Shielding design for RCS

Matteo Magistris, Marco Silari, Stefania Trovati

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Introduction

- Ambient dose equivalent rates: the CERN guidelines have been used.
- Beam intensities:
  - ^{6}He: $9.32*10^{11}$ particles/bunch
  - ^{18}Ne: $2.62*10^{11}$ particles/bunch
- Cycle rate 10 Hz
- For the yearly ion throughput the duty cycle has been considered: 1/3 for ^{6}He and 1/1.8 for ^{18}Ne.
- Losses: injection, decay, RF capture and acceleration losses.
- Shielding calculations: Monte Carlo simulations and analytical models.

Radiation areas: classification

Area classification	Ambient dose equivalent limit	Ambient dose equivalent rate guideline
Non-designated area	1 mSv y^{-1}	0.5 μSv h^{-1}
Supervised radiation area	6 mSv y^{-1}	3 μSv h^{-1}
Simple controlled radiation area	20 mSv y^{-1}	10 μSv h^{-1}

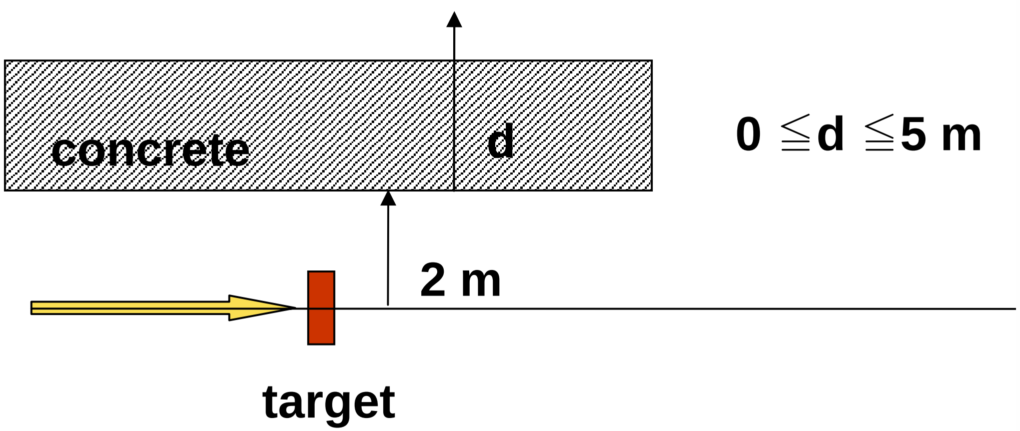
Methods

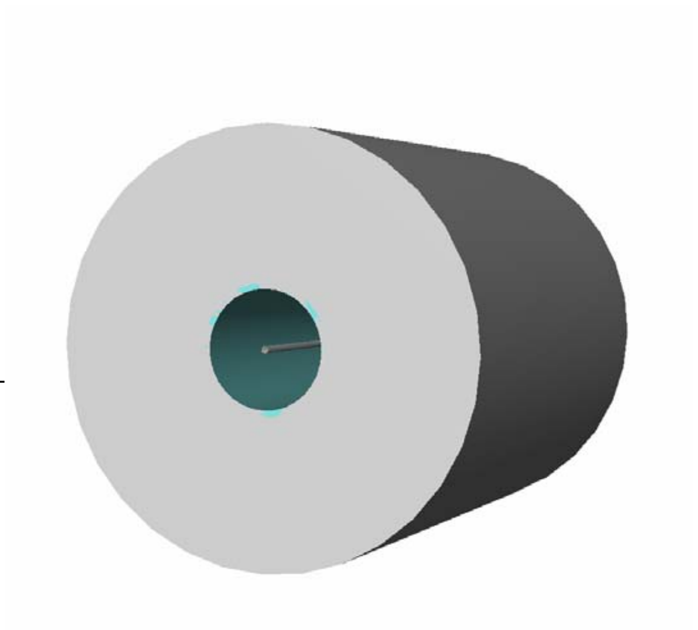
- Monte Carlo calculations (FLUKA) of ambient dose equivalents at 4 representative energies.
- Analytical calculations of attenuation lengths in concrete.
- Analytical calculations of shielding thicknesses for ambient dose equivalent rate guidelines.

