International MUON Collider Collaboration

Summary of the RP Working Group

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2nd Muon Community Meeting

13 July 2021

List of challenges identified by RP WG

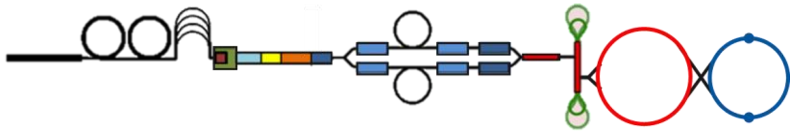
Neutrino radiation challenges

Unprecedented: Substantial neutrino induced radiation hazard at very far distance from the source

1. Refined dose model
2. Mitigation by movers

‚Conventional' radiation challenges

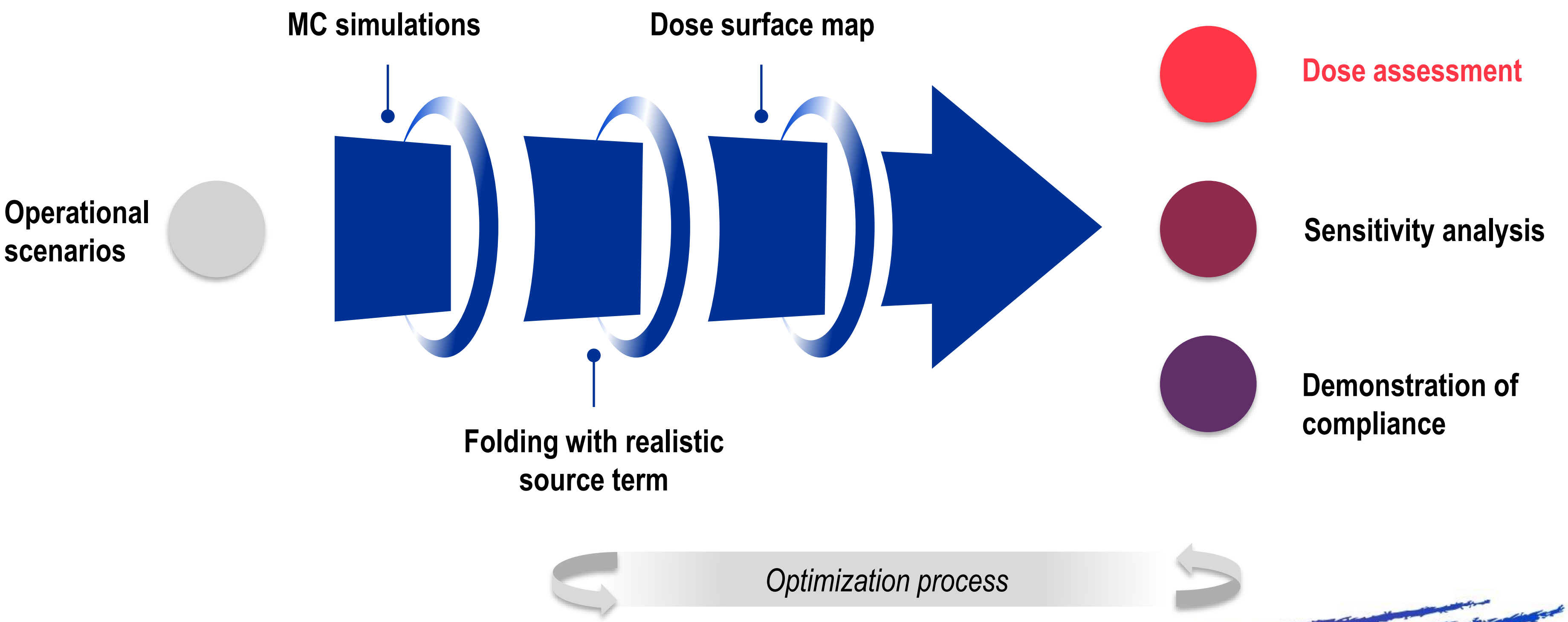
PROMPT AND RESIDUAL RADIATION	AIR AND HE ACTIVATION	WATER AND SOIL ACTIVATION	RADIOACTIVE WASTE



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

3. Test facility
4. Key areas of the complex

Overview of work related to a refined dose model



Operational scenarios

- Dose model shall be based on the stipulated collider parameters

Tentative target parameters

Defined by the Muon Beam Panel

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Reasonably conservative
- each point in 5 years with tentative target parameters
- FCC-hh to operate for 25 years
- Aim to have two detectors
- But might need some operational margins

Note: focus on 3 and 10 TeV
Have to define staging strategy

Tentative target parameters
Scaled from MAP parameters

Comparison:
CLIC at 3 TeV: 28 MW

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

D. Schulte Muon Collider, March 23, 2021 14

- A dose model will be defined for each parameter set
- Prioritization (?):
  - 3 TeV
  - 10 TeV
  - 14 TeV

