Neutrino Flux Basics and RP considerations

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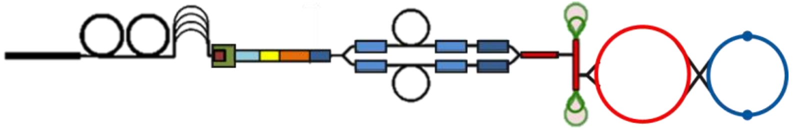
Muons Magnets Working Group
11/05/2023

Two main RP challenges related to the muon collider

‚Conventional' radiation challenges

PROMPT AND RESIDUAL RADIATION	AIR AND HE ACTIVATION	WATER AND SOIL ACTIVATION	RADIOACTIVE WASTE



‚Conventional' radiation challenges are principally well understood and can mitigated to acceptable levels, but to be addressed at an early design stage

→ **First look at arc region (presented here)**

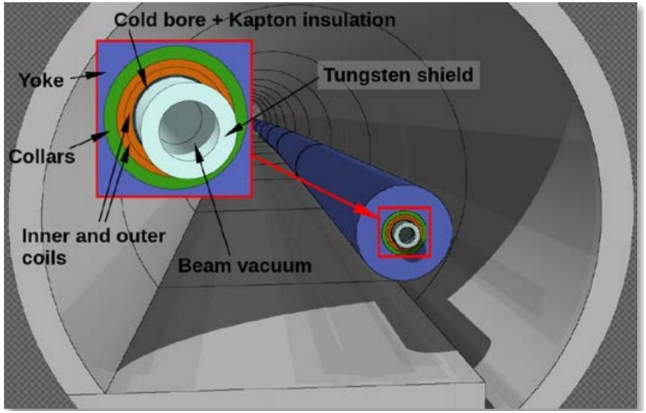
→ Assessment of TT7 activation levels for possible extension for demonstrator (EDMS 2887993)

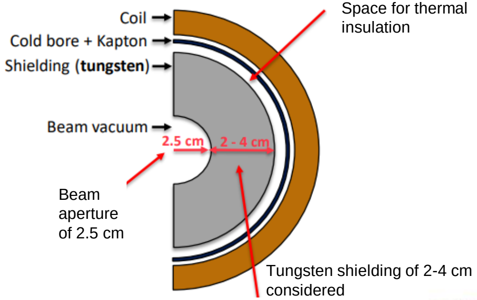
Neutrino radiation challenges

An unprecedented challenge is to ensure that showers created by neutrinos emitted from the collider ring interacting close to the Earth's surface result in very low radiation levels

Introduction

- Heat load and radiation damage in the accelerator and collider magnets have been investigated by A. Lechner and D. Calzolari in the past
  - ➢ A. Lechner et al, Report from WG on Beam-matter interaction / target systems, https://indico.cern.ch/event/1252027/
    - Radiation load to superconducting magnets due to muon decay (and beam halo losses) was quantified
    - Generic shielding studies for the arc regions of the 3 TeV and 10 TeV colliders (considering dipoles only) were performed
    - Shielding design is mainly driven by
      A) the total power leaking through the shielding and
      B) the cumulative ionizing dose in coils and
      less by the power density and cumulative DPA in coils
    - The studies showed that 3-4 cm of tungsten in the arcs is needed
- A first RP assessment of the given generic shielding design has now been performed

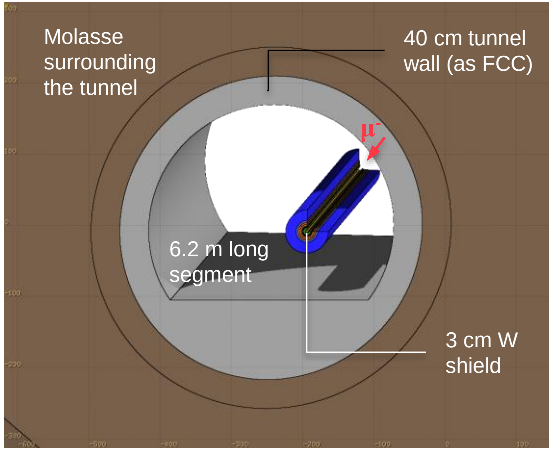




Generic arc dipoles model

FLUKA model of an arc dipole section

FLUKA input kindly provided by A. Lechner, D. Calzolari and then further extended for RP specific studies



- Simplification by simulating μ^- decay electrons only and taking μ^+ in normalization into account
- Additional user defined importance biasing to enhance precision in the molasse region

Material compositions

Molasse $1.9\ g/cm^3$	%
O	38.96667
Ca	24.09823
Si	18.29324
C	5.033333
Fe	4.87652
Al	4.353187
K	2.158053
Mg	0.806933
Ti	0.44576
Na	0.334453
Mn	0.146976
Ba	0.094069
Sr	0.086827
P	0.061959
Cr	0.052803
Zn	0.02921
Zr	0.02565
S	0.023169
Ni	0.017219
V	0.013971
W	0.010545
Co	0.00775
Cu	0.006371
Pb	0.003777
Eu	6.87E-06

Concrete tunnel $2.42\ g/cm^3$	%
O	49.2875
Ca	20.091
Si	18.867
C	5.62
Al	2.063
Fe	1.118
Mg	0.663
K	0.656
H	0.6
Na	0.453
Sr	0.399
Ti	0.347
P	0.048
Pb	0.0464
Mn	0.0387
Zn	0.0241
Ba	0.0179
S	1.2E-02
Zr	7.4E-03
Eu	4.2E-05

Generic LHC composition

Low C Steel $7.87\ g/cm^3$	%
Fe	98.2
Ni	1
Mn	0.4
Cu	0.2
Si	0.1
C	0.1

2 types of low C steel tested

Low C Steel 2 $7.8\ g/cm^3$	%
Fe	98.2519
Mn	1.002
Si	0.401
C	0.249
P	0.0412
S	0.0184
Cr	0.0165
Ni	<0.01
Mo	<0.005
Co	<0.005

Measured LHC TAN composition

- Detailed material compositions for yoke (low C steel) and concrete were assumed
- Very conservative soil composition and density (tested also w/ 7.5% water content, but similar (slightly better) results; here dry molasse results shown)

Study parameters

- **Source term:**
  - Negative muon decay electrons assuming muon beam of **5 TeV/c** (decay positrons from positive muon beam are taken into account by a factor 2 in normalization; neutrino radiation is neglected)
  - Realistic arc lattice not taken into account
  - Muon bunch intensity of 1.8E+12 with frequency of 5 Hz (i.e. 1.56E21 μ-decays over full lifetime for the whole collider with 10 km circumference)

