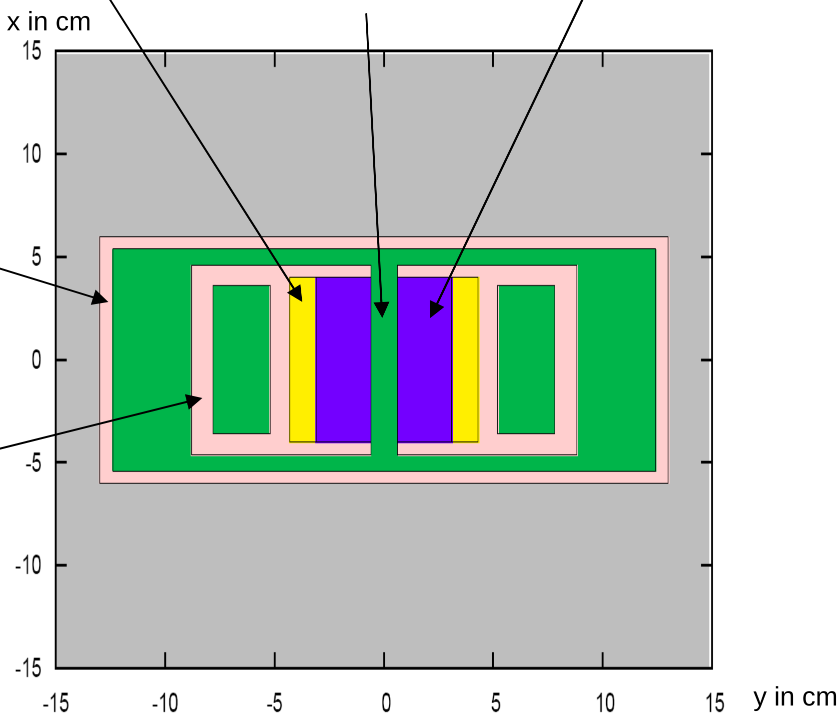
Cooling system
Copper (scaled density)
15 x 80 mm^2

Jaws
C, Cu, W
25 x 80 mm^2

Gap
Full width: 12mm

Tank
Stainless Steel
Thickness: 6 mm

Structure
Stainless Steel
Thickness: 6/10 mm



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

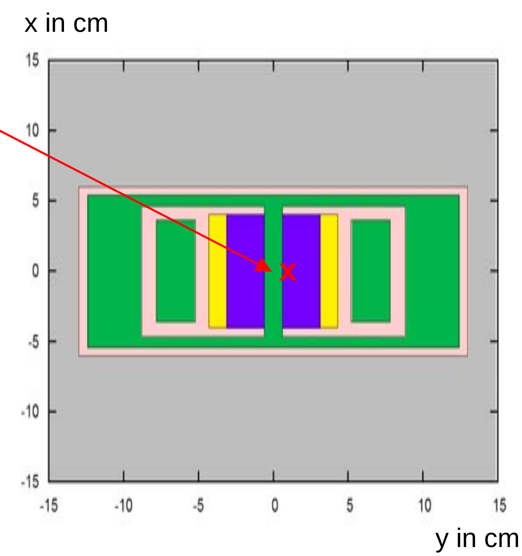
Generic FLUKA Simulations – *Irradiation Conditions*

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:

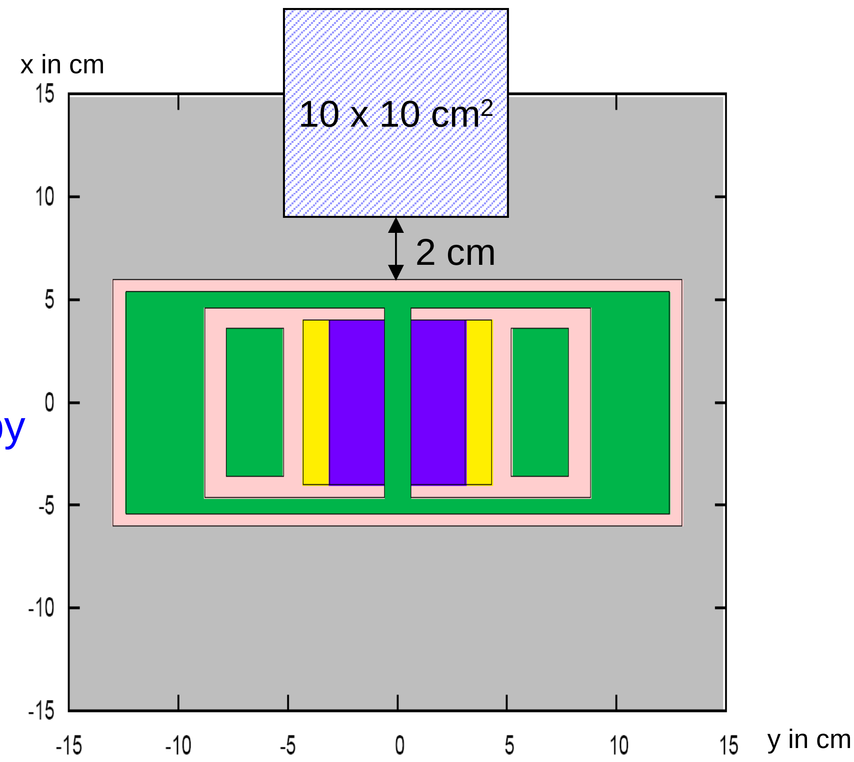
hadrons	-	until stopped
$e^{\pm}$ (residual radiation)	-	100 keV
photons (residual radiation)	-	10 keV

FLUKA Simulations – *Scoring*

- Scoring of residual ambient dose equivalent rate in

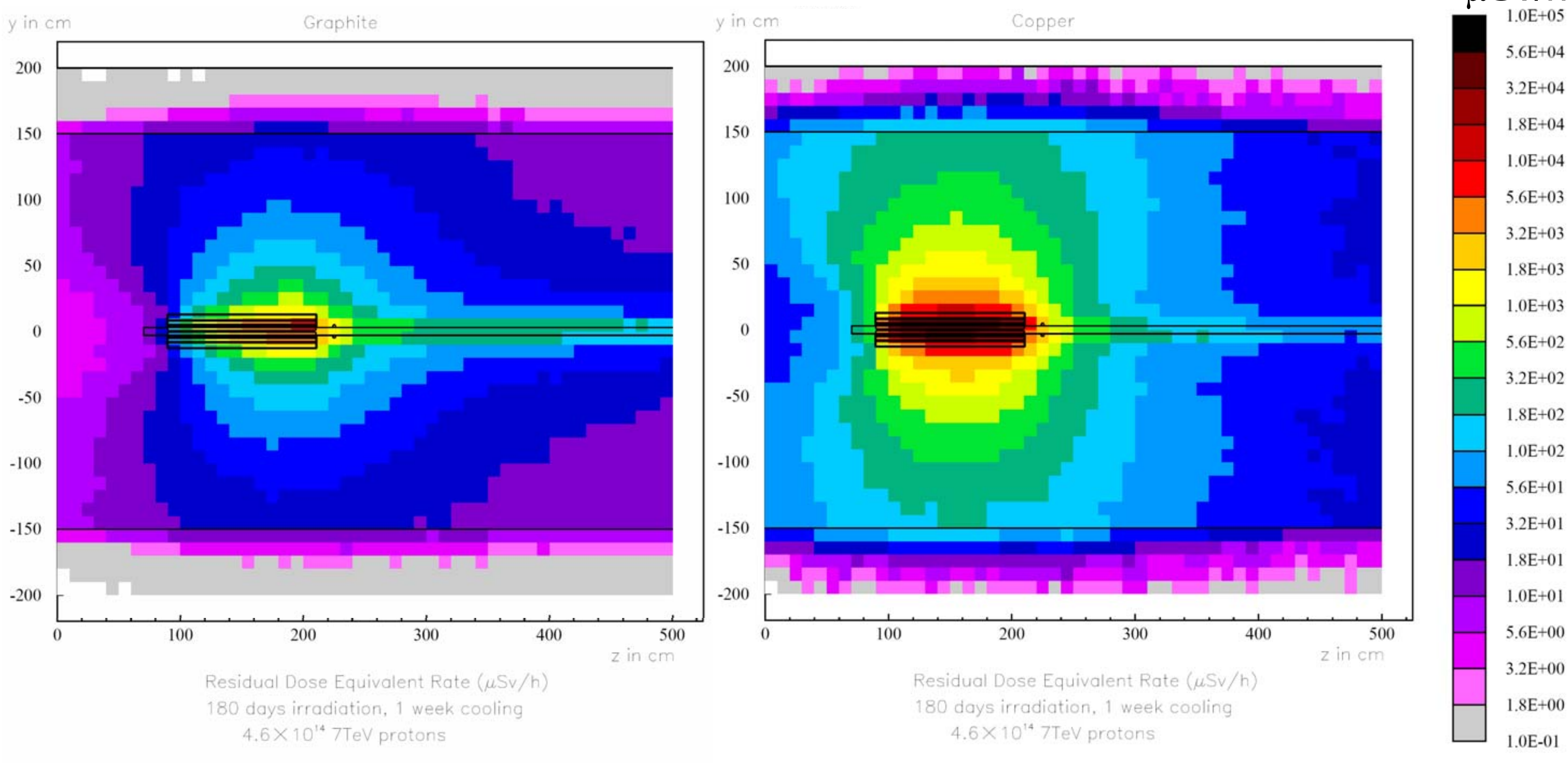
  1) 2D binning for horizontal section of ± 5cm around beam axis (for overview)
  2) 1D-binning in bins of 10 x 10 x 10 cm³ above tank and along entire collimator length (for detailed analysis)

