RP considerations for a neutrino induced dose model

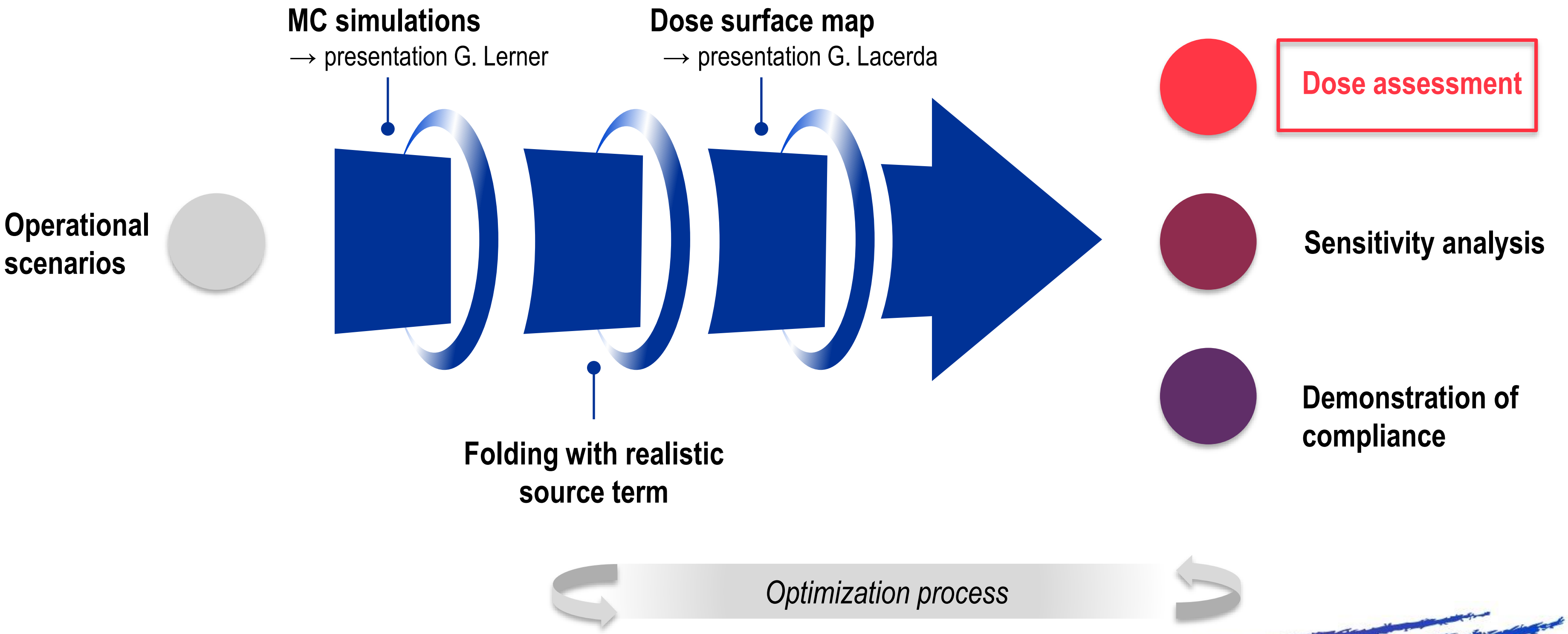
International MUON Collider Collaboration

C. Ahdida, P. Vojtyla, M. Widorski, H. Vincke

Accelerator Design Meeting

31/01/2022

Overview of work related to a refined dose model



Dose assessment

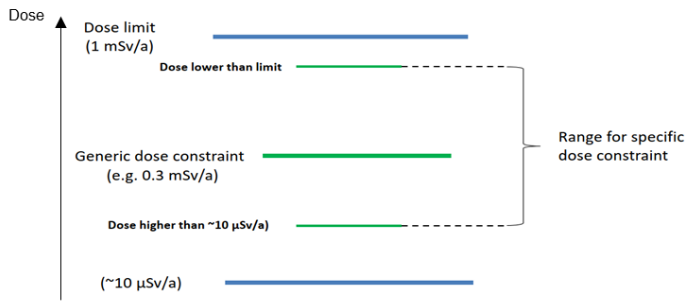
- Aim is to optimize the facility such as to keep the dose at **O(10) μSv/year** for members of the public
- Identify representative person from public for a dose assessment
- Take all exposure pathways to ν-induced radiation* into account
  - External
    - Directly from secondary particle shower and ν
    - *Indirectly via activated/contaminated material (soil, air)*
  - *Internal:*
    - *Inhalation of activated/contaminated air*
    - *Ingestion of activated/contaminated water and food*