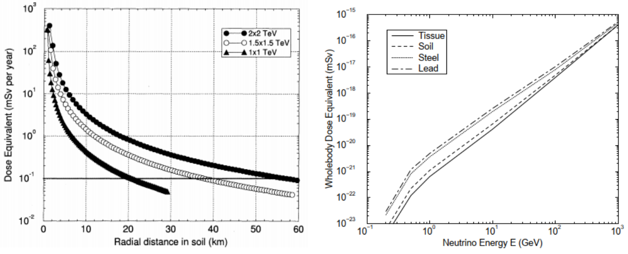
Past Monte Carlo simulations

Few examples

- **Comprehensive MARS15** simulations with a sophisticated neutrino interaction model crucial for induced dose calculated and secondary particle for monitoring
  → Mokhov and Ginneken, Neutrino Radiation at Muon Colliders and Storage Rings, 2000
- Studies for E_{com} 0.5, 1, 3, and 4 TeV muon colliders:
  - Effective dose for broad and pencil neutrino beams
  - Secondary particle equilibrium and non-equilibrium cases
  - Maximum and whole-body values for variety materials upstream the tissue-equivalent phantom
  - Contributions from both the collider ring and field free drifts
  - Standalone case of monoenergetic neutrino beams of energies from 100 MeV to 10 TeV
  - Idea of vertical wobbling of muon beams in the ring was introduced and calculated showing substantial effect of dose reduction
- Good agreement with **FLUKA simulations**
  → Bartosik et al., Preliminary Report on the Study of Beam-Induced Background Effects at a Muon Collider, 2019

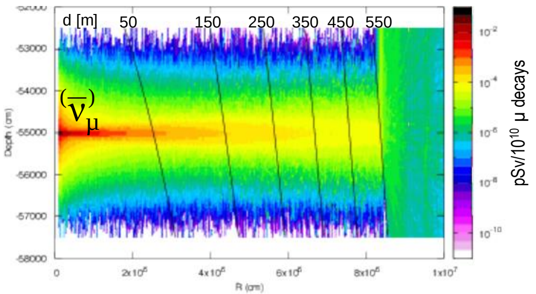
→ To build on extensive accomplishments for additional MC studies

MARS15 dose eq. vs. distance + E_ν for diff. materials



Mokhov and Ginneken, Neutrino Radiation at Muon Colliders and Storage Rings, 2000

FLUKA H*(10) for 2 TeV vs. distance + depth



Bartosik et al., Preliminary Report on the Study of Beam-Induced Background Effects at a Muon Collider, 2019

Plans for Monte Carlo simulations

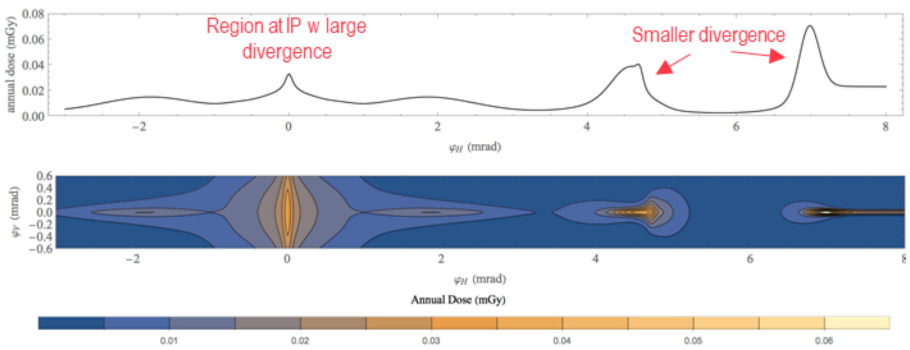
- Simplified FLUKA and MARS simulations with a **pencil muon beam** for the given operational scenarios (E_{com} 3, 10, 14 TeV (tbc)) to evaluate main parameters for the dose predictions, such as:
  - **Dose distribution** for different distances (collider depths) assuming secondary particle equilibrium (i.e. inside material) → Folding w realistic source term
  - **Sensitivity studies** for underlying assumptions (e.g. material properties, nu_e/mu and antineutrino)
  - **Differences** of possibly relevant **dosimetric quantities** (e.g. effective dose, ambient dose equivalent, eff. dose equivalent)
  - Difference to a more realistic **full path assessment**

  → Sensitivity analysis
  - **Secondary particle spectra** needed to design suitable monitoring instrumentation → Demonstration of compliance
- Benchmarking of **neutrino interaction models** → Sensitivity analysis

Folding with a realistic source term

- Evaluate **dose distributions** for a **realistic neutrino source term** (well defined via μ decay) taking into account:
  - The **real lattice** (collider, injection, accelerators)
- Fold the information from MC simulations to estimate the dose distributions
  → more precise and less conservative dose estimation than analytical approach taking additional spread of secondary particle distribution into account
- **Identification** of **critical regions** (high dose areas)
- **Optimization** of the **source term** (e.g. lattice, wobbling) with respect to the dose
- **Sensitivity study** of underlying assumptions (e.g. closed orbit positions)