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



Residual Dose Rates - *Overview*

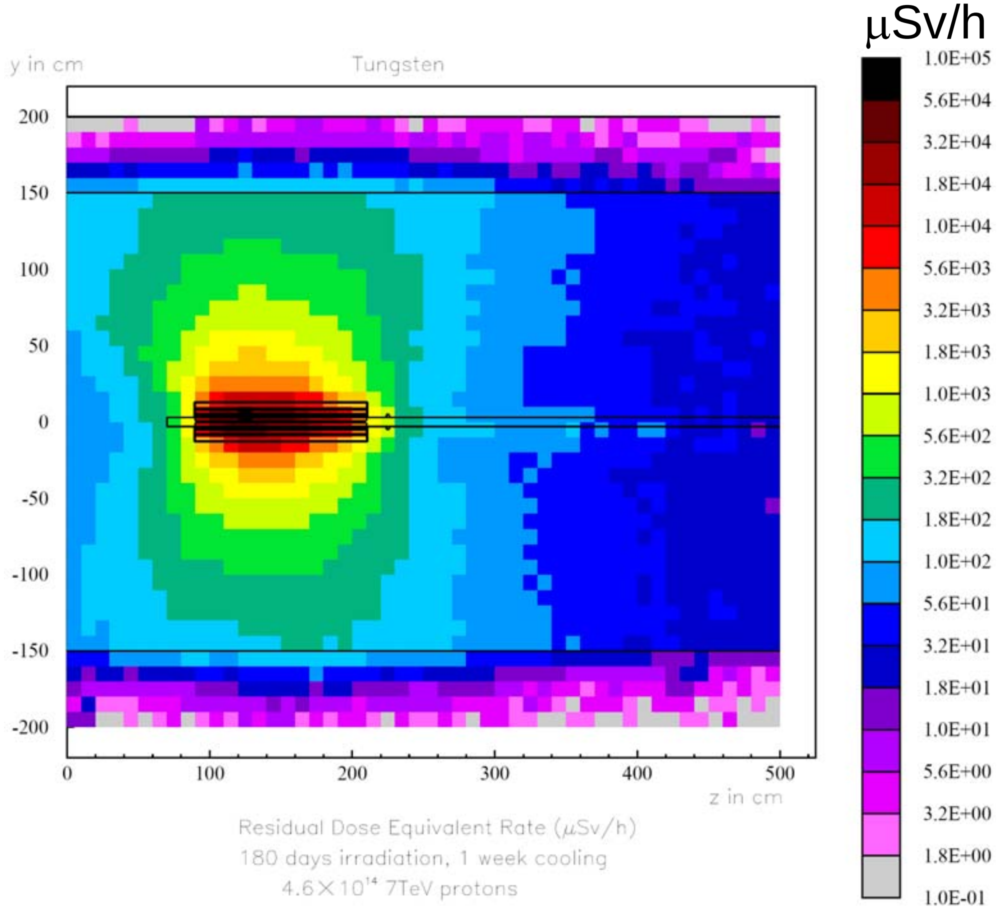
Carbon	Copper	μSv/h



t_{cool} = 1 week