Prompt radiation

Residual radiation

Negligible

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

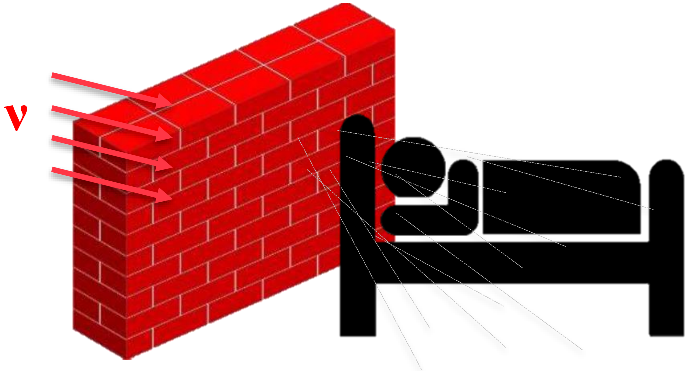


IAEA Safety Standards, General Safety Guide, No. GSG-9

* Other sources of radiation from MUC (e.g. from target area) can be considered negligible at location where ν break the ground

100 rem = 1 Sv

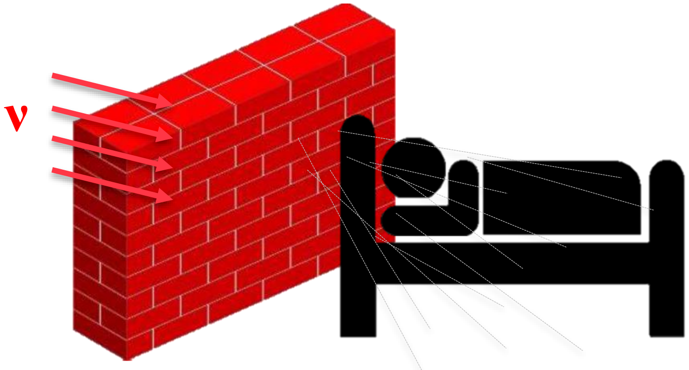
External exposure



The radiation hazard arises primarily from particle showers initiated by ν interactions in material near the person

100 rem = 1 Sv

External exposure



- **General worst case scenario**: maximum exposure and irradiation conditions (e.g. sick person in bed 24/7 at location of max. dose)

  → **Optimization** to **O(10) μSv/year** to be aimed at for whole collider!

- 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 modifying factors for realistic population groups could possibly allow to decrease the dose estimate for certain regions

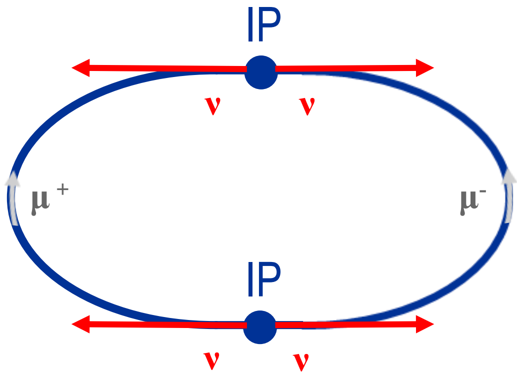
  – Depends on acceptance by authorities

  – Needs to take possible future developments into account

  – Uncertainty of the dose surface map

100 rem = 1 Sv

Critical sections of muon collider



- King, B. J.: *Proc. 1999 Particle Accelerator Conf.*, p. 318 (1999).
- Mokhov, N. V., Van Ginneken, A.: *Proc. 1999 Particle Accelerator Conf.*, p. 3074 (1999).
- N.V. Mokhov and A. Van Ginneken, Neutrino radiation at muon colliders and storage rings, *Proc. 9th Int. Conf. Rad. Shielding,* J. Nucl. Sci. Tech. **S1** 172 (2000); Fermilab-Conf-00/065.