Example of using analytical approach for region around IP



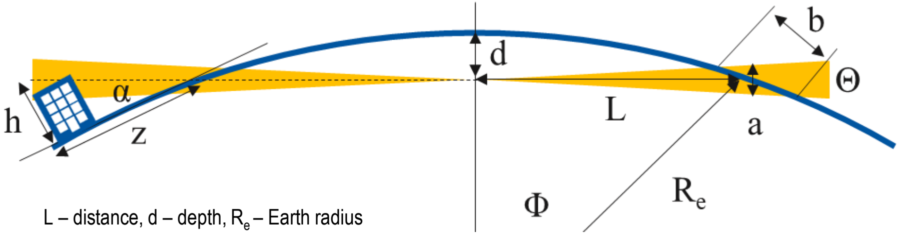
C. Carli, Considerations on Radiation, Muon Collider Design Meeting, 08.03.2021
(3 TeV, 100 m depth, analytical approach based on B. King)

› Dose surface map

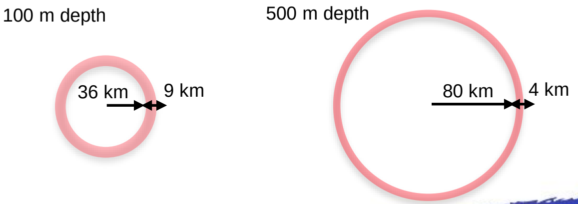
› Sensitivity analysis

Dose surface map

- Establish **surface map of dose**
- **Optimization** w.r.t. depth, orientation and inclination
- Investigation of different **site options**
- Evaluation of **uncertainties** of methodology (e.g. accuracy of terrain model) ➤ Sensitivity analysis
- Findings from simplified geometrical considerations (Earth as perfect sphere, no beam divergence, no collider inclination) for ν beam:
  - ν disk has a height (a) of ~1-2.5 m and traverses a region of width (b) of ~100-450 m
  - For dose additional spread of few m due to sec. particle shower
  - Exit angle of ν radiation is very small, wherefore **impacted area** can be of **several km** depending on height considered



E_{com} [TeV]	3	10	10	14	14
d (m)	100	200	300	400	500
L (km)	36	51	62	71	80
a (m)	2.5	1.1	1.3	1.1	1.2
b (m)	449	135	135	96	96

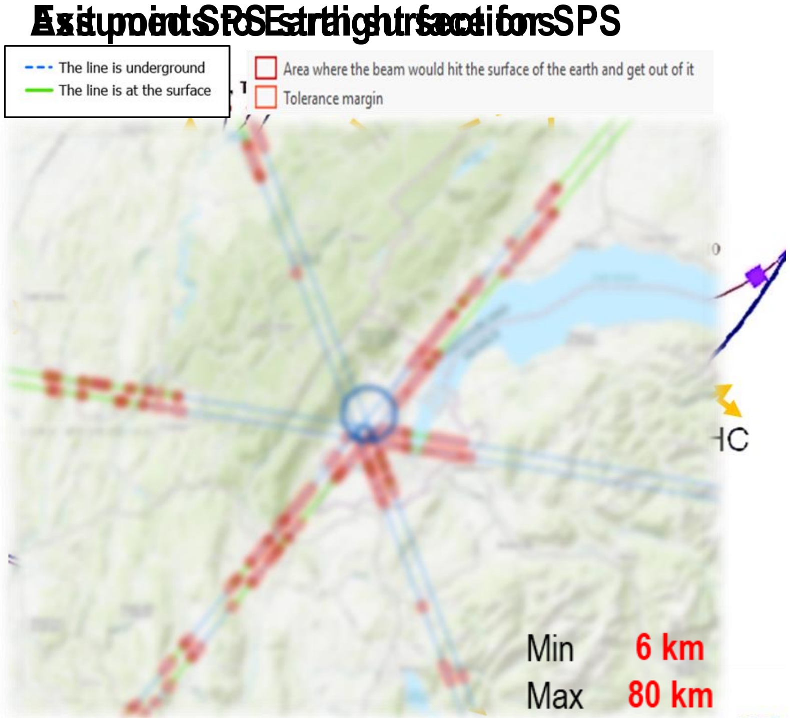


$L^2 = R_e^2 - (R_e - d)^2$
$\Theta \sim 1/\gamma$
$a \approx 2\,\Theta L$
$b \approx a/\Phi$, $\sin\Phi = L/R_e$

See also paper from Johnson, Rolandi and Silari, Radiological Hazard Due to Neutrinos from a Muon Collider, 1998