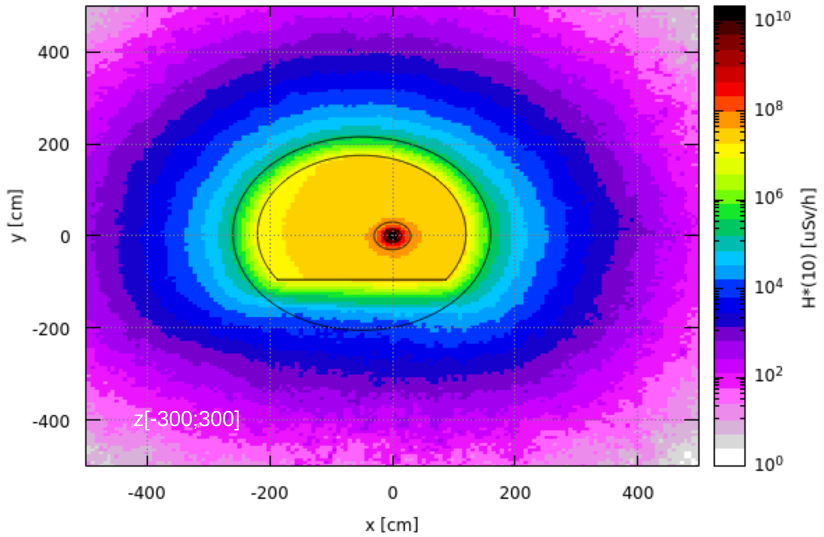
- **Operational assumptions:**
  - 200 days operation/year
    (conservative 100% machine availability)
  - 10 years of operation with 2 years shutdown in the middle

- **Topics addressed:**
  - Prompt radiation with particle breakdown
  - Residual radiation for different cool-down times and material compositions
  - Radioactive waste
  - Soil activation

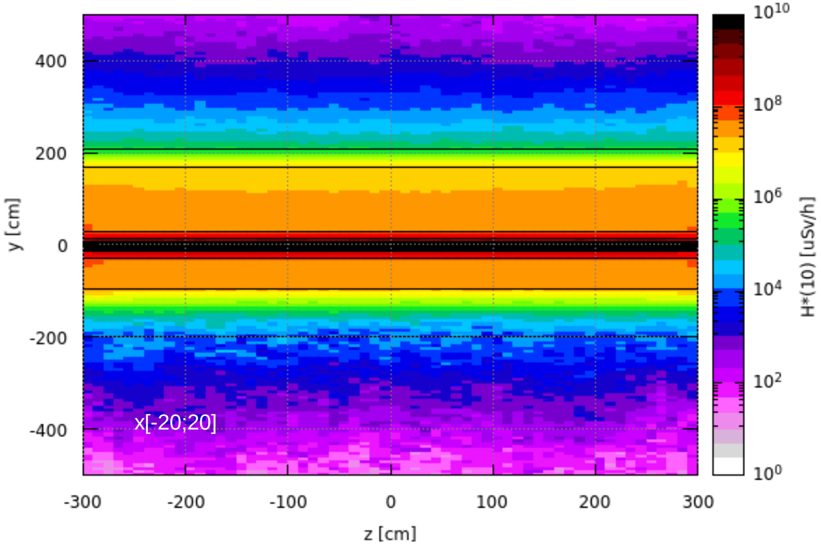
Prompt ambient dose equivalent rate H*(10) for (generic) arc dipoles

Preliminary

Cross-sectional view



Side view

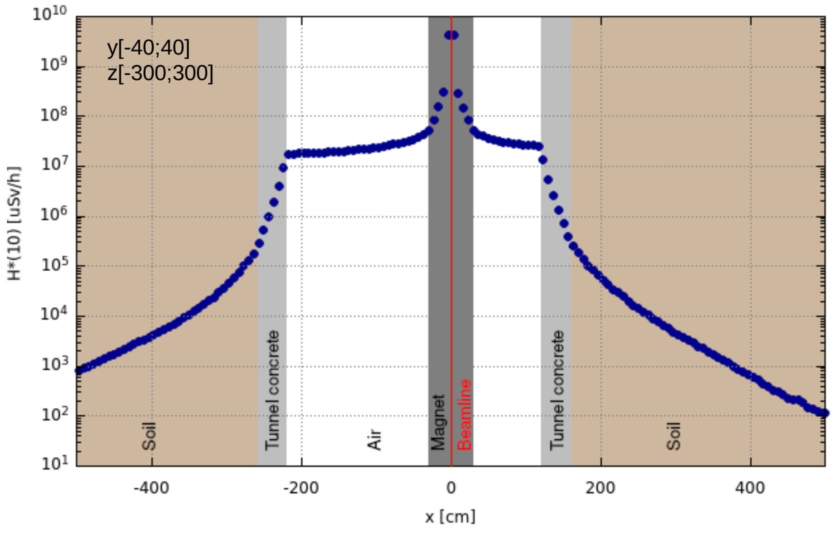


- Very high prompt ambient dose equivalent rate inside of the tunnel and several hundreds of mSv/h in the surrounding soil

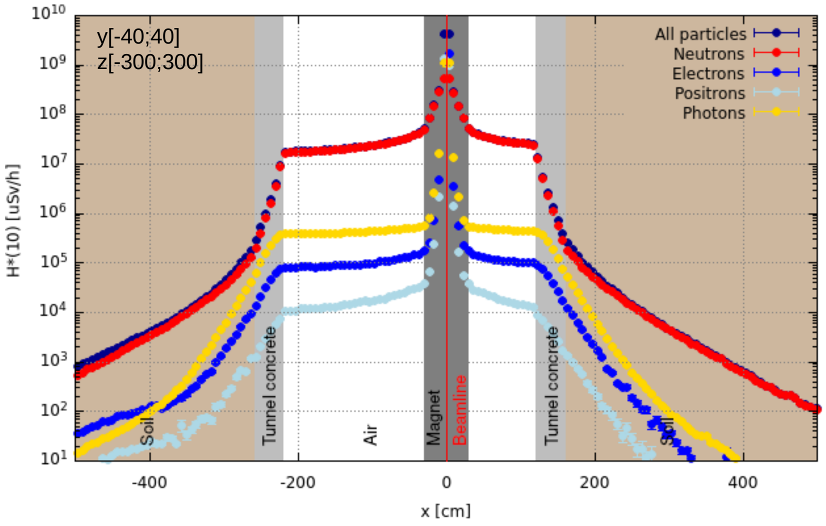
Prompt ambient dose equivalent rate H*(10) – particle breakdown