- Radiation hot spots in the disk occur directly downstream from **straight sections** in the collider ring
- Previous studies (see references given here and 1st Muon Community Meeting) have shown substantial dose at far distance particularly from straight sections around the **Interaction Point (IP)**
- Possibly mitigation in the arcs by using movers (NF workpackage)

→ **Focus** at first on refined dose estimation on the Earth's surface for the **4 radiation cones** coming from the **2 IPs** for $\mathbf{E_{com} = 10\ TeV}$

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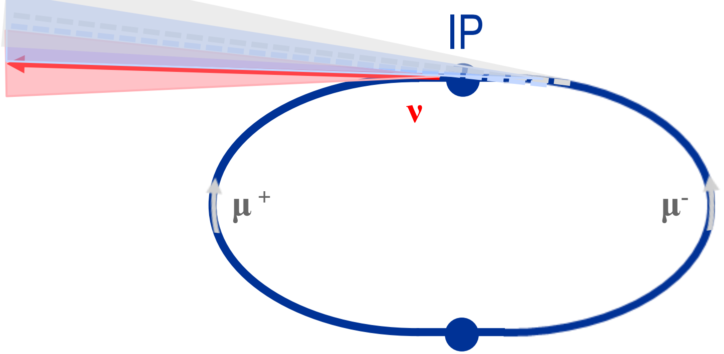

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→ **Focus** at first on refined dose estimation on the Earth's surface for the **4 radiation cones** coming from the **2 IPs** for $\mathbf{E_{com}}$ **= 10 TeV**

→ Evaluate if there are significant contribution from other straight sections

- King, B. J.: *Proc. 1999 Particle Accelerator Conf.*, p. 318 (1999).
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Occupancy dose modification factor

- **Occupancy factor** (f_{OC}): fraction of time regularly spent in the area of concern while being exposed to a given radiation source
- International guidelines give default values, but site studies provide more precise estimates
- f_{OC} = 1 not unlikely at place of residence (e.g. ill/very old persons, persons working at home)
- For workers (incl. farmers) 50 weeks with 40 h/w is typically assumed (f_{OC} = 0.23)
- Site specific occupancy factors to be studied in the future, BUT depend on acceptance by authorities
- Also how to control developments for the far future (even for lakes/oceans such as wind electricity plants)?

Examples of occupancy factors based on international guidelines

Exposure situation	Adults	Children/ adolescents
Residence	1.0	1.0
Work (school)	0.2	0.09
Irrigated field (farmer)	0.2	0.06
Gardening	0.06	0.06
Presence at a river bank	0.18	0.12
Immersion in water	0.03	0.03
Boating	0.02	<0.02

More information can also be found in: *P. Vojtyla, EDMS 2010454 and NCRP 123*

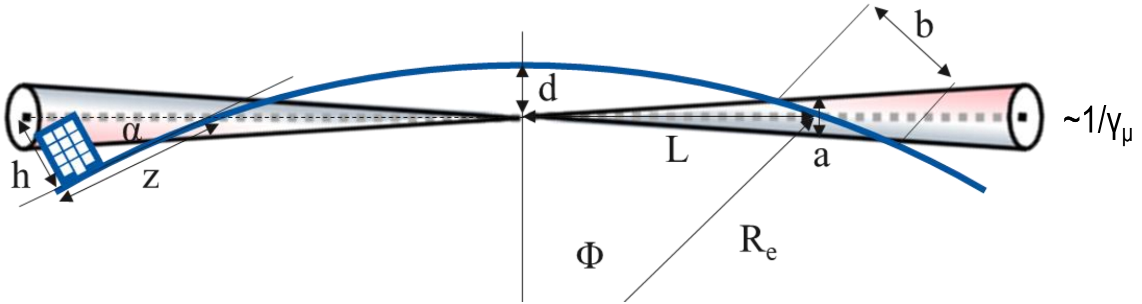
Exclusion areas

Exclusion areas seem attractive, but problems to be considered:

Public acceptance	• Public awareness of „dangerous areas next door due to a particle accelerator at far distance“ • Fencing-off impact area may attract public interest and create doubts on actual control
Acceptance by authorities	• Acceptance by authorities also for exclusion areas required
Other aspects	• Uncertainties connected to the surface dose map to be well-understood • Impacted area may be very large • High costs