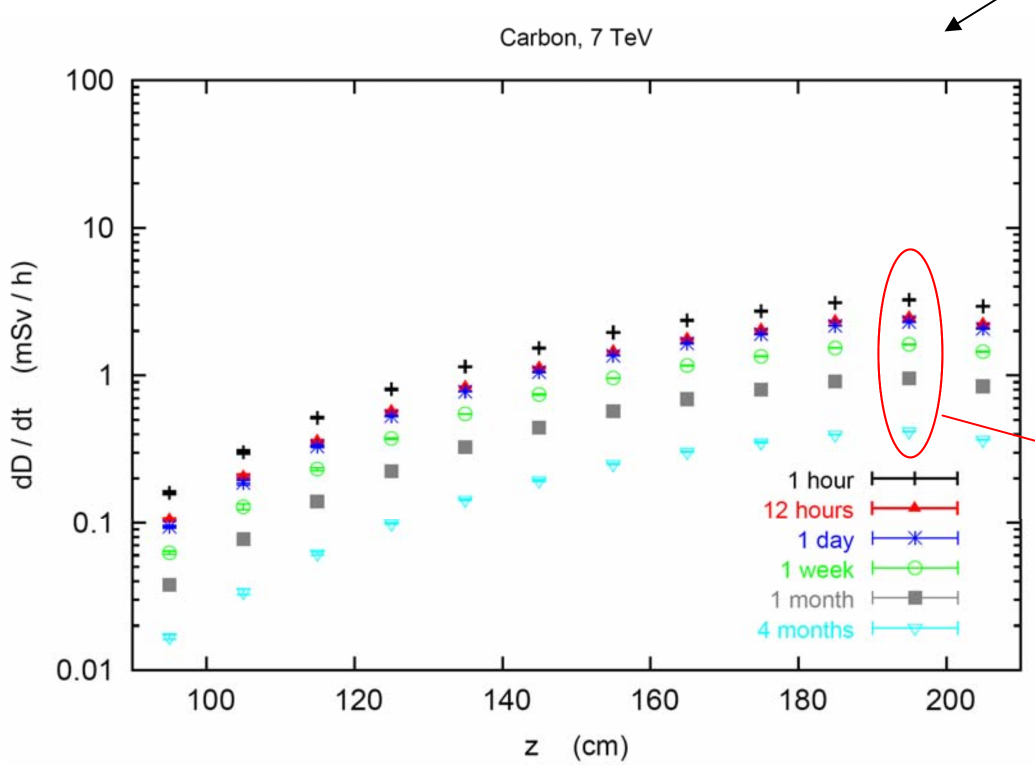
Residual Dose Rates - *Overview*

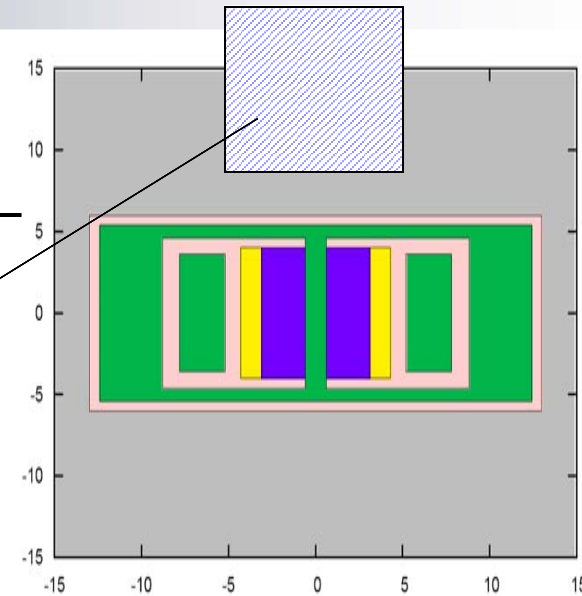
Tungsten



t_{cool} = 1 week

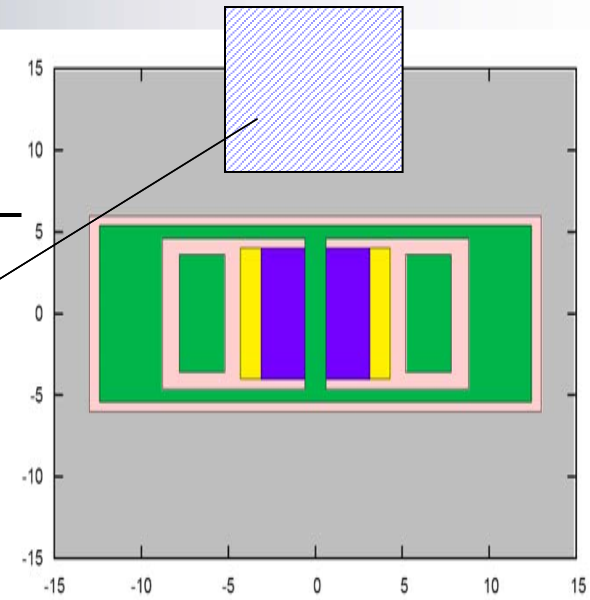