Preliminary study of where ν break ground for LHC/SPS straight sections

- A preliminary study of where ν would come out the earth's surface for LHC and SPS straight sections was performed
- Methodology is based on Geode Survey Database and Digital Surface Model for Europe (EU-DEM v1.1)
- **3D model** of where ν break ground was developed
- For SPS the longest distance (80 km) is on the other side of the Jura and for the LHC (263 km) it is on the other side of the alps
- The depth of the SPS and its "horizontality" bring some uncertainty on the exact locations
  → no single exit point for both SPS and LHC straight sections
- Assumed **accuracy** of terrain model ~± 30 m and 0.1 deg of the beam → further investigations for higher precision planned
- Technical student already started work on **automating** the **production** of **such maps** according to the collider position → will allow **optimization** w.r.t. depth, orientation and inclination



Y. Robert

Dose assessment

- Identify representative person from public for a final dose assessment
- As a **general worst case scenario**, one would have to assume maximum exposure and irradiation conditions (e.g. sick person lying in bed 24/7 at the location of the maximum dose)

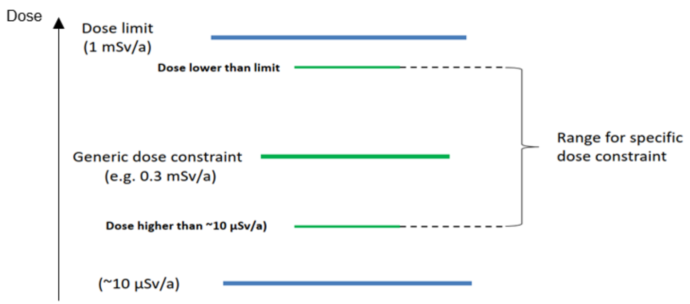
→ **Dose optimization** to **O(10) μSv/year**

- Depending on the dose surface map, for certain regions of higher dose (e.g. for critical straight sections), possible exclusion of such a worst case scenario even for the far future

→ Dose higher than O(10) μSv/year depending on possible exposure scenarios (e.g. lake, mountains, ocean, exclusion area)

- Depends on acceptance by authorities and public
- Uncertainty of the dose surface map → Sensitivity analysis

ICRP and IAEA Safety standards –
Relationship between dose limit, generic and specific dose constraint, and optimization level

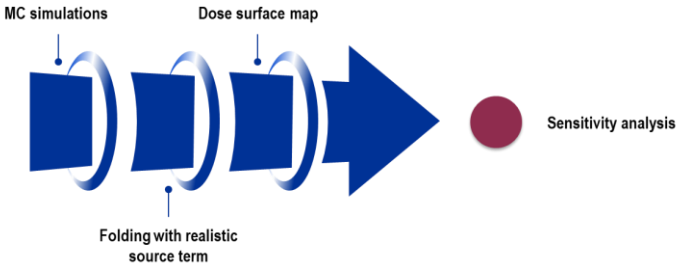


IAEA Safety Standards, General Safety Guide, No. GSG-9

100 rem = 1Sv

Sensitivity analysis and demonstration of compliance

Sensitivity analysis



- Uncertainties of dose estimate to be defined based on the various underlying parameters and assumptions
- This includes uncertainties for the dose distribution as well as its projection on the surface

Demonstration of compliance

- Evaluate means to demonstrate compliance of the dose estimates, both at the source (emission) and impact side (immission)

Source side

- Measure muon beam parameters (e.g. divergence)

Impact side

- Design suitable monitoring instrumentation for measuring the dose from the secondary particles

Proposed workpackage description

Neutrino radiation

1. **Refined dose model**
   A refined dose model for a reliable and precise estimation of neutrino-induced doses outside the complex shall be developed and used for a collider ring optimization to minimise the dosimetric impact on the public

Proposed workpackage tasks– Refinded dose model

Preliminary – Timeline tbd

- **Input:** Specific collider parameters (E, circumference) are needed as input for the refined dose model
- **MC simulations**
  - MC simulations (FLUKA, MARS) to evaluate main parameters for the dose predictions and their uncertainties
  - Benchmarking of neutrino interaction models
- **Folding with realistic source term**
  - Evaluation of a realistic neutrino source term and folding with dose distributions from MC simulations
  - Further optimization and sensitivity analysis
- **Surface map**
  - Surface map of the dose for given site options
  - Further optimization and sensitivity analysis
- **Dose assessment + demonstration of compliance**
  - Perform final dose assessment and develop possible methods to demonstrate compliance

