# RP summary of 1st Muon Community Meeting

International MUON Collider Collaboration

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

1st Muon Community Meeting

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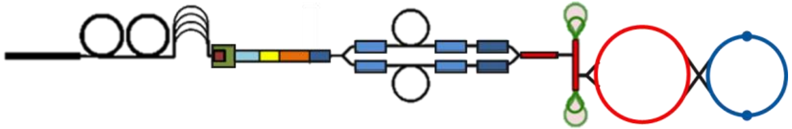
# Two major RP challenges related to the muon collider

## ‚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 levels as low as reasonably possible, but to be addressed at an early design stage (e.g. for high power target complex)

**→ Discussion with MPC working group started**

## Neutrino radiation challenges


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

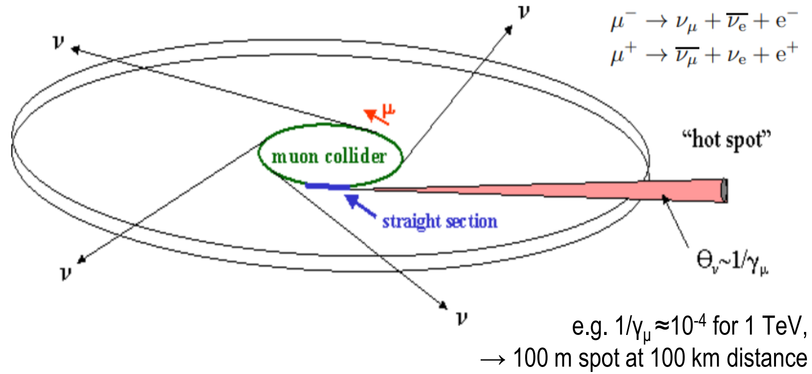
# Neutrino radiation from a muon collider

- The muon decays in a muon collider produce a **neutrino radiation disk** emanating out tangentially from the collider ring with a characteristic opening angle for the cone of $\sim 1/\gamma_\mu$
- **Radiation hot spots** in the disk will occur directly downstream from **straight sections** in the collider ring
- The **neutrino attenuation length** is too long for a sufficient attenuation of the beam by any practical amount of shielding material, even with 80 km earth in between

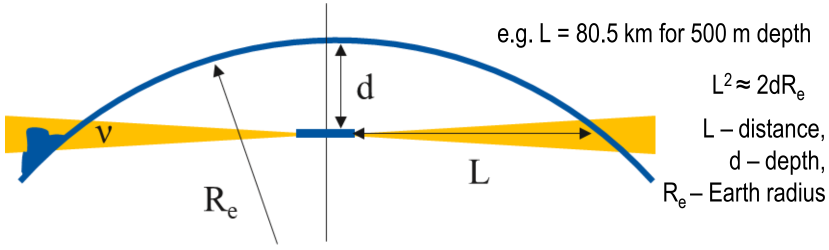
$$\lambda = 0.5 \cdot 10^6 \text{ km } (1 \text{ TeV}/E_\nu) \cdot (3 \text{ g cm}^{-3}/\rho)$$

$\lambda$ – attenuation length, $E_\nu$ – neutrino energy, $\rho$ – material density

→ The main **radiation hazard** from TeV-scale neutrinos is due to **muons** and **hadronic showers** from nuclear interactions in the shielding material upstream. $\nu$ interactions in people themselves only account for ~0.1% of the dose




King, 'Neutrino Radiation Challenges and Proposed Solutions for Many-TeV Muon Colliders', 2000