	Energy MeV	Attenuation Length g cm^{-2}	Source term H_0 Sv m^{-2} per primary
He	100	61.6 ± 0.7	(1.68 ± 0.12)E-015
He	200	73.9 ± 0.7	(3.14 ± 1.48)E-015
He	400	94.1 ± 0.2	(3.69 ± 0.09)E-015
He	787	108.5 ± 0.9	(4.51 ± 0.14)E-015
Ne	100	58.4 ± 0.7	(1.15 ± 0.10)E-015
Ne	250	78.3±1.1	(5.79 ± 0.36)E-015
Ne	640	102.9±0.3	(9.72 ± 0.09)E-015
Ne	1650	113.7 ± 0.4	(12.22 ± 0.08)E-015

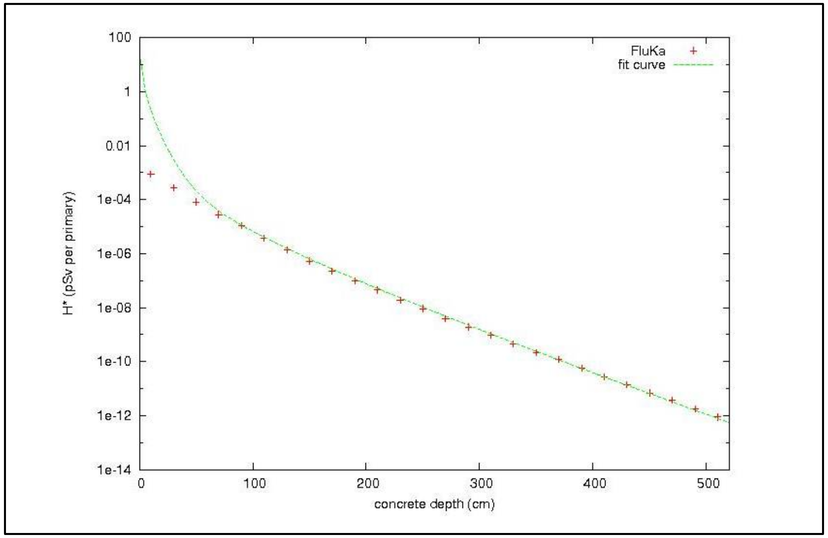
FluKa simulations

- Beam on a cylindrical copper target (r=10 cm ; dz= 0.5 cm)
- 2 mm thick iron beam pipe
- Air tunnel: r = 2 m
- Concrete (ρ = 2.35 g cm^{-3}) layer of 5 m, segmented in 20 cm slabs





Analytical calculations



The MC calculations can be parametrized using an exponential function of the form:

$$H = \frac{H_0}{(d+2)^2} \exp(-\frac{d}{\lambda})$$

From the fit we have H_0 (H extrapolated at 1 m distance from the source) and λ.

Loss assumptions

- Injection → 30% of the incoming beam
- RF capture and acceleration → ~ 16% ^{6}He, ~24 % ^{18}Ne
- Decay → ~ 3.8 % ^{6}He, ~1.4 % ^{18}Ne
- Beam-gas interaction → no losses
- Extraction → no losses

Injection losses (point losses)

30% of the beam is lost against the injection septum:

– ^{6}He

$0.3*(9.32*10^{12})/0.7 \approx 4*10^{12}$ part/s lost

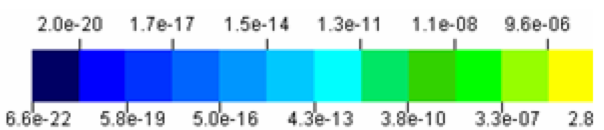
$$H^* = \frac{4\cdot10^{12}\cdot1.68\cdot10^{-15}\cdot3600}{(d+2)^2}\exp\left(-\frac{d}{0.26}\right)$$