Residual Dose Rates - *Carbon*

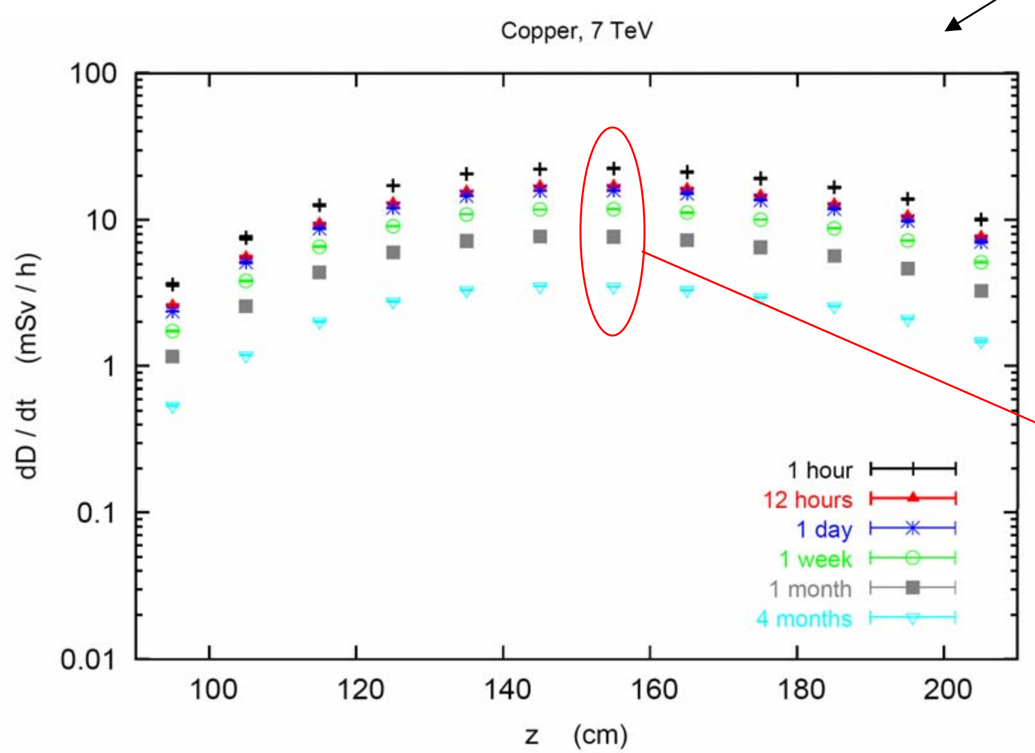




t_{cool}	(mSv/h)
1 hour	3.3
12 hours	2.5
1 day	2.3
1 week	1.6
1 month	0.96
4 months	0.42