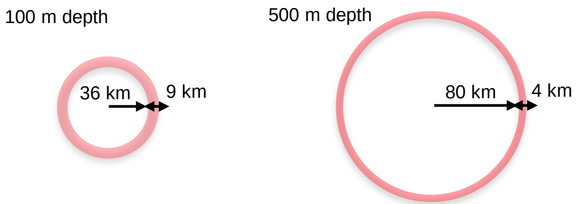
Recap: simplified geometrical considerations

Assumptions: Earth as perfect sphere, no beam divergence, no collider inclination



L – distance, d – depth, R_e – Earth radius

- Neutrino disk has a height (a) of ~1-2.5 m and traverses a region of width (b) of ~100-450 m
- Exit angle of ν radiation is very small, wherefore **impacted area** can be of **several km** (depending on ground profile)



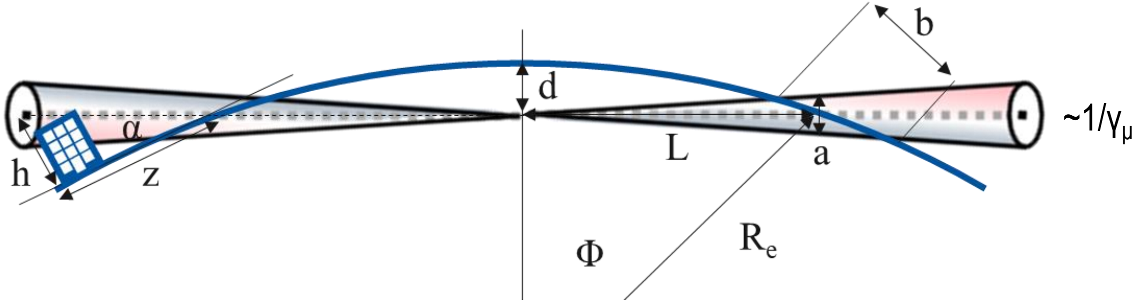
E_{com} [TeV]	3	10	10	14	14
d (m)	100	200	300	400	500
L (km)	36	51	62	71	80
a (m)	2.5	1.1	1.3	1.1	1.2
b (m)	449	135	135	96	96
α (rad)	0.006	0.008	0.010	0.011	0.013
z (km) for h = 50 m	9	6	5	4	4

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

$b \approx a/\Phi$, $\sin\Phi = L/R_e$, $\alpha \approx \mathrm{acos}\,(1 - d/R_e)$, $z \approx h/\tan(\alpha)$

Additional dose spread

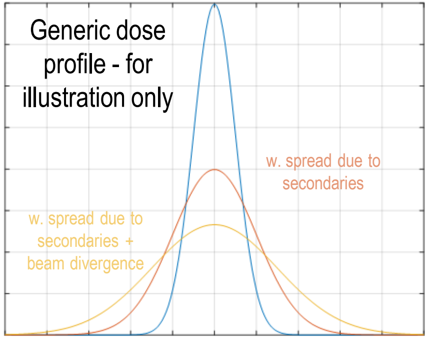
Assumptions: Earth as perfect sphere, no beam divergence, no collider inclination