Preliminary

H*(10) distribution along y



Particle breakdown



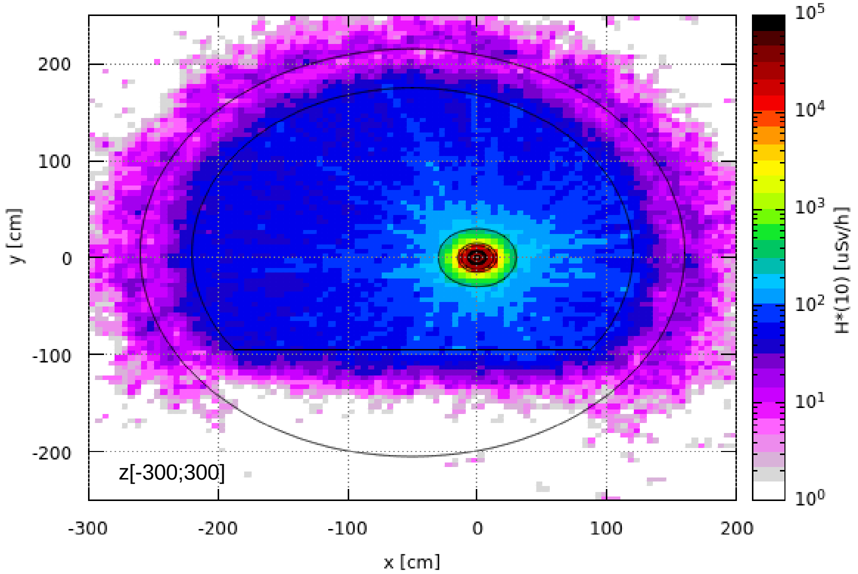
➢ The ambient dose equivalent rate is dominated by neutrons created in photo-nuclear interactions

Residual ambient dose equivalent rate H*(10) – generic low C steel composition

International MUON Collider Collaboration

Preliminary

H*(10) cross-sectional view, 1 week cool-down



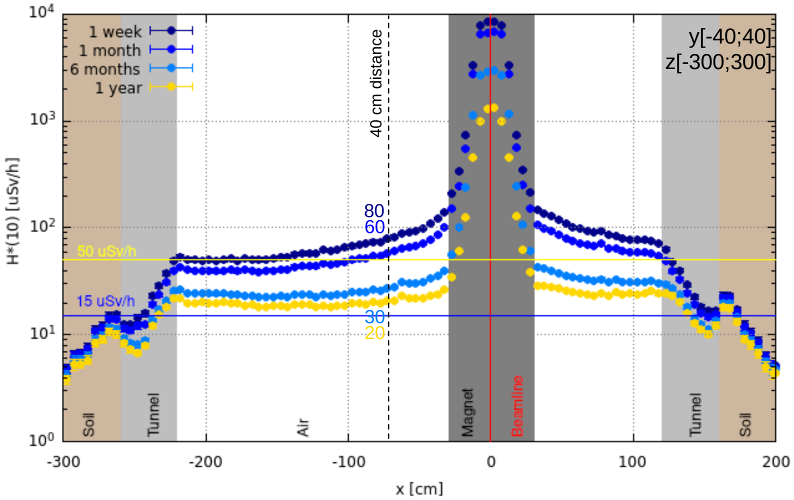
Radiation area classification

	Area	Annual dose limit (year)	Ambient dose equivalent rate – permanent occupancy	Ambient dose equivalent rate – low occupancy	Airborne activity concentration	Surface contamination	
	Non-designated	1 mSv	0.5 µSv/h	2.5 µSv/h	0.05 CA	1 CS	
Radiation Area	Supervised	6 mSv	3 µSv/h	15 µSv/h	0.1 CA	1 CS	
	Simple Controlled	20 mSv	10 µSv/h	50 µSv/h	0.1 CA	1 CS	Controlled Area
	Limited Stay	20 mSv	-	2 mSv/h	100 CA	4000 CS	
	High Radiation	20 mSv	-	100 mSv/h	1000 CA	40000 CS	
	Prohibited	20 mSv	-	> 100 mSv/h	> 1000 CA	> 40000 CS	

Residual ambient dose equivalent rate H*(10) – generic low C steel composition

Preliminary

H*(10) distribution along y, different cool-down times



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			permanent occupancy	low occupancy			
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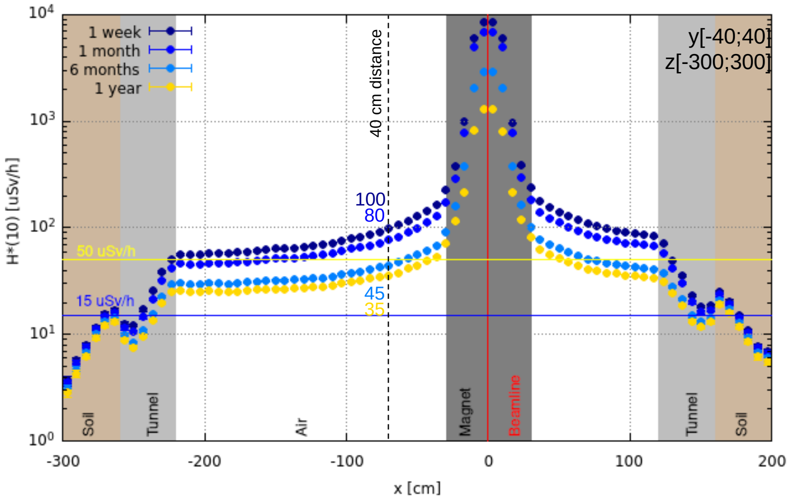
Radiation Area	Limited Stay	20 mSv	-	2 mSv/h	100 CA	4000 CS	Controlled Area
Radiation Area	High Radiation	20 mSv	-	100 mSv/h	1000 CA	40000 CS	Controlled Area
Radiation Area	Prohibited	20 mSv	-	> 100 mSv/h	> 1000 CA	> 40000 CS	Controlled Area

- High dose rates requiring a Limited Stay Area classification for cooling times of a couple of months (< 6 months)
- Optimization of interventions (e.g. remote operations, quick connections, cool-down, etc.) is required