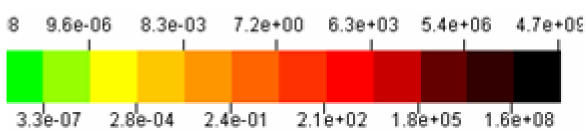
H_0 source term

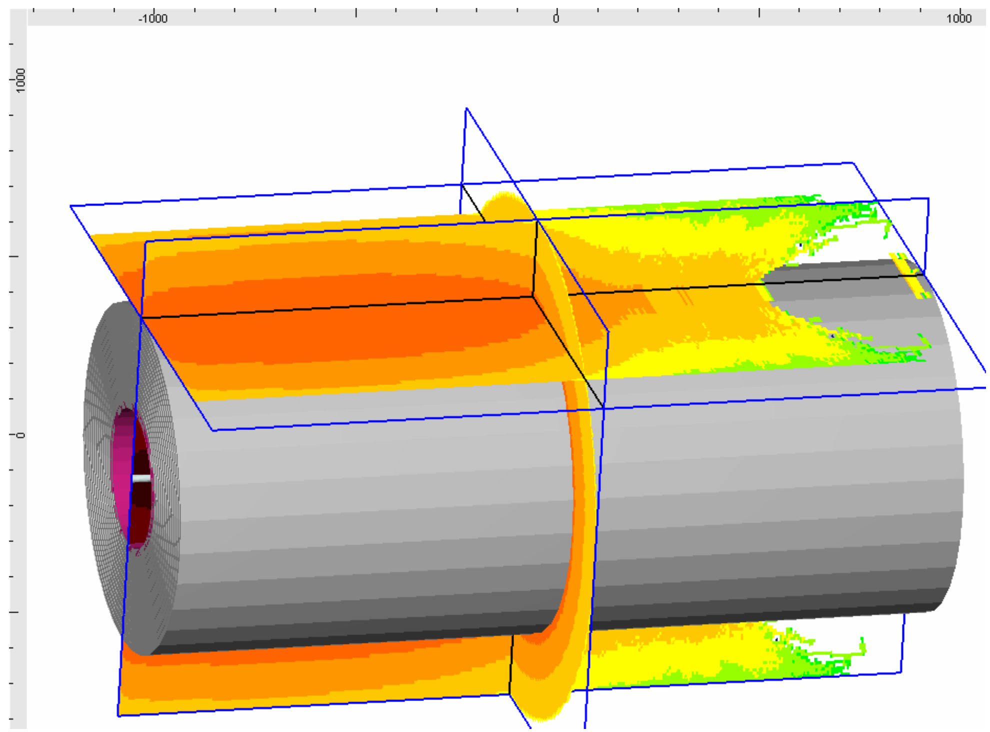
Seconds to hour conversion factor

Injection losses

Ambient dose equivalent rate limits (μSv h^{-1})	^{6}He Shielding thickness (cm)	^{18}Ne Shielding thickness (cm)
0.5	345	310
3	300	270
10	275	240







Decay losses

- Decay losses are distributed over straight sections and dipoles in the arcs (120 m).
- 3 energy intervals: the shielding is calculated for the sum of the 3 contributions.
- Analytical calculation:

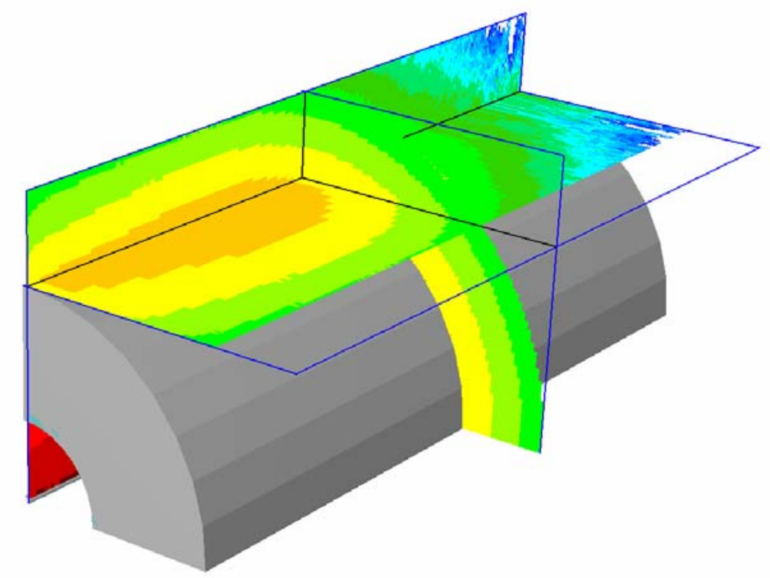
$$H^* = \frac{H_0 \cdot \%(lost\ \ part) \cdot 3600}{(d+2)^2} \cdot \frac{10}{120} \cdot \exp(-\frac{d}{\lambda})$$