Johnson et al, 'Radiological Hazard Due to Neutrinos from a Muon Collider', 1998

# Comparison of a few past studies

*Renormalized to 3.3e20 $\mu$ decays per year!*

| Study | Study type | $E_{com}$ [TeV] | Depth [m] | Annual Dose [μSv] Arcs | Annual Dose [μSv] Straight Sec. | Comments |
|---|---|---|---|---|---|---|
| Johnson et al. (1998) | Analytical | 4<br>10 | 200<br>500 | 30<br>180 | 280<br>1770 | $P(E_{\nu})$ from Cossairt et al. Assumption of x10 higher dose at straight section than bending section |
| King (2000) | Analytical | 4<br>10 | 300<br>100 | 20<br>950 | | Average radiation dose in plane of idealized circular muon collider. Gy != Sv |
| Mokhov et al. (2000) | MARS MC | 3<br>4 | 270<br>280 | ~10<br>~25 | | Average radiation dose in plane of idealized circular muon collider |
| Bartosik et al. (2019) | FLUKA MC | 2<br>3 | 50-550<br>50-550 (270) | ~30-5<br>~115-10 (20) | 15, 150<br>55, 550 | For straight section all values are for d = 550m and for different section length / ring length ratio |
| Schulte (2021) | Analytical | 10<br>14 | 500<br>200 | 180<br>10* | 625 | Average dose for ideal circle. Peak in arcs from 0.2 m “mini” straights. *Avg. circle w **full mitigation** (± 1 mrad) |
| Carli (2021) | Analytical | 3<br>3 | 100<br>100 | 10<br>35-100 | 35<br>30 | - Simple case w/o divergence; Gy != Sv like King; “mini” straights<br>- **MAP lattice (focusing structure+divergence)** |

Only a subset of dose estimates is shown for comparison

- All previous studies show a **substantial dose** at far distance, particularly from straight sections, but still **room for improvement**
- A **reliable dose estimation** is needed on the basis of an optimized beam lattice for reaching O(10) μSv
- **O(10) μSv** is an ambitious target, but seen adequate based on **international guidelines, legal frameworks** as well as **public acceptance**

100 rem = 1Sv

# Radiation assessment & optimization

**Input needed for a more refined radiation dose model**

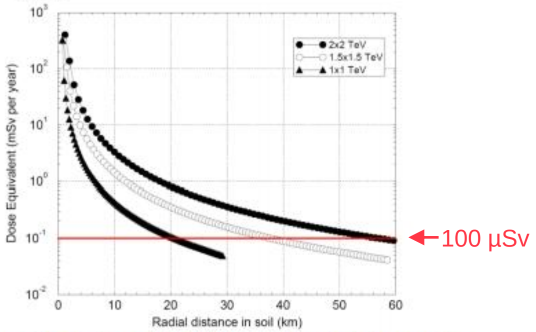
- Operation modes and scenarios for a specific collider design
- Source term definition and **optimization/mitigation**
- Topographical model
- “Full path assessment” of exposure scenarios between source and location where radiation hazard will become trivial
- Sensitivity of dose assessment on study parameters (alignment, current, optics, material properties)
- Validation of simulation models and codes
- Consider potential accident scenarios (“what could go wrong”)
- Means of control to assess dose impact, both at the source (emission) and impact side (immission)

Assessment for planned and potential exposure situations:

- Identify representative person(s)
- Dose assessment to representative person(s)
- Compare to dose objective, dose constraints and limits

# Possible mitigation measures – N. Mokhov

## 1. Place collider deep underground

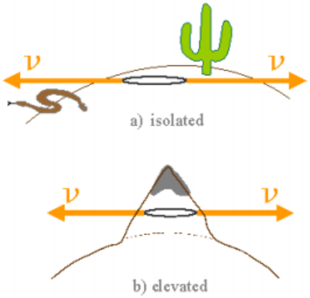



Around the 2, 3 and 4 TeV rings in orbit plane with $1.2\times10^{21}$ decays/yr *vs* distance in soil from ring center

- Dose decreases with radial distance in soil (depth of the collider)
- Only partly a solution (feasibility of depth, Earth's curvature)

## 2. Isolated Site

- Desert
- Mountain region
- Remote island

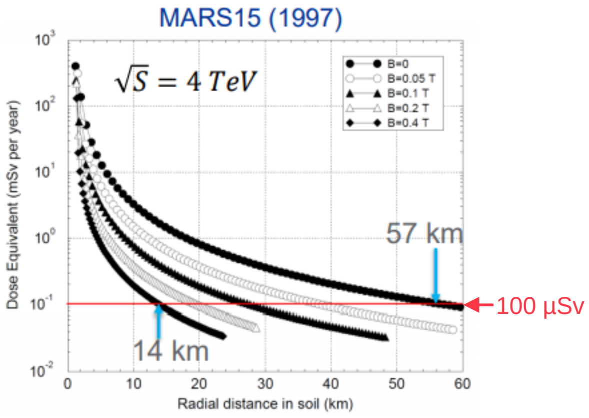



- Challenges for infrastructure and regulatory and public acceptance (control over area difficult)