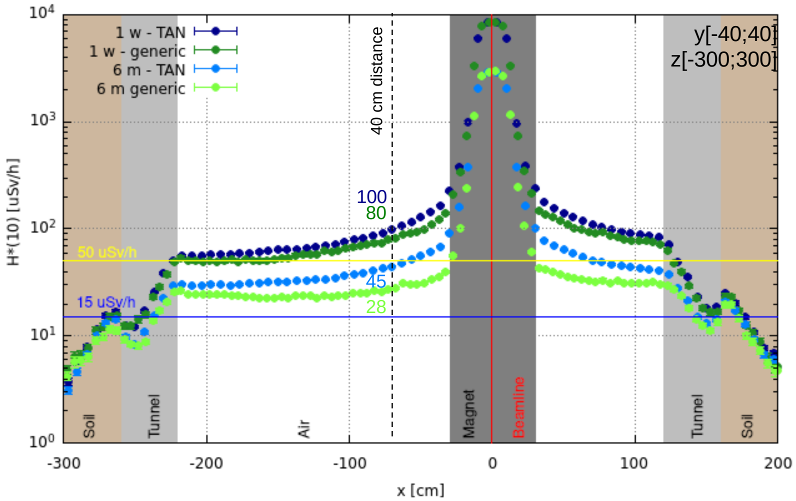
Residual ambient dose equivalent rate H*(10) – LHC TAN low C steel composition

Preliminary

H*(10) distribution along y, different cool-down times



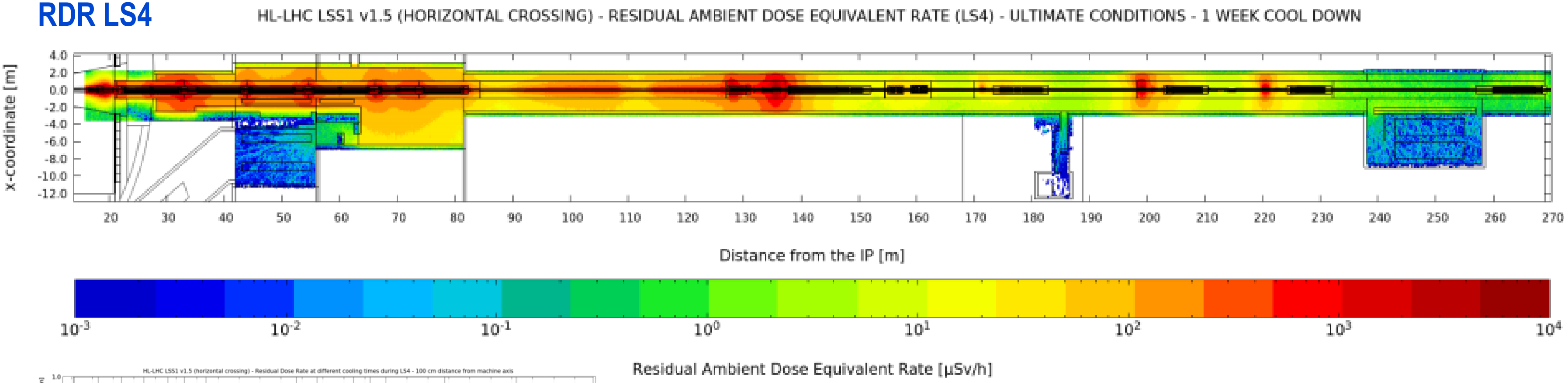
Comparison of steel compositions

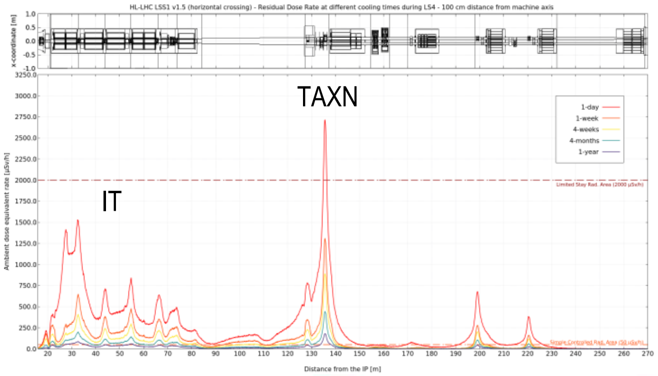


- High dose rates requiring a Limited Stay Area classification for cooling times of a couple of months (< 6 months)
- Approximately 20% higher H*(10) for TAN composition after 1 week and 60% after 6 months at 70 cm distance
- Precise knowledge of material composition is important

Residual ambient dose equivalent rate H*(10) comparison to HL-LHC LSS1

RDR LS4



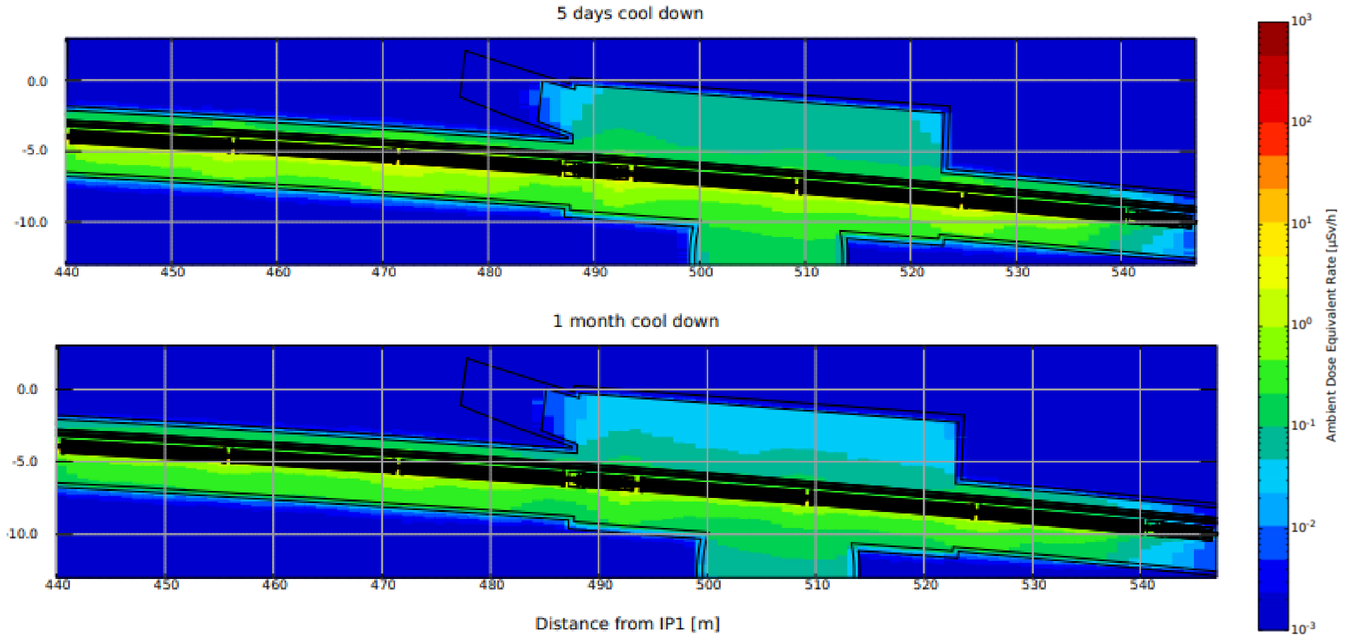


A. Infantino, M. Maietta, "Radiation levels in HL-LHC LSS1 and LSS5: update to optics v1.5", EDMS 2405113 v.0.1

- Several hundreds of uSv/h in inner triplet region for 1 week of cool-down

Residual ambient dose equivalent rate H*(10) comparison to LHC arc (TI18)