L – distance, d – depth, R_e – Earth radius

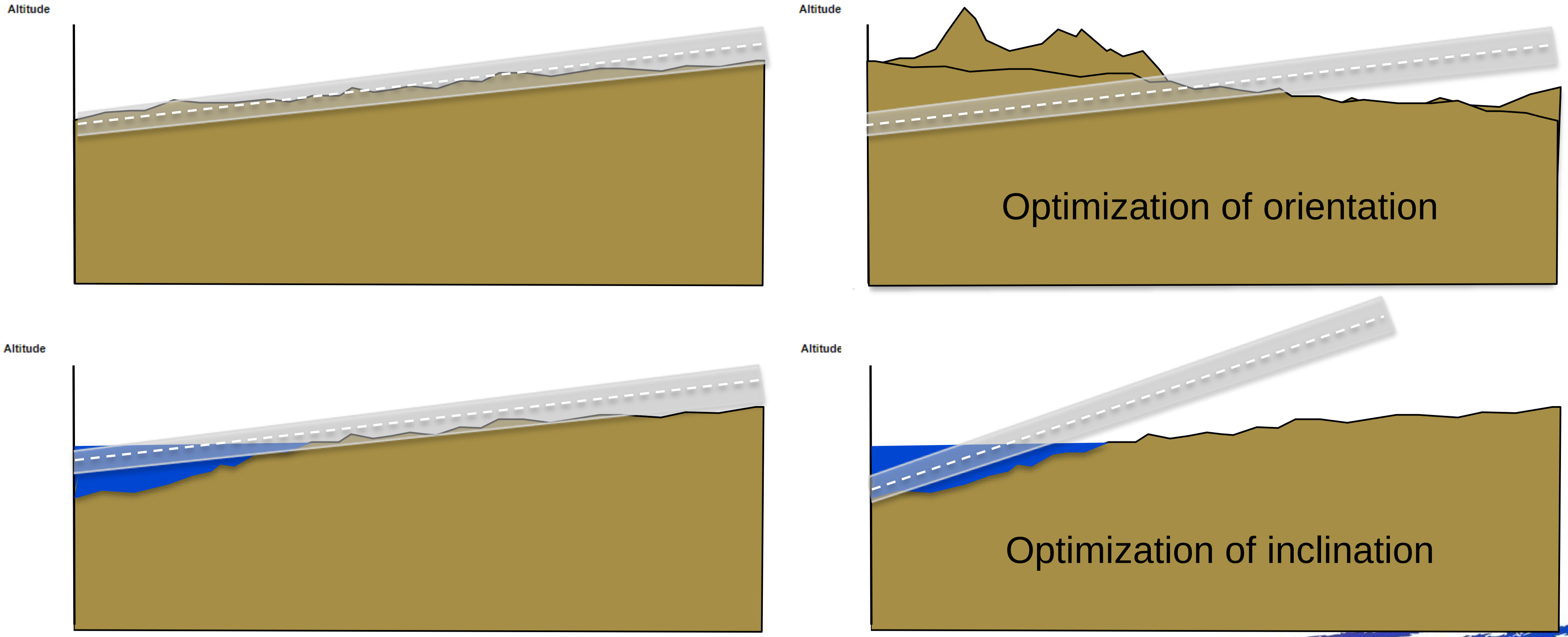
- Next to widening of dose distribution due the μ decay, add. spread due to:
  - Secondary particle shower → evaluated by MC simulations
  - Beam divergence → evaluated from collider lattice (dominant)

  } → *decrease peak dose*
- Even when ν travel above-ground, persons may be exposed to it and its secondaries (e.g. in tall buildings)
  - Feature for determining when ν are higher than a given height above the ground will be taken into account in the surface map
  - Also dose evolution above-ground to be better understood with MC studies
- Impacted area may be very large and still several kilometers behind where the ν break the ground!



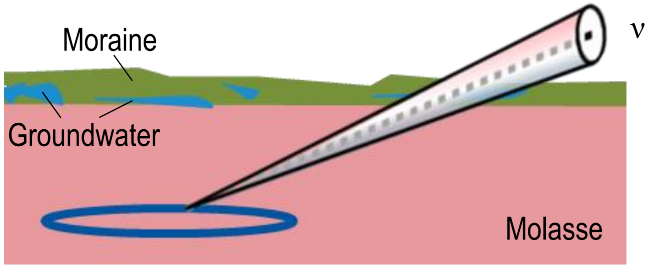
Optimization of collider placement

For illustration only



Risk of ν-induced activation?

- The ν-induced radiation could also cause activation of soil and to a lesser extent air
- In addition to the prompt radiation, persons could then be exposed to residual radiation at the location where ν break the ground
- It can be assumed that the collider is deep underground inside the impermeable molasse → no contact with shallower aquifers and not suitable for exploitation of drinking water
- Therefore, only activation in the more shallow moraine region would be relevant
- What levels of radiation would cause a substantial soil activation?