100 rem = 1Sv

# Possible mitigation measures – N. Mokhov

## 3. Minimize field-free regions




- Strong dose reduction by increased magnetic fields
- Straight sections could be shortened by using continuous combined function magnets
- Beam wobbling by vertical wave field shifting the orbit longitudinally, CJ & NM (1997)

## 4. Reduce muon beam intensity with same luminosity

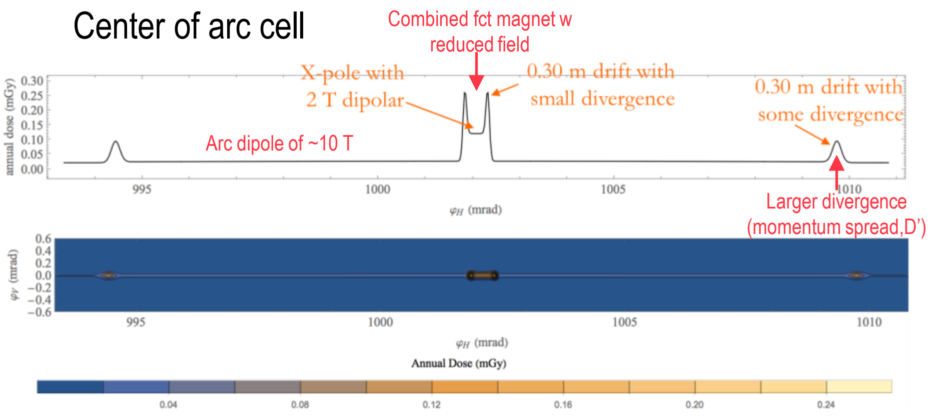
- Better cooling, e.g., optical stochastic cooling, might reduce the emittances by several orders of magnitude, thus greatly reducing the required muon beam currents keeping luminosity the same
- Better focussing: its strength could be increased by the use of plasma or other exotic focusing method at IP