RDR Run3



A. L. Elie, A. Infantino, M. Maietta, "HSE-RP studies and activities linked to SND installation, operation and maintenance", EDMS 2650049

- Dose rates within classification of a Supervised Radiation Area (15 uSv/h) even for short cooling times
- Few hotspots close to known loss points (e.g. half-cell 9 due to diffractive protons from the IP)
- For HL-LHC similar situation is expected

Radioactive material

When is a material radioactive?

Specific and total activity exceed clearance limits (LL values)
as given in the Annex of EDMS 942170 (adopted from Swiss legislation)

Examples: 0.1 Bq/g for ^{22}Na, ^{54}Mn, ^{60}Co
1000 Bq/g for ^{55}Fe

OR

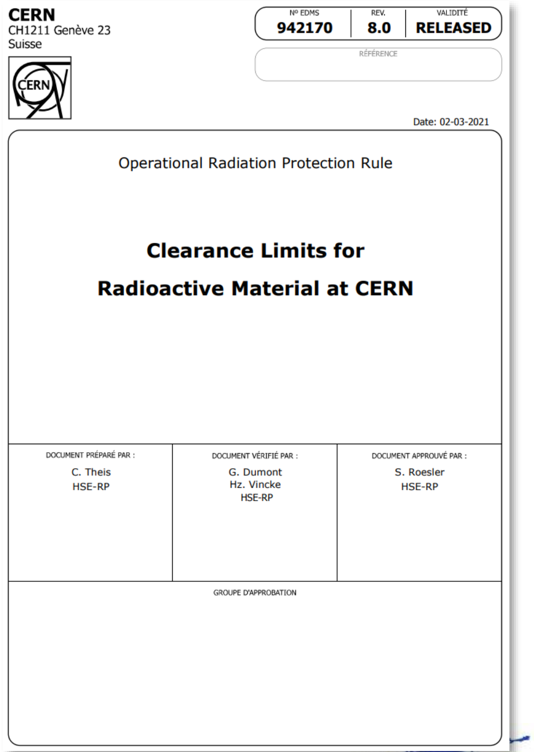
Sum rule for mixture of radionuclides: $\sum_{i=1}^{n} \frac{a_i}{LL_i} < 1$

Net ambient dose equivalent rate > 0.1 µSv/h in 10 cm distance

OR

Surface contamination exceeds limits
as given in the Annex of EDMS 942170 (> 1 CS)

Sum rule for mixture of radionuclides: $\sum_{i=1}^{n} \frac{c_i}{CS_i} < 1$


CERN
CH1211 Genève 23
Suisse

Nº EDMS	REV.	VALIDITÉ
942170	8.0	RELEASED

RÉFÉRENCE

Date: 02-03-2021

Operational Radiation Protection Rule

Clearance Limits for Radioactive Material at CERN

DOCUMENT PRÉPARÉ PAR :	DOCUMENT VÉRIFIÉ PAR :	DOCUMENT APPROUVÉ PAR :
C. Theis HSE-RP	G. Dumont Hz. Vincke HSE-RP	S. Roesler HSE-RP

GROUPE D'APPROBATION

Radioactive waste zoning

Preliminary

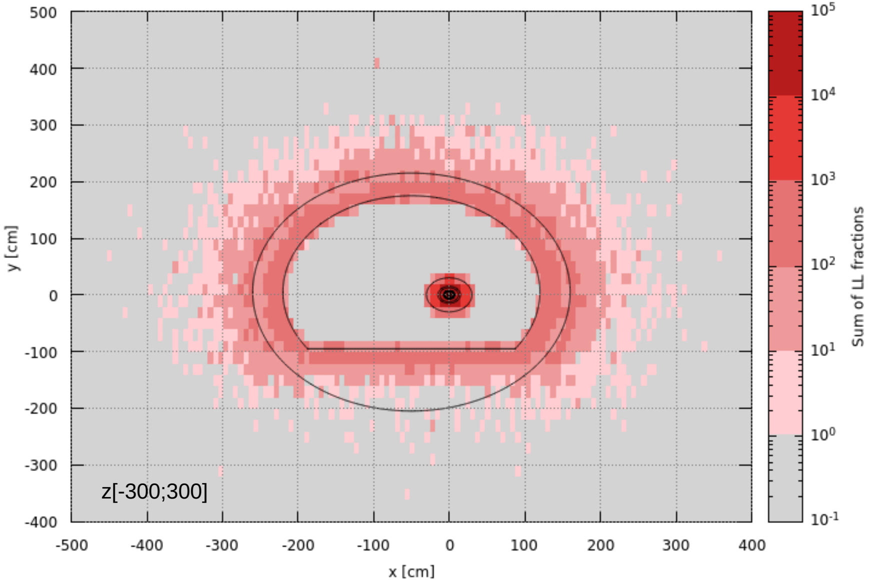
- Radioactive waste zoning according to the LL criterion:

$$\sum_{i=1}^{n} \frac{a_i}{LL_i} \; .$$

If > 1 to be considered radioactive

If < 1 to be considered as non-radioactive

Sum of LL fractions for 1 year of cool-down



Soil activation

- The collider is expected to be placed **deep underground** in view of the requirements related to the neutrino flux
- The placement should ideally be done in deep **impermeable molasse** that is **not in contact with shallower aquifers** in moraine above and **not suitable** for **drinking water exploitation**
- Environmental impact expected from molasse activation can be investigated with activation studies in combination with a dedicated hydrogeological study
- For the proposed **ECN3 high-intensity facility** located in the **shallow moraine** region preliminary and **very conservative** soil activation constraints were evaluated:

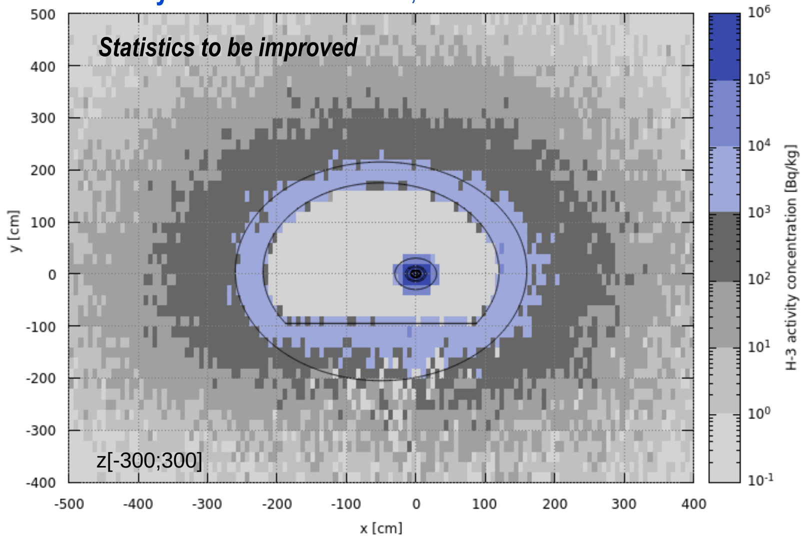
H-3 < 1000 Bq/kg **Na-22 < 50 Bq/kg**

- These design goals are based on the activity concentration of longer-lived radionuclides, H-3 and Na-22, which are both **soluble radionuclides** likely to be transported by groundwater and therefore critical for the protection of groundwater resources
- For a suitable placement of the **muon collider** ring, these design goals are **expected** to be **significantly smaller**

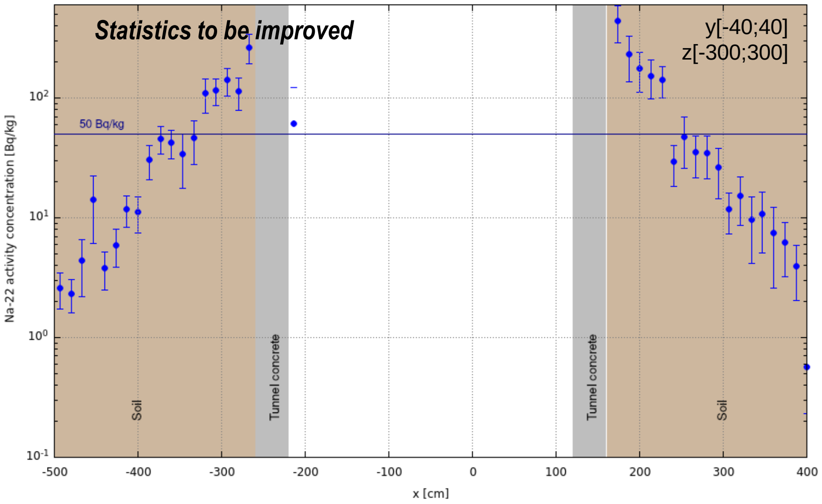
Activity concentration of longer-lived radionluclides in soil

Preliminary

H-3 activity concentration in soil, 1 h cool-down



Na-22 activity concentration in soil, 1 h cool-down



- ➢ Preliminary results show H-3 activity concentration levels in the soil that are mostly below 1 kBq/kg used as conservative design goal for shallow ECN3 facility
- ➢ NA-22 activity concentration levels in the soil that exceed the conservative design goal of 50 Bq/kg used for shallow ECN3 facility

➢ Soil activation around the collider arcs expected to be acceptable with adequate collider placement

Summary of arc dipoles study

- Non-negligible neutron flux due to photo-nuclear interaction caused by the muon decays in the arc dipoles
- Residual radiation levels in the arc dipoles region similar to HL-LHC inner triplets region
- Also, radioactive soil thickness around the tunnel similar to HL-LHC
- Soil activation around the collider arcs expected to be acceptable with adequate collider placement

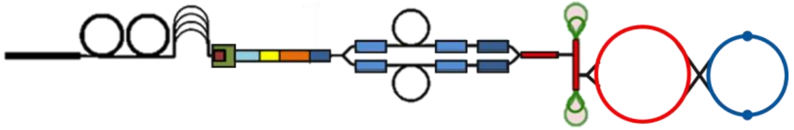
Next studies (tbd):

- Evaluation of radiation levels during commissioning

Two main RP challenges related to the muon collider

‚Conventional' radiation challenges

PROMPT AND RESIDUAL RADIATION	AIR AND HE ACTIVATION	WATER AND SOIL ACTIVATION	RADIOACTIVE WASTE



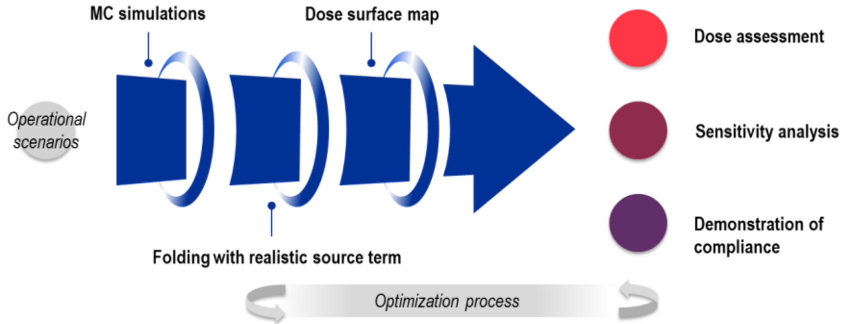
‚Conventional' radiation challenges are principally well understood and can mitigated to acceptable levels, but to be addressed at an early design stage

Neutrino radiation challenges

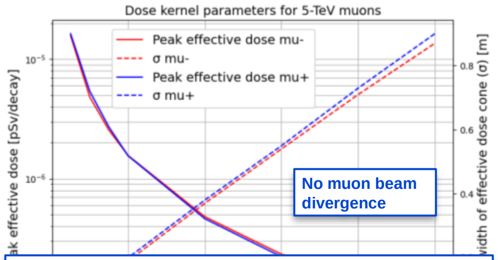
An unprecedented challenge is to ensure that showers created by neutrinos emitted from the collider ring interacting close to the Earth's surface result in very low radiation levels

Recap of neutrino flux basics

- One of the challenges of a high energy muon collider is to ensure that showers created by neutrinos interacting close to the Earth's surface result in very low radiation levels
- A **refined dose model** for an accurate estimation of neutrino-induced radiation is being developed and used for a **collider ring optimisation** to **minimise** the **effective dose** to members of the public down to a negligible level



Extensive FLUKA simulations [1]