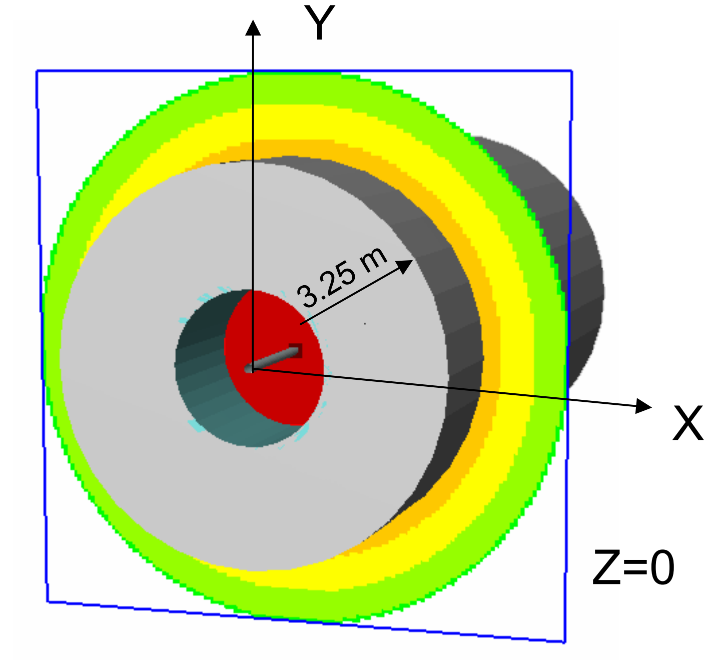
Approximation: a uniform beam loss of 1 W/m is equivalent to a point loss of 10 W every 10 m (in terms of shielding).

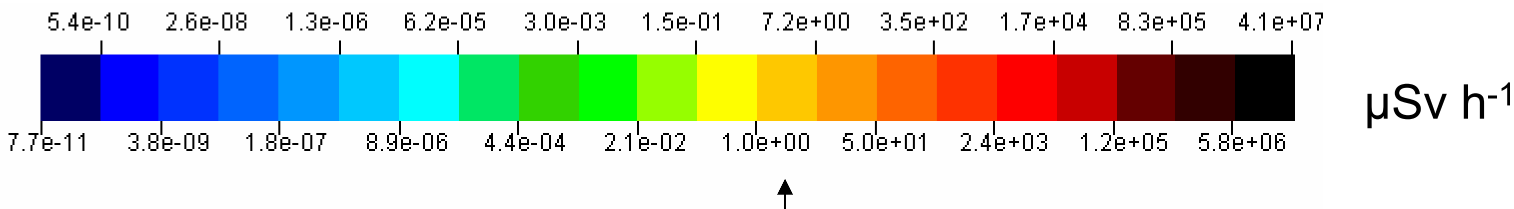
Decay losses %

	100-200MeV	200-400MeV	400-787MeV
He	1.00%	0.80%	1.80%
	100-250MeV	250-640MeV	640-1650MeV
Ne	0.45%	0.20%	0.70%

Ambient dose equivalent rate guidelines (μSv h^{-1})	^{6}He Shielding thickness (cm)	^{18}Ne Shielding thickness (cm)
0.5	390	375
3	325	305
10	275	255







- For a 325 cm shielding thickness we have ~3 μSv h^{-1}.
- The shielding provides an attenuation factor of 10^{-5} of the ambient dose equivalent rate.