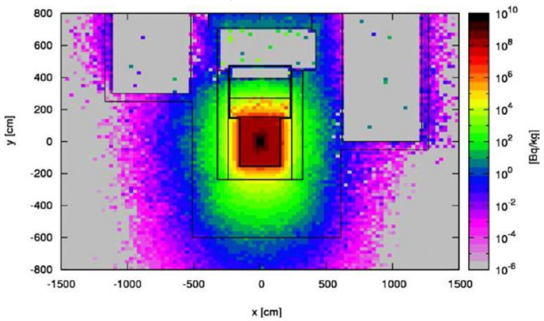


Example of siting in the Geneva area

CENF Earth activation studies

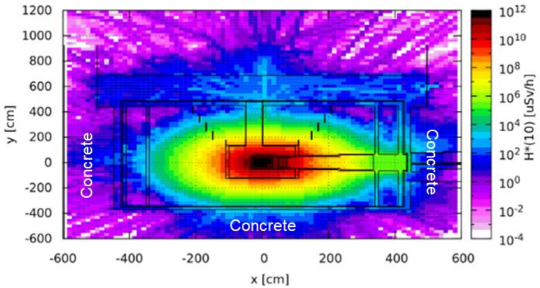
Cross-sectional views of CENF target area

H-3 activity concentration



Prompt ambient dose equivalent rate

Neutron-dominated



- Earth activation and groundwater contamination studies were performed in the past for the proposed CERN Neutrino Facility (CENF)
- Particularly soluble radionuclides likely to pass through the karstic system are critical for the protection of groundwater resources
- To minimise related radiological risks, the specific activities of the leachable radionuclides H-3 and Na-22 should remain below the following design goals:

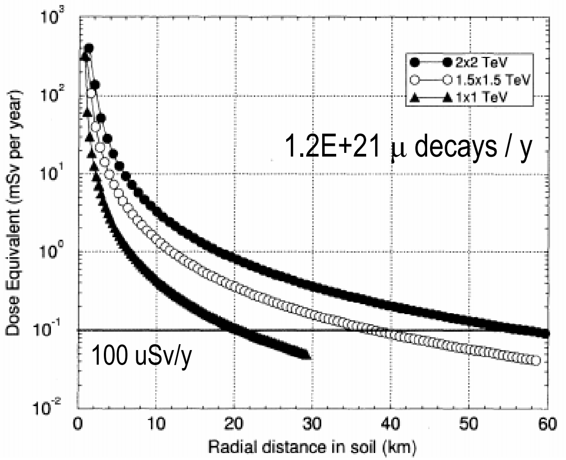
H-3 < 10 Bq/kg, Na-22 < 2 Bq/kg

- When studying the relation between the prompt radiation and the soil activation for the CENF facility, it was found that the above-given limits are not exceeded with prompt dose rates of 1 mSv/h or below

Expected activation levels for MUC

- Reminder: optimization goal is to O(10) uSv/y, where ν break the ground
- A dose rate of 1 mSv/h corresponds to an annual dose of 4e3 mSv/y when assuming 180 days of operation
- Previous MARS simulations show the annual prompt dose for 2/3/4 TeV com as a function of the radial distance in soil from the collider ring center
- Several orders of magnitude margin to the limit where soil activation becomes relevant
- Also for 10 TeV case with different secondary particle fields, the soil activation is expected to be negligible, but to be confirmed with FLUKA simulations
- Air activation where the ν break the ground is expected to be even less critical in view of the optimization goal of O(10) uSv/y above-ground

Annual dose equivalent



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Dosimetric quantities

- One must be careful when comparing results of different studies as the dosimetric quantities can differ (only few discussed here):

Absorbed dose

$$D = \frac{\Delta E}{\Delta m}$$

$$[J * kg^{-1}] = [Gy]$$

Does not take biological aspects into account, but same dose not necessarily same risk

Dose equivalent

ICRP60: $H_T = \sum_R w_R \times D_{T,R}$

ICRP26: $H_T = D_T \times Q \times N$

$$[J * kg^{-1}] = [Sv]$$

Absorbed dose in organ/tissue adjusted for radiation type w radiation weighting factors

	ICRP 26 Q	ICRP 60 w_R	ICRP 103* w_R	Part 20 w_R
Photons, all energies	1	1	1	1
Electrons and muons, all energies	1	1	1	1
Neutrons, all (unknown) energies	10	Step function	continuous function	10
< 10 keV		5	2.5	2 to 2.5
10 - 100 keV		10	2.5 to 10	2.5 to 7.5
100 - 2 MeV		20	10 to 20	7.5 to 11
2 to 20 MeV		10	7 to 17.5	8 to 9
> 20 MeV		5	5 to 7	3.5 to 8
Protons, energy > 2 MeV	10	5	2	10
Alpha particles, fission fragments heavy nuclei	20	20	20	20