Next studies:
- **Contribution of neutrino energy ending in the shower for different neutrino energies**
- **Better understanding the differences of abs./eff. dose for different energies (1.5 and 5 TeV muons)**

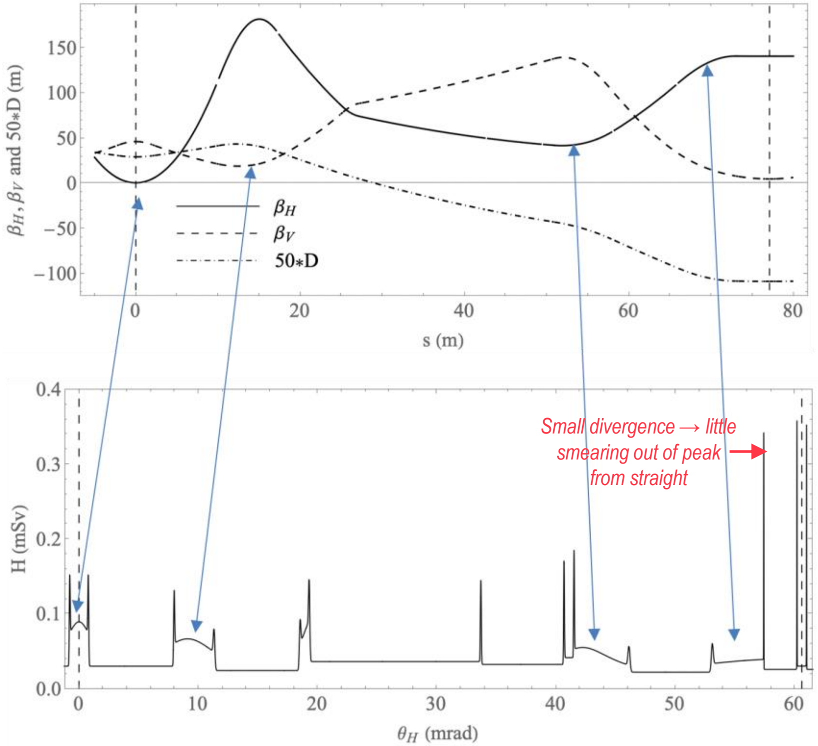
- Gaussian approximation of effective dose kernel yielding peak dose and dose width
- Very similar effective dose parameters for positive and negative muons
- Estimation of effective dose and weighting factor to convert from absorbed dose (W)
- Assessment of the widening of the radiation cone due the lateral extension of the shower (d)
- General verification of the simplified expressions
- Results well reproduced with $W \approx$1.32 Sv/Gy and $d \approx$ 0.15 m

- ➢ Used as input for the analytical estimates [2] based on treatment by B. King [3]
- ➢ Conversion from absorbed to effective dose by weighting factor (W = 1.32 Sv/Gy), however lateral extension of shower neglected (d = 0 m) (good enough and easier)
- ➢ Folding with a beam divergence assumed Gaussian becomes trivial

Radiation from an arc cell

Results for arc cell of latest lattice version [2, 4]

$\sqrt{s} = 10\,TeV$



Assumptions

- Eff. dose for 1 y (5000 h, 5 Hz) operation at 100 km distance
- No magnetic fields between magnets (hard edge model)

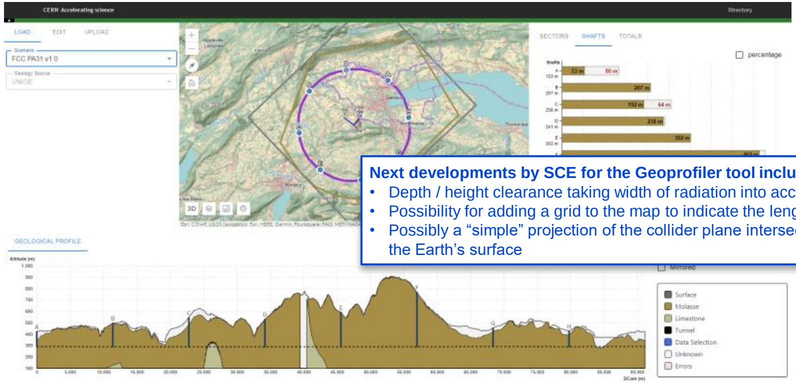
Observations

- Spikes from short (0.3 m) straight sections
- Divergence from beam (D') reduces height of peak
  - Optimized lattice design to avoid small D' at short straights?
- Mitigation measures needed

Mitigation measures

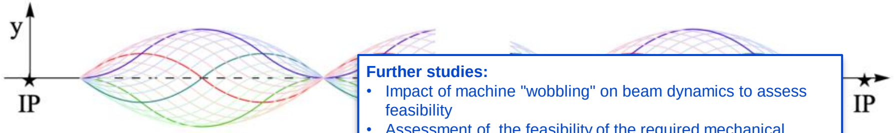
- **Optimization of collider placement**
  - Deep underground installation of collider
  - Careful positioning/inclination such that elevated neutrino flux from straights with IPs point to uncritical areas (owned by lab, detector, ocean, ...) → for the moment a slope of max. 2.5% assumed (max. slope?)
  - Geoprofiler tool [5] available and developed further to identify locations where neutrinos reach Earths' surface
- **Optimization of lattice**
- **Machine "wobbling"**
  - Periodic deformations of the whole machine to spread otherwise very localised neutrino flux over larger surface [2]
  - Succession of parabolic pieces (additional magnetic field needed)
  - Amplitude of ± 0.15 m and period of 600 m would allow a modulation of the slope of ±1 mrad
  - Reduction of peaks by a factor 100 for a 10 TeV com collider

Geoprofiler interface



Next developments by SCE for the Geoprofiler tool include:
- Depth / height clearance taking width of radiation into account
- Possibility for adding a grid to the map to indicate the length
- Possibly a "simple" projection of the collider plane intersecting the Earth's surface

Arc with an integer vertical machine deformation periods



Further studies:
- Impact of machine "wobbling" on beam dynamics to assess feasibility
- Assessment of the feasibility of the required mechanical movement system

Summary of neutrino studies

- A formalism based on analytical derivations and refined by extensive FLUKA simulations to estimate the effective dose levels, where neutrinos generated by muon decays in a collider reach the Earth's surface has been developed
- Numerical evaluations for the arc cell of the latest 10 TeV com muon collider version has been performed
- FLUKA studies have as well already been carried out for a beam energy of 1.5 TeV for a 3 TeV com muon collider
- For a typical 10 TeV com collider, "wobbling", i.e., periodic deformation of the whole machine outside the long straight sections housing the experiments is mandatory to keep the dose at negligible values

Next studies:

- Refinement of model around the transitions between magnets and straight sections (so far hard edge model for magnets)
  → input from Magnets WG
- Assessment of the impact of machine "wobbling" on beam dynamics to evaluate feasibility
- Assessment of the feasibility of the required mechanical movement system
- Usage and further development of Geoprofiler tool to identify an appropriate site and collider positioning
  → what is the maximum slope acceptable for the magnets?