RF capture and acceleration losses

✓All losses are concentrated in 6 points: QP1,QP2,QP3,QP4,QP5,QP6

✓3 energy intervals: the shielding is calculated for the sum of the 3 contributions.

^{6}He	100-200 MeV	200-400 MeV	400-787 MeV
QP1	1.00%	0.35 %	0.35 %
QP2	1.50%	1.00 %	1.40 %
QP3	0.50%	0.30 %	0.30 %
QP4	1.50%	0.50 %	1.40 %
QP5	1.20%	0.70 %	1.30 %

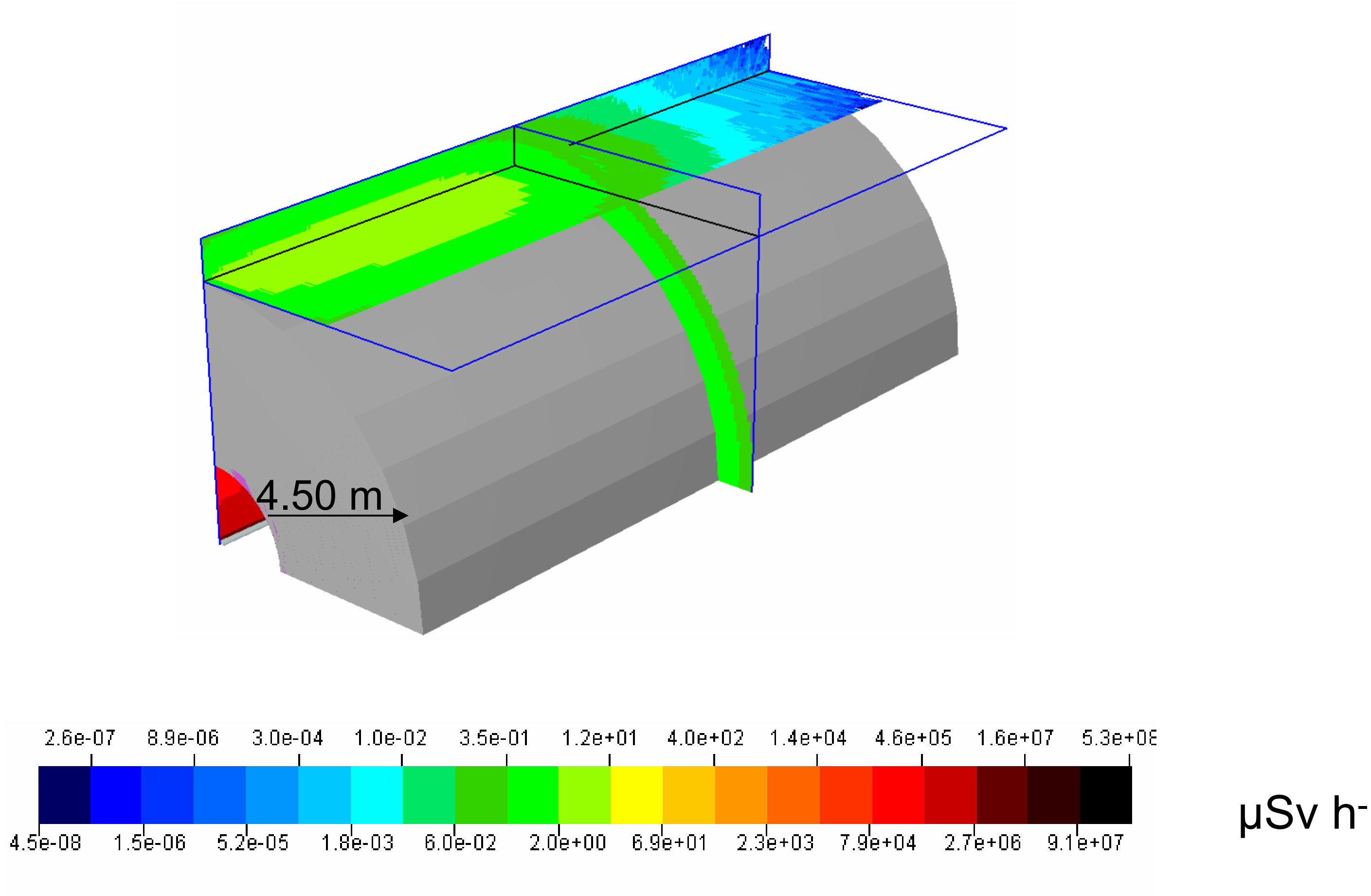
^{18}Ne	100-200 MeV	250-640 MeV	640-1650 MeV
QP1	2.35%	1.40 %	1.30 %
QP2	0.80%	0.95 %	0.30 %
QP3	1.50%	2.75 %	1.50 %
QP4	0.90%	0.75 %	0.40 %
QP5	2.85%	1.90 %	1.05 %
QP6	1.00%	0.75 %	0.50 %