*ICRP 116 (2010), which is available in FLUKA, uses same factors as ICRP 103

Source: US NRC

ICRP Publication 103

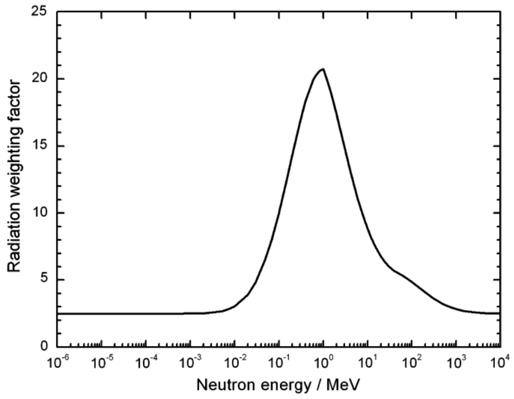

Fig. 1. Radiation weighting factor, w_R, for neutrons versus neutron energy.

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Effective dose

ICRP60: $\mathrm{H} = \sum_T w_T \times H_T$

ICRP26: $H_E = \sum_T w_T \times H_T$

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Whole body dose is obtained by organ/tissue weighting factors

Protection quantities

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Alpha particles, fission fragments heavy nuclei	20	20	20	20

w_T	ICRP 26	ICRP 60	ICRP 103*	Part 20
Gonads	0.25	0.20	0.08	0.25
Breast	0.15	0.05	0.12	0.15
Red bone marrow	0.12	0.12	0.12	0.12
Lung	0.12	0.12	0.12	0.12
Thyroid	0.03	0.05	0.04	0.03
Bone surfaces	0.03	0.01	0.01	0.03
Colon	-	0.12	0.12	-
Stomach	-	0.12	0.12	-
Bladder	-	0.05	0.04	-
Oesophagus	-	0.05	0.04	-
Liver	-	0.05	0.04	-
Brain	-	-	0.01	-
Kidney	-	-	-	-
Salivary Glands	-	-	0.01	-
Skin	-	0.01	0.01	-
Remainder	0.30[6]	0.05[7]	0.12[8]	0.30[9]

*ICRP 116 (2010), which is available in FLUKA, uses same factors as ICRP 103

Source: US NRC

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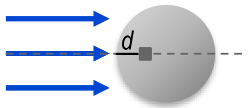
Protection quantities

Ambient dose equivalent H*(d)

Operational quantity

Dose equivalent at a depth d in the ICRU sphere.
This is an operational quantity for area monitoring

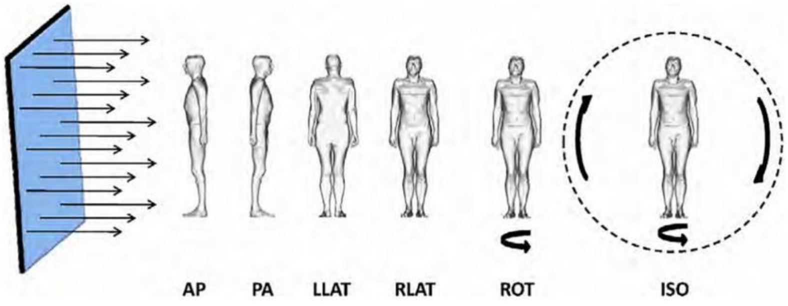


ICRU sphere ,Ø - 300 mm

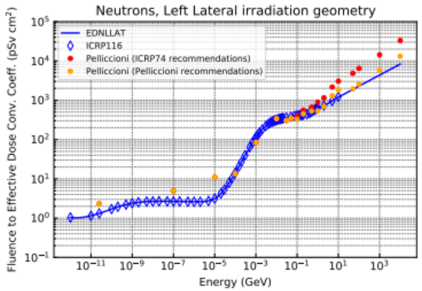
- Inconsistencies between the various protection and operational quantities arise as a consequence of their respective definitions
- According to ICRP the "**effective dose** is used for regulatory purposes worldwide" to provide means of demonstrating compliance with dose limits