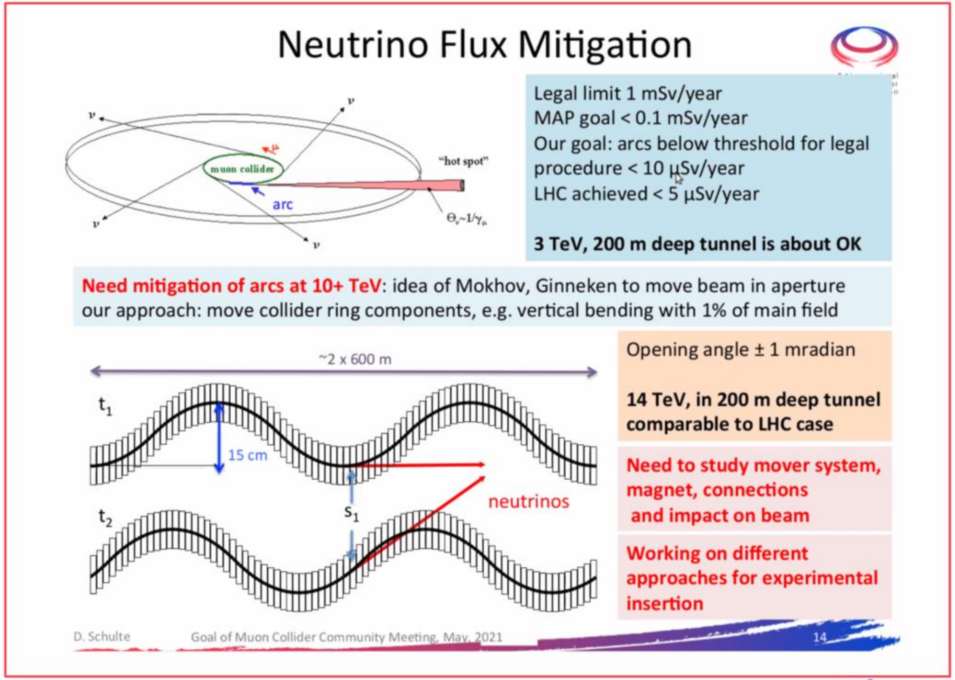
Proposed workpackage description

Neutrino radiation

1. **Refined dose model**
   A refined dose model for a reliable and precise estimation of neutrino-induced doses outside the complex shall be developed and used for a collider ring optimization to minimise the dosimetric impact on the public
2. **Mitigation by movers**
   Mitigation by movers, which move the beam line components to change the beam direction by deforming the beamline in the vertical plane

Mitigation using movers

- Mitigation studies on the so-called neutrino radiation:
  - One possibility would be to move the beam line components to change the beam direction (by deforming the beamline in the vertical plane).
  - Very low frequency movements of components within 15 cm.



From H. Mainaud Durand

Proposed workpackage tasks and timeline – Mitigation using movers

3 key issues

Very preliminary work plan

- *K1: Development of large stroke/high resolution movers*
  - Study of SOTA / establishment of requirements (tech. Student) [ASAP]
  - Study of different options, concepts, up to the engineering (PhD student) [2022-2024]
  - Qualification of prototypes (tech student) [2025]
- *K2: Development of remote solutions to control the position of components*
  - Study of solutions + concepts of alignment sensors (PhD student) [2022-2024]
  - Development of first options / solutions / qualification of prototypes (fellow) [2024-2026]
- *K3: Accuracy of absolute position needed (underground vs surface)*
  - Some synergies with Geodetic studies undertaken for FCC
  - Adapt them to the specific case of muon collider: simulations (Post-doc) or development of specific methods (PhD student)

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From H. Mainaud Durand

Proposed workpackage description

Neutrino radiation

1. **Refined dose model**
   A refined dose model for a reliable and precise estimation of neutrino-induced doses outside the complex shall be developed and used for a collider ring optimization to minimise the dosimetric impact on the public
2. **Mitigation by movers**
   Mitigation by movers, which move the beam line components to change the beam direction by deforming the beamline in the vertical plane

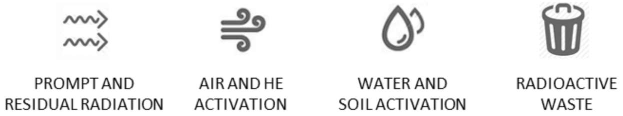
Additional RP challenges

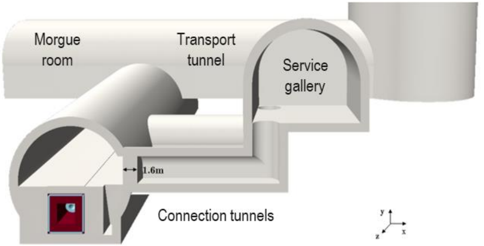
3. **Test facility**
   The test facility design will have to be optimised w.r.t. prompt and residual radiation, air/He/N activation, water and soil activation, and radioactive waste production, particularly when aiming at potentially upgrading to O(4) MW beam power
4. **Key areas of the complex**
   Similarly to the test facility, also for the key areas of the muon collider complex, the main RP challenges should be investigated at an early design stage