RF capture and acceleration losses

	Limits *µSv h-1*	*Shield thickness (cm)* *He*	Shield thickness (cm) Ne
QP1	**0.5**	**430**	**515**
	3	**360**	**440**
	10	**315**	**390**
QP2	**0.5**	**480**	**470**
	3	**410**	**400**
	10	**365**	**350**
QP3	**0.5**	**420**	**525**
	3	**350**	**450**
	10	**305**	**405**
QP4	**0.5**	**480**	**470**
	3	**405**	**400**
	10	**360**	**350**
QP5	**0.5**	**475**	**510**
	3	**405**	**435**
	10	**360**	**390**
QP6	**0.5**	**-**	**475**
	3	**-**	**405**
	10	**-**	**355**

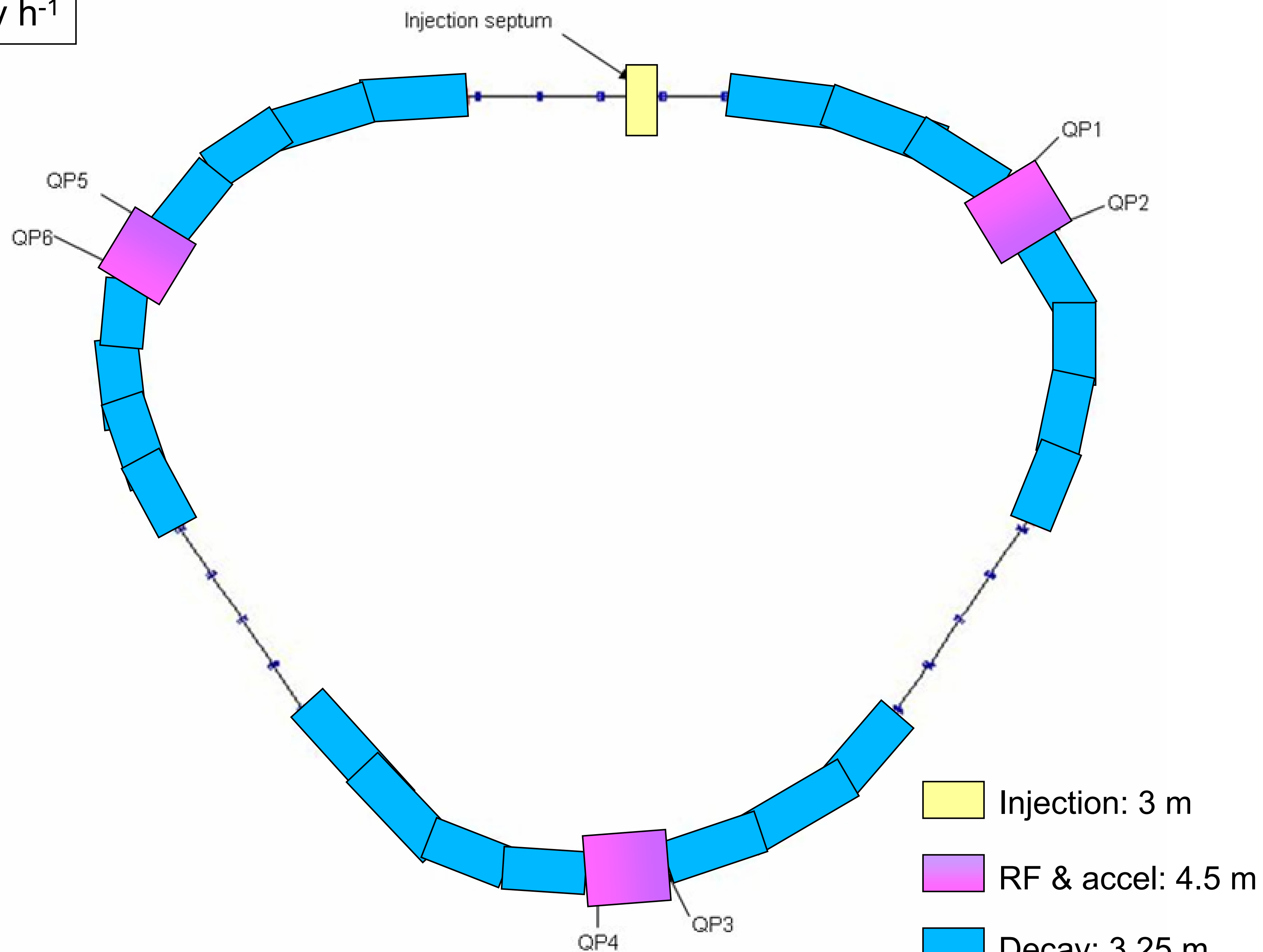
RF capture and acceleration + decay losses