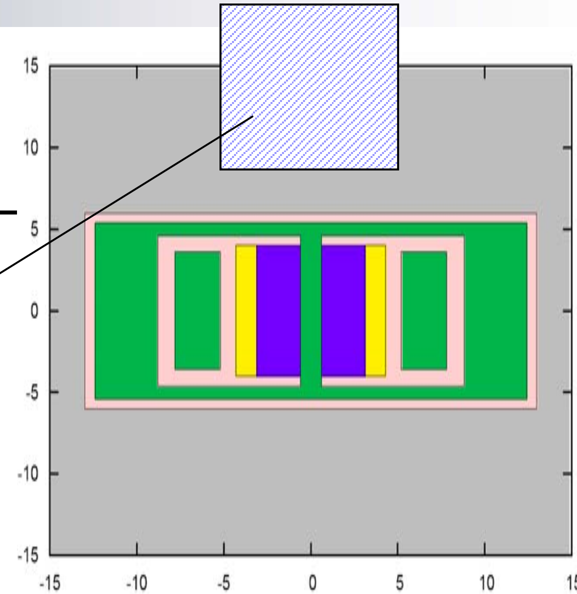
Residual Dose Rates - *Copper*

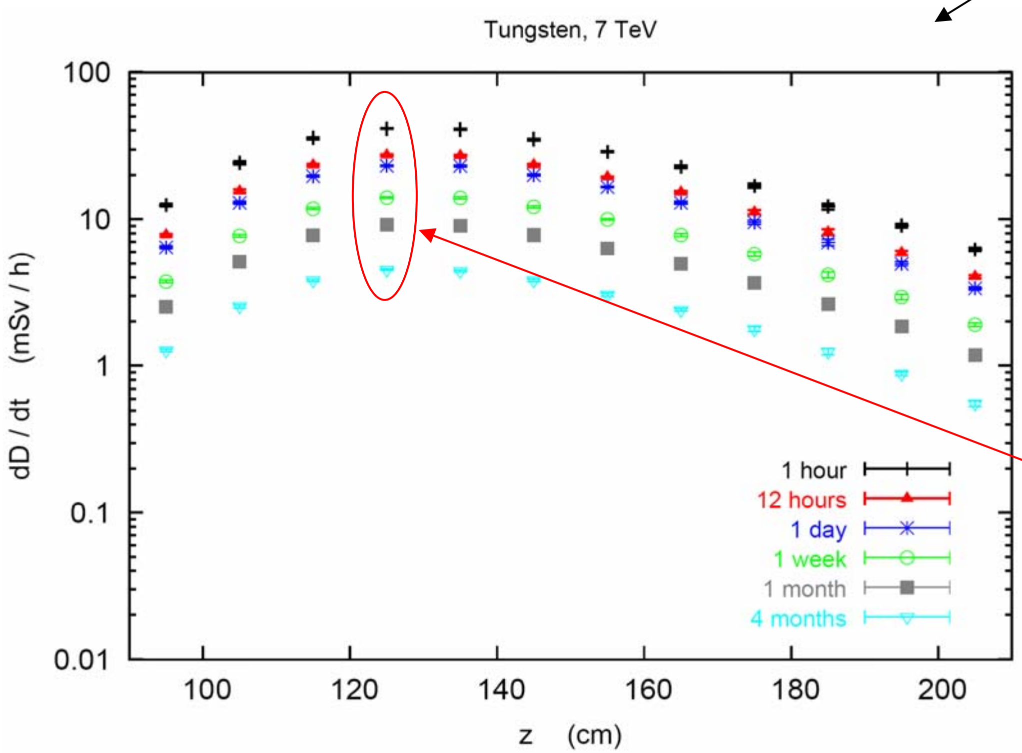




t_{cool}	(mSv/h)
1 hour	22.5
12 hours	17.2
1 day	15.9
1 week	11.8
1 month	7.7
4 months	3.5