→ To be further investigated when optimizing the ν source term

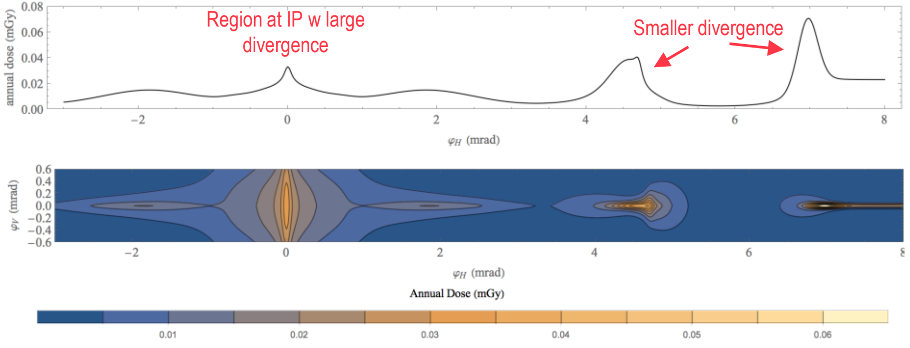
100 rem = 1Sv

# Dose estimation with MAP lattice – C. Carli

Center of arc cell




Region around IP




According to paper of B. King Gy!=Sv

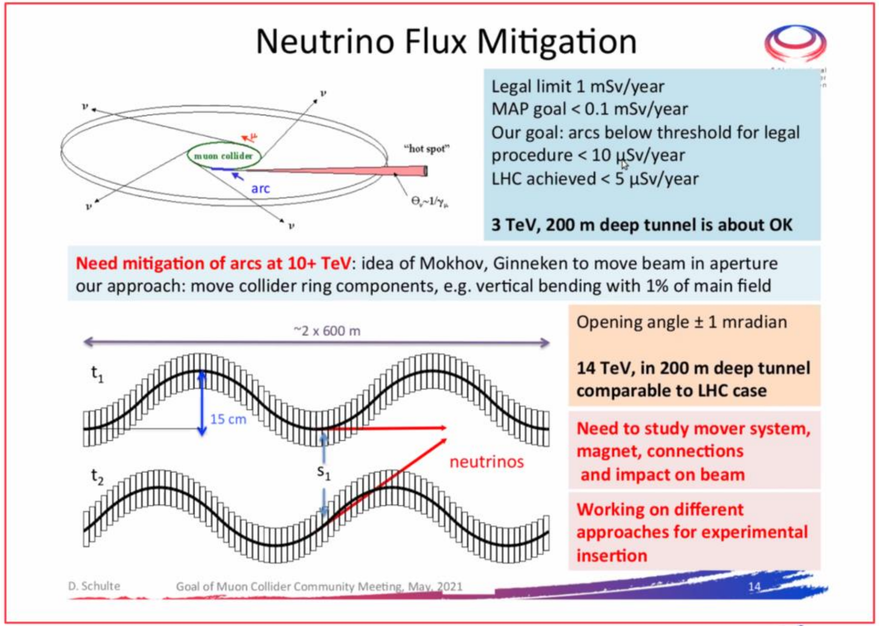
- Based on analytical approach by B. King
- Application to 3 TeV c.o.m. lattice from MAP study (9e20 $\mu$ decays per year, depth = 100)
- Findings from the arcs: higher doses for reduced field sections and peak doses for small (30 cm) drift sections
- Findings close to IP: beam divergence relatively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

100 rem = 1Sv

# Mitigation using movers – H. Mainaud Durand

- 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.




- Brief overview of state of the art including Full Remote Alignment System (FRAS): ± 5 mm

# 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)

# R&D items connected to RP

- **Important work** ahead to tackle the **neutrino induced radiation hazard** at a muon collider
- **Two main R&D items:**
  1. Work related to a refined radiation dose model including optimization (e.g. lattice optimization, MC model)
  2. Work related to "wobbling" of the machine with movers in arcs (preliminary work plan was set up)

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***Thank you***
***for your attention!***

# Muon collider luminosity goals

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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 |
| $\varepsilon_L$ | MeV m | 7.5 | 7.5 | 7.5 |
| $\sigma_E$ / E | % | 0.1 | 0.1 | 0.1 |
| $\sigma_z$ | 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

→ Assuming a run time of 1.5e7 s (174 days) results in 3.3e20 muon decays per year for the 3 TeV case

# Mitigation using movers – H. Mainaud Durand

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## Very preliminary work plan

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- *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)

# Past studies on neutrino radiation hazard

A potential neutrino radiation hazard has been addressed generically (analytically and by Monte Carlo (MC) simulation) in the past (selection of papers/presentations):

1. Carli, Considerations on Radiation, Muon Collider Design Meeting, 08.03.2021
2. Schulte, Radiation Mitigation Introduction, Muon Collider Design Meeting, 18.01.2021
3. Bartosik et al., Preliminary Report on the Study of Beam-Induced Background Effects at a Muon Collider, 2019
4. Pastrone, Future plans towards a muon collider, nuSTORM, 2019
5. Neuffer and Shiltsev, On the Feasibility of a Pulsed 14 TeV c.m.e. Muon Collider in the LHC Tunnel, 2018
6. Silari and Vincke, Neutrino Radiation Hazard at the Planned CERN Neutrino Factory, 2002
7. Mokhov and Ginneken, Neutrino Radiation at Muon Colliders and Storage Rings, 2000
8. King, Neutrino Radiation Challenges and Proposed Solutions for Many-TeV Muon Colliders, 2000
9. Johnson, Rolandi and Silari, Radiological Hazard Due to Neutrinos from a Muon Collider, 1998
10. Agosteo and Silari, Radiation Calculations for the New Muon/Photon Test Facility at CERN, 1997

# Limitation for public exposure in ICRP and IAEA Safety Standards

Effective **dose limit** for a member of the public for the exposure from **all sources**

III.3. For public exposure, the dose limits are:

(a) An effective dose of 1 mSv in a year;

(b) In special circumstances[68], a higher value of effective dose in a single year could apply, provided that the average effective dose over five consecutive years does not exceed 1 mSv per year;