	Limits *µSv h⁻¹*	*Shield thickness (cm) He*	Shield thickness (cm) Ne
QP1	0.5	440	515
	3	370	440
	10	325	390
QP2	0.5	485	470
	3	415	400
	10	365	355
QP3	0.5	435	525
	3	365	455
	10	320	405
QP4	0.5	485	475
	3	410	405
	10	365	355
QP5	0.5	480	510
	3	410	440
	10	365	390
QP6	0.5	-	480
	3	-	410
	10	-	360



- For a 450 cm shielding thickness we have ~3 $\mu Sv\ h^{-1}$.
- The shielding provides an attenuation factor of 10^{-8} of the ambient dose equivalent rate.

3 μSv h-1



Injection septum
QP1
QP2
QP3
QP4
QP5
QP6
Injection: 3 m
RF & accel: 4.5 m
Decay: 3.25 m

Summary of results of simulations

- At injection the worst case is represented by ^{6}He. For a 3 μSv h^{-1} limit the minimum shielding thickness must be of 3 m.
- During the cycle the worst case for decay losses is represented by ^{6}He. For a

  3 μSv h^{-1} limit the minimum shielding thickness must be of 3.25 m over a 10 m section of the tunnel.
- During the cycle the worst case for RF capture and acceleration losses is represented by:
  - ^{6}He for QP2 and QP4. For a 3 μSv h^{-1} limit the minimum shielding thickness must be of 4.10 m and 4.15 m respectively.
  - ^{18}Ne for QP1, QP3, QP5 and QP6. For a 3 μSv h^{-1} limit the minimum shielding thickness must be of 4.40 m, 4.50 m, 4.35 m and 4.05 m, respectively.
- For RF capture and acceleration losses + Decay losses almost the same thicknesses must be used: the contribution from decay is negligible with respect to the RF capture and acceleration one.

Calculation uncertainties

- Sources: nuclear models implemented in the code; ion intensities and loss intensities; concrete density; intrinsic uncertainty in the fit model; uniform beam loss approximation; target material; reference energies…
- A factor of 3 in dose rate intensity should be considered for safety reasons.
- We therefore recommend to add 1 more attenuation length to every shielding thickness for a safety margin.

Summary

Location	From calculations	Recommended
Injection septum	3 m	3.25 m
Arcs	3.25 m	4.70 m
QPs (2 & 4)	4.10; 4.15 m	4.55; 4.60 m
QPs (1; 3; 5; 6)	4.40; 4.50; 4.05; 4.35 m	4.90; 5.00; 4.55; 4.85 m

Outlook

- Report on preliminary shielding design
- Start study of the PS shielding
- RCS activation studies: looking for the right code for the calculations

Acknowledgments

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