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		Cu		W	
	450GeV	7TeV	450GeV	7TeV	450GeV	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 C/Cu	450 GeV W/Cu	7 TeV C/Cu	7 TeV 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

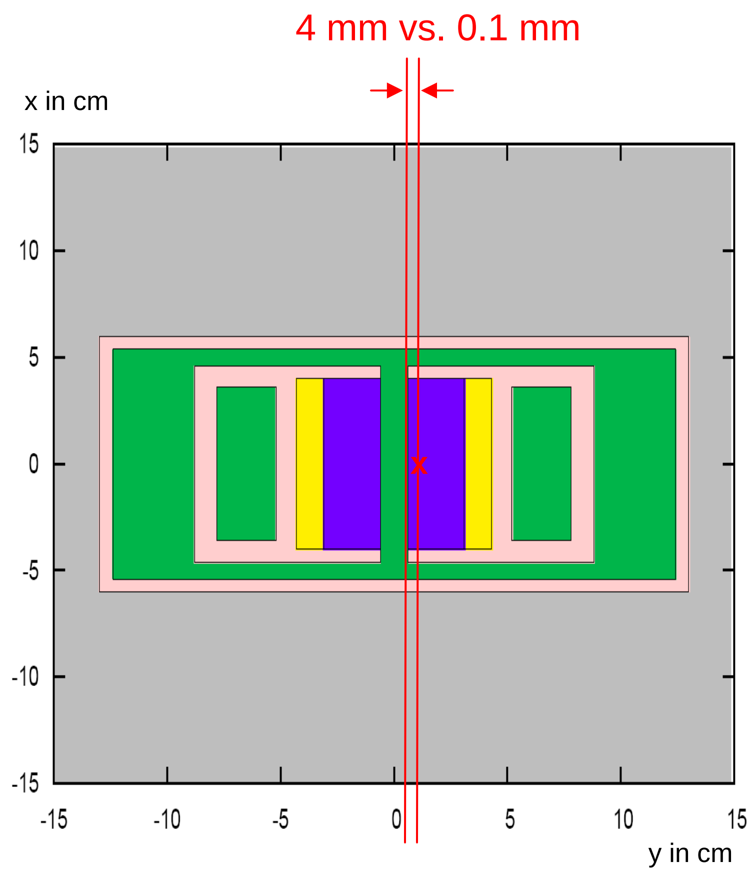
t_{cool}	Carbon Pb/p(2.6TeV)	Copper Pb/p (2.6 TeV)
1 hour	205.0	211.0
12 hours	206.4	211.6
1 day	206.5	212.1
1 week	205.1	213.6
1 month	204.5	213.5
4 months	206.1	212.4

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

Conclusions and recommendations

Residual dose rates

- The activated construction material of the collimator has a significant influence on many observables.
- Decrease of residual dose rate with cooling time beyond one day (up to four months) is similar for all studied cases (drop by a factor of five).
- Tungsten jaws lead to 20-30% higher dose rates than copper jaws and carbon jaws to a factor of ~five lower dose rates than for copper jaws.
- Residual dose rates scale with beam energy (if cascade is fully developed inside jaw) as $E^{0.83}$.
- Almost perfect scaling of residual dose rates with number of nucleons (for Pb beam).
- Some effect of the collimator aperture can be observed (secondary particles escape through gap).

Conclusions and recommendations

Long-term activation and radioactive waste

- Can be dominated by trace elements (*e.g.,* Co in iron) in both construction and jaw material. Thus, if there is a choice in an acceptable cost range consider elemental composition and consult RP in case of doubt. In any case record detailed composition of *all* components.
- Minimize the use of heavy material and avoid toxic material (alpha emitter, difficult and expensive waste treatment).

Others

- We can extend the generic study to include any materials which you consider.
- Of course, once the design is relatively stable they should be confirmed with more detailed simulations as done for Phase-1 collimators and passive absorbers.