Additional RP challenges

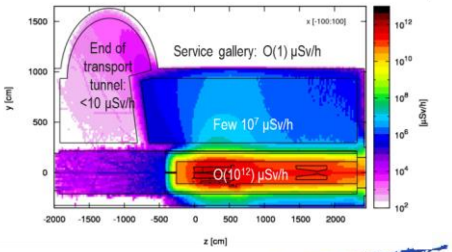
- Based on the experience from past design studies (LLBNO, BDF, CENF), the **radiological environmental impact** of a MW facility, should be **manageable** at the present state of technology
- The past studies have however also shown that the **RP considerations strongly determine** the **design** of high power facilities
- When aiming at a O(4) MW facility several RP aspects should be studied beforehand such as (non-exhaustive list of examples):
  - The required shielding and other infrastructure (e.g. morgue room) as well as streaming of radiation through shafts (e.g. avoided by chicanes)
  - The required depth of the facility for avoiding ground water activation and a hydrogeological study
  - He/N vessel around the most critical region (target) to avoid air activation
  - The possibility for minimizing the radioactive waste production
  - Uncertainties related to H-3 out-diffusion may impact air/He/water activation

→ Precise evaluation based on FLUKA simulations needed





Prompt dose rates



Proposed workpackage resources

Preliminary – More information to come

Task	Staff [pm]	postdoc [pm]	student [pm]	Cash [kEUR]	Comment
MC simulations					SY-STI (CERN), Fermilab, HSE-RP (CERN)
Folding w realistic source term					BE-ABP (CERN)
Surface map					SCE-SAM (CERN)
Dose assessment	0.25 – 0.35 FTE/y				HSE-RP (CERN); includes also coordination+discussion for above tasks
Mitigation with movers					BE-GM (CERN)
Test facility	0.25 FTE/y + 0.1 FTE/y (tbd)	1-2 senior fellows – 2022-2025 (tbd)			HSE-RP (CERN); includes radiation protection and environmental assessment
Key areas of complex					

Additional people interested in participating to define and carry out the work are of course very welcome!

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CERN

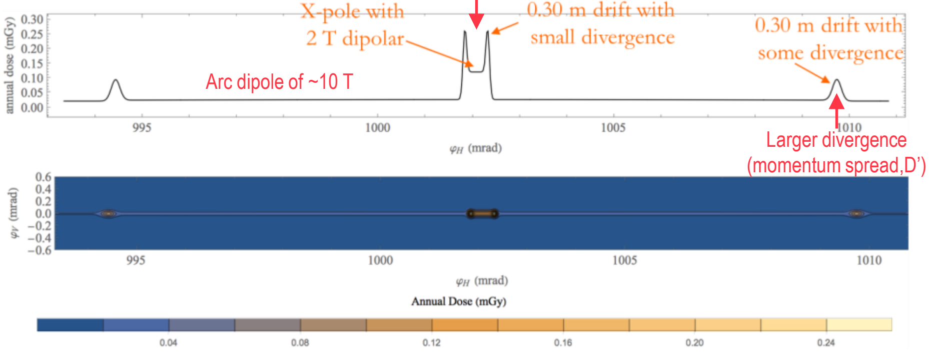
Thank you for your attention!

Dose estimation with MAP lattice – C. Carli

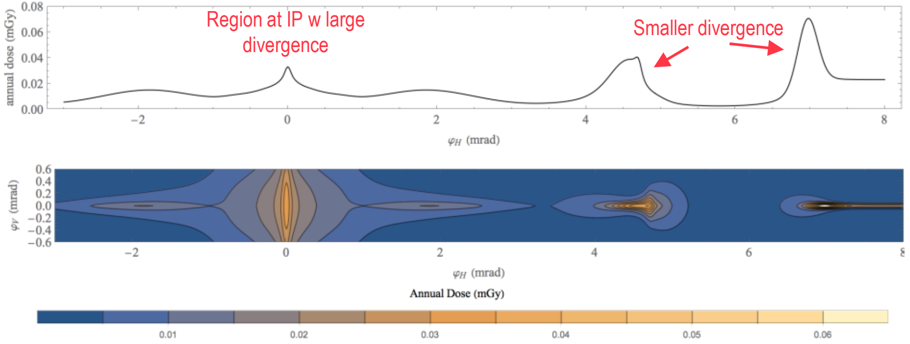
International UON Collider Collaboration

CERN

Center of arc cell



Region around IP



According to paper of B. King Gy!=Sv

- Based on analytical approach by B. King
- Application to 3 TeV c.o.m. lattice from MAP study (9e20 μ decays per year, depth = 100)
- Findings from the arcs: higher doses for reduced field sections and peak doses for small (30 cm) drift sections
- Findings close to IP: beam divergence relatively large at IP and higher dose from regions with smaller vertical/horizontal divergence

- Conclusions:
  - Beam divergence not always negligible (contributions from D' w large momentum spread), which mitigates radiation from straight sections → avoid combined function magnets w too low dipolar field components
- Outlook:
  - Improve lattice designs in arcs (e.g. avoid short straight sections w D'=0, increase dipolar component of combined function magnets)

