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Neutrino Flux around Muon Colliders and 7 Ways to Mitigate it

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Workshop Muon-Driven Colliders

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