References

[1] G. Lerner, "FLUKA Simulations of Neutrino-Induced Radiation at a Muon Collider”

[2] C. Carli et al., “Neutrino generated Radiation from a high Energy Muon Collider”, IPAC23

[3] B. J. King, "Potential Hazards from Neutrino Radiation at Muon Colliders", arXiv:physics/9908017

[4] K. Skoufaris et al., "First Design of a 10 TeV Centre of Mass Energy Muon Collider", IPAC23, contribution MOPL064

[5] G. Lacerda et al., "GEOPROFILER: A geological and radiological Tunnel Optimization Tool", Proc. of the 16th workshop on Accelerator Alignment

International
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Collaboration

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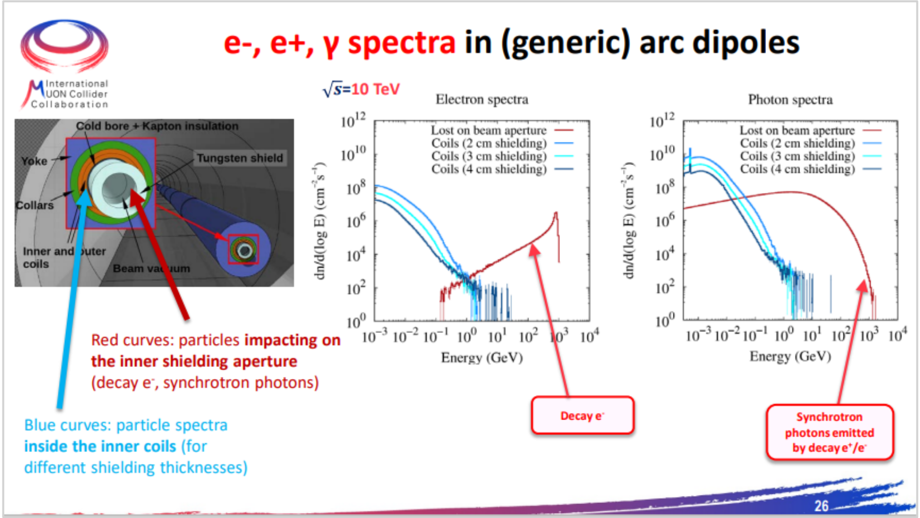
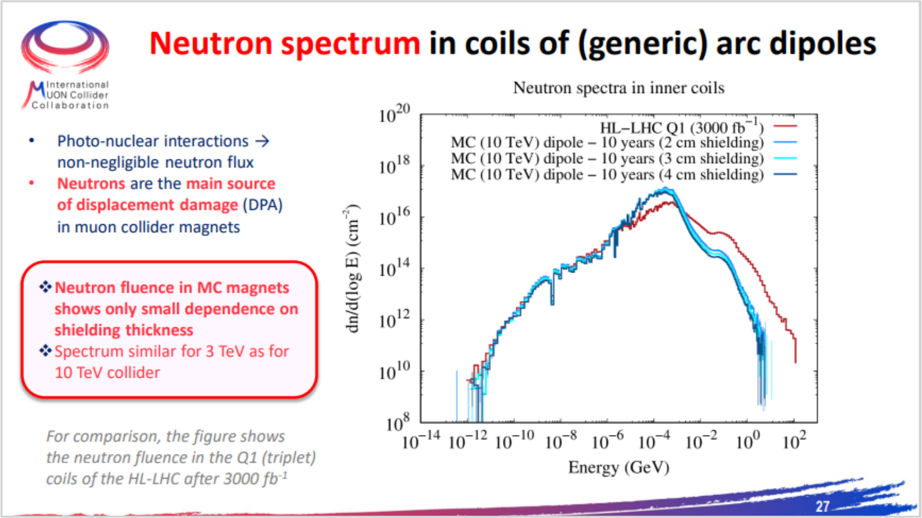
Thank you
for your attention!

Particle spectra in (generic) arc dipoles – Recap

A. Lechner et al, Report from WG on Beam-matter interaction / target systems, https://indico.cern.ch/event/1252027/





HL-LHC ultimate scenario even with 4000 fb^{-1}!

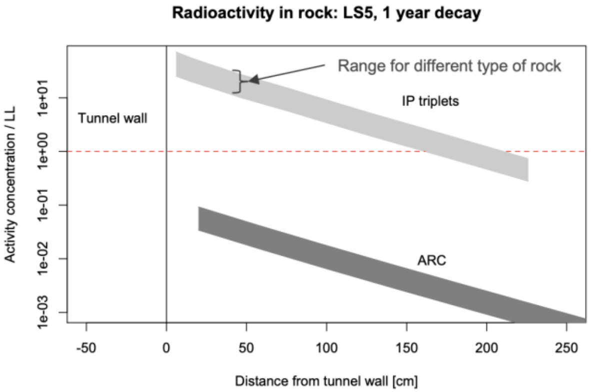
Main parameters for latest 10 TeV lattice

Muon energy E	5000 GeV
Relativistic γ	47 300
Circumference C	8670 m
Intensity per beam and bunch N	2×10^{12}
Repetition rate f_r	5 Hz
Physical rms emittances $\varepsilon_H = \varepsilon_V$	0.528 nm
Twiss beta at the interaction point β^*	1.5 mm
Bunch length rms	1.5 mm
Relative momentum spread rms	10^{-3}
Luminosity	20×10^{34} cm^{-2} s^{-1}
Power per beam	7.2 MW

FCC-hh IP & Arc Ground Activation

M. Widorski et al., *Radiation protection at the FCC*, EDMS 1961537

FCC-hh IP & ARC: Ground activation



Comparable to scaled values determined for HL-LHC civil engineering works.

Methodology
- Particle fluence spectra scored in first meters of rock after the tunnel wall (2 material compositions)
- Calculation of isotope production with ActiWiz3Creator for 25 years operation and 1 year cool-down
- Evaluation in fractions of clearance value (LL 2018)

Results

→ In IP sectors, the first 2 m would be above LL limit; in ARCs below limits

→ LL limit applies to scenarios where the material would be extracted and used/disposed

→ Transfer factor to the biosphere is the relevant factor here: not known but usually very small (very low mobility, large dilution)

→ No relevant environmental impact expected

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