Mitigation using movers – H. Mainaud Durand

Studies to undertake / points to check (only subset given here)

- Study in further details the state of the art concerning adjustment solutions
- Have a better understanding of the requirements
  - Range of movers ? Resolution? Accuracy?
  - Long-term stability, impact of vibrations?
  - Frequency of adjustment?
  - Constraints from other equipment like cryo and vacuum (acting forces, flexibility)?
  - Weight, size and number of components?
- Study and develop alignment solutions and associated sensors for allowing to do such remote adjustment

Identified key issues

K1. Development of large stroke/high resolution movers to perform safe remote displacements

K2. Development of remote solutions to control the position of components (for circular collider), adapted to such ranges of displacements

K3. Study of the accuracy needed / necessity to develop a solution to determine in a continuous way the absolute position of components underground vs. surface

+ specific points to address (impact on other equipment, safe control system)

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PRELIMINARY STUDY

If we extend the LHC straight insertion
where would the neutrinos come out to the surface of the earth?

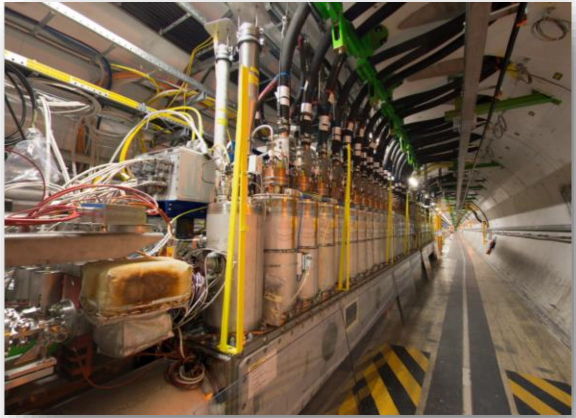
CERN

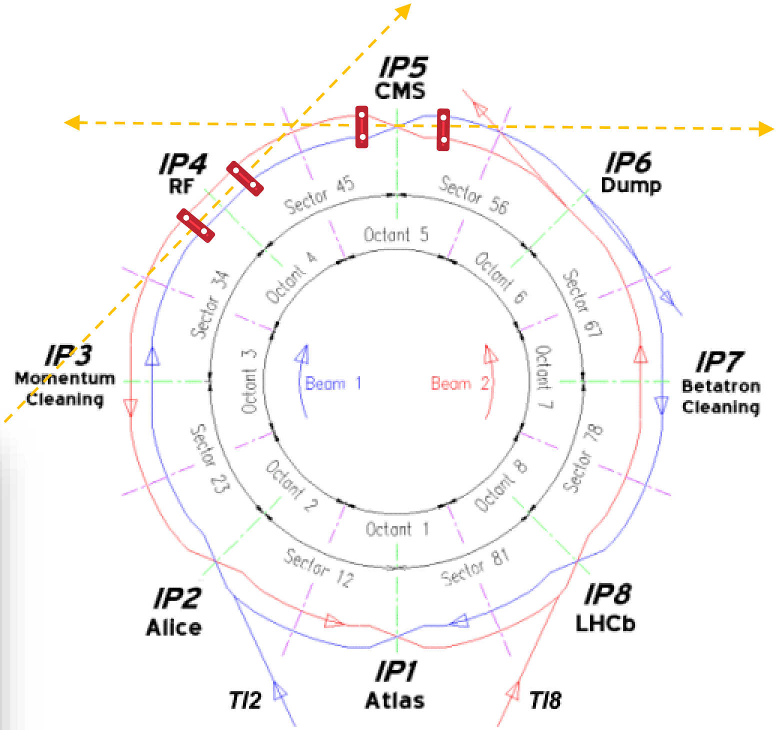
Problem:

« If we extend the LHC straight insertions where would the neutrinos come out the surface of the earth?"

Hypothesis:

The LHC straight insertions directions are given by the lines built **from the middle of Beam 1 and Beam 2 DFBA elements** on each side of the Insertion Point.





International MUON Collider Collaboration

PRELIMINARY STUDY

If we extend the SPS straight sections
where would the neutrinos come out to the surface of the earth?