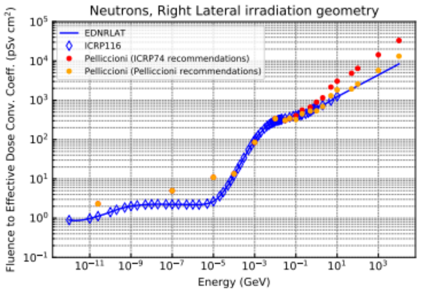
Conversion coefficients

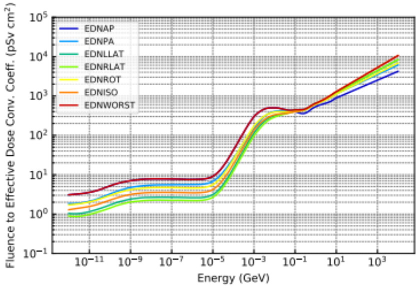
- Protection quantities, such as effective dose, are not measurable
- Conversion coefficients provide numerical links between protection and physical field quantities (e.g. particle fluence)
- These coefficients are defined for Reference Person (anthropomorphic phantoms)
- ICRP/ICRU reference conversion coefficients are available



Fluence-to-effective dose conversion coefficients for neutrons







- Conversion coefficients w extrapolated values 10 GeV - 10 TeV in FLUKA
- Use of max. value of all irradiation geometries (WORST)

D. Bozzato, EDMS 243988

Conclusions

- Optimization to **O(10) μSv/year** to be aimed at for whole collider!
- Occupancy dose modifying factors for realistic population groups could possibly be applied for certain regions of higher dose

  → BUT depends on acceptance by authorities

  → Possible future developments and uncertainties to be taken into account

  → To be investigated for most critical regions of the collider coming from the 2 IPs

  → Impacted area may be very large and still several kilometers behind where the ν break the ground

  → Orientation and inclination of the collider can help to minimize the impacted area
- Exclusion areas seem attractive, but applying this protective measure seems to be unrealistic
- **No risk of ν-induced activation** in public areas is expected
- Be aware of **differences** between the **various protection and operational quantities** as a consequence of their respective definitions
- **Effective dose** is to be used for regulatory purposes worldwide to provide means of demonstrating compliance with dose limits

International
MUON Collider
Collaboration

CERN

Thank you
for your attention!

Optimization for public exposure

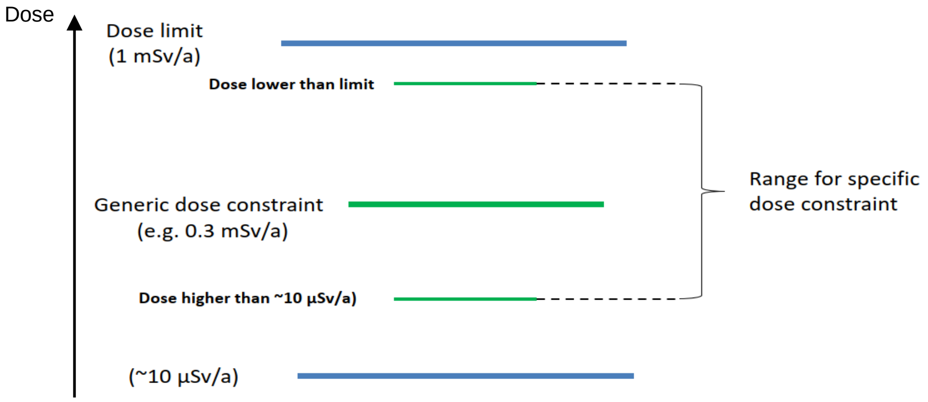
IAEA GSG-8

- **Exemption from regulatory control** if doses remain at **O(10 µSv/year)** and < 1 mSv/year for low probability events (10^{-2} per year)

→ Common practice for nuclear installations to stay below 10 µSv/year (in France even 1 µSv/year)

CERN Safety Code F

- **Optimisation** can be considered as respected if the practice never gives rise to an annual dose above **10 µSv** for members of the public



→ To be aimed at keeping doses at O(10) µSv/year!

https://edms.cern.ch/ui/file/335729/LAST_RELEASED/F_E.PDF

100 rem = 1Sv