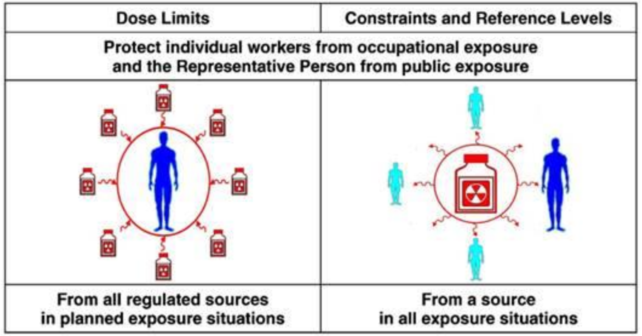
Effective **dose constraint** for a member of the public for a **single source**

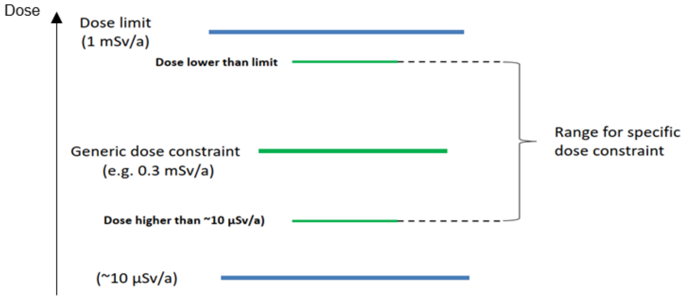
2.23. A constraint is a prospective and source related value of individual dose (dose constraint) or risk (risk constraint) that is used in planned exposure situations as a parameter for the optimization of protection and safety for the source, and that serves as a boundary condition in defining the range of options in optimization.

2.24. A dose constraint is a level of dose above which it is unlikely that protection is optimized. It represents a basic level of protection and will always be lower than the pertinent dose limit. However, treating a dose constraint as a target value is not sufficient, and it is expected that optimization of protection will establish an acceptable level of dose below the dose constraint.

**100 rem = 1Sv**

ICRP Publication 103




[68] For example, in authorized, justified and planned operational conditions that lead to transitory increases in exposures

# Optimization for public exposure

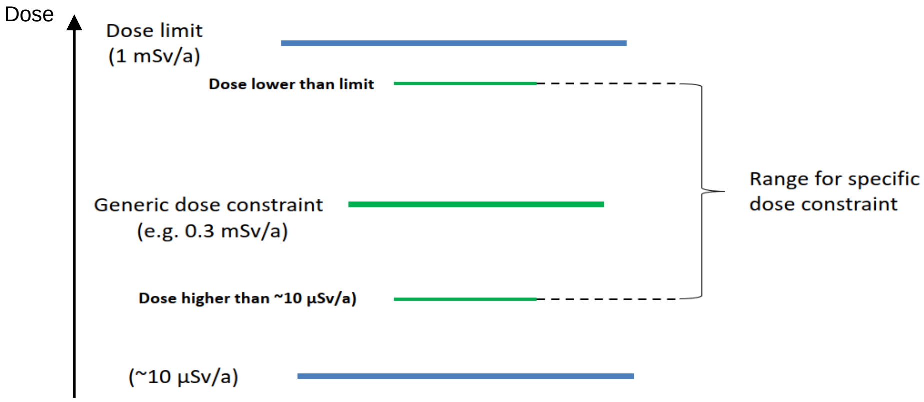
**IAEA GSG-8**

- **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

# Public awareness & acceptance

Beside what is legal, public acceptance will be key:

- Dealing with radiation fear & control on communication
- Only dose levels far below exposure from natural sources are generally accepted
- Exclusion areas seem attractive, but side effects should be considered:
  - Public acceptance (and benefit) decreases with distance from the collider
  - Public awareness of „dangerous areas next door caused by a far-away particle accelerator"
  - Fencing-off impact area may attract public suspicion and create doubts on actual control ("how can one be precise over such a distance")
  - Combination with an experiment may simplify communication und create local benefit
  - Locating the impact point in an inaccessible or non-residential area (ocean, lake, mountain area) may simplify acceptance by authorities and public, but control over area remains difficult