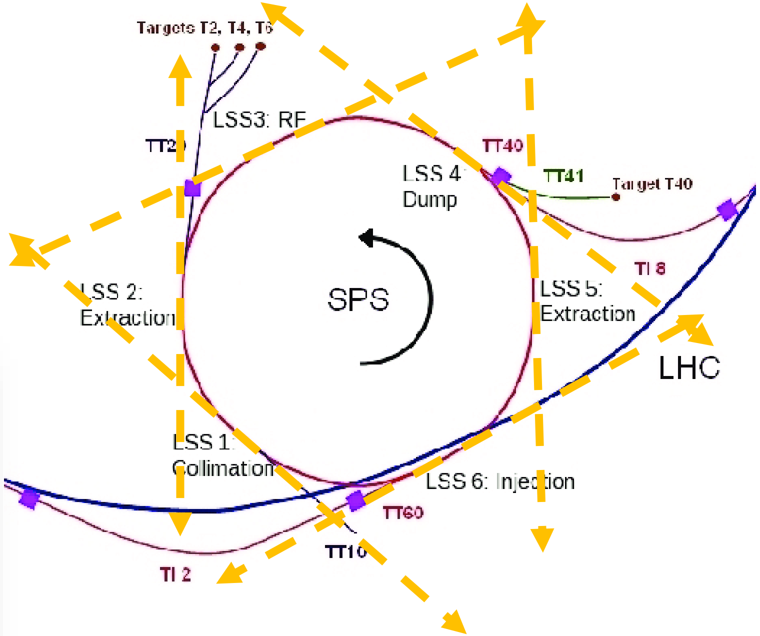
CERN

Problem:

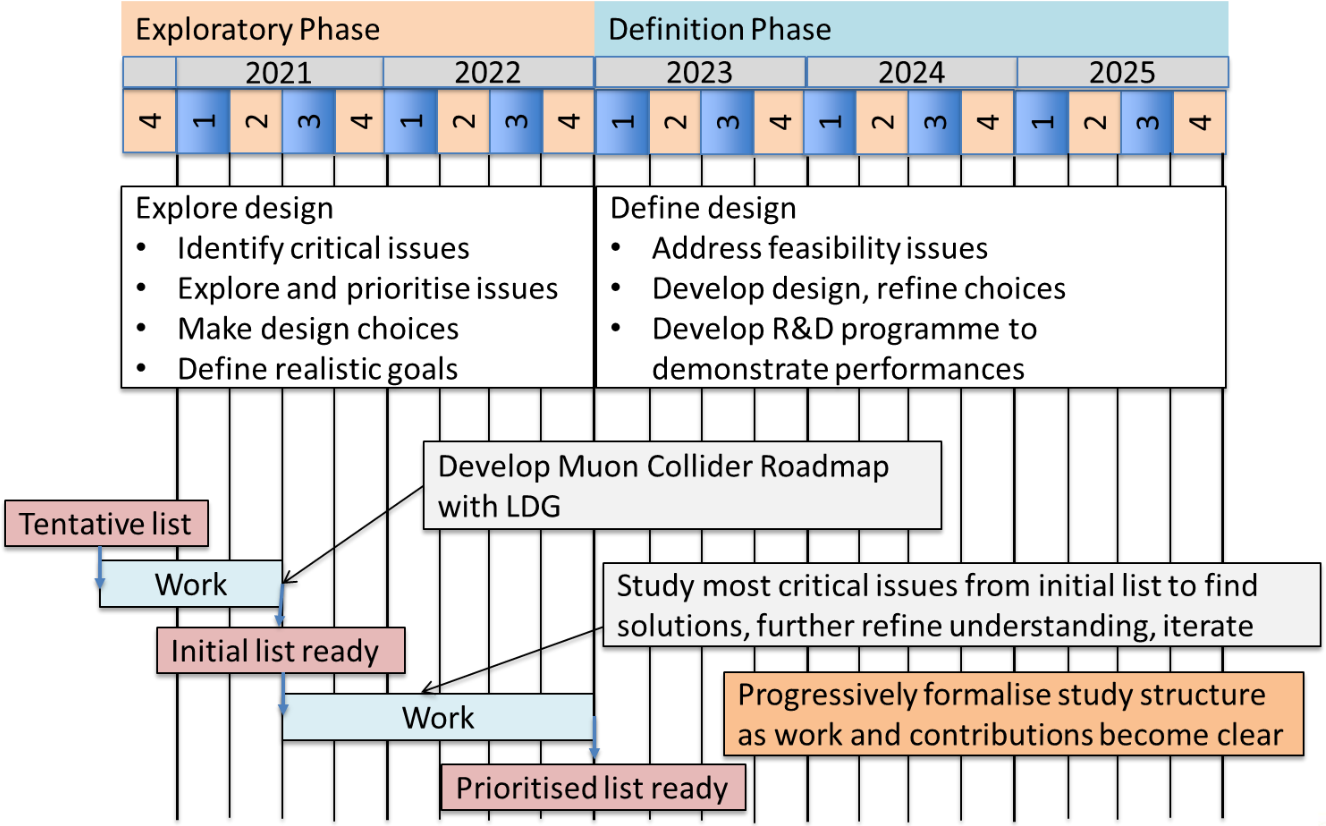
« If we extend the SPS straight sections where would the neutrinos come out the surface of the earth?"

Hypothesis:

The SPS straight sections directions are given by the lines built on dipole **MBA X1590 beam exit points on one side and MBA X2030 beam entrance point on the other side.** *(X for the SPS point)*



Timeline until next ESPPU



Technically Limited Long-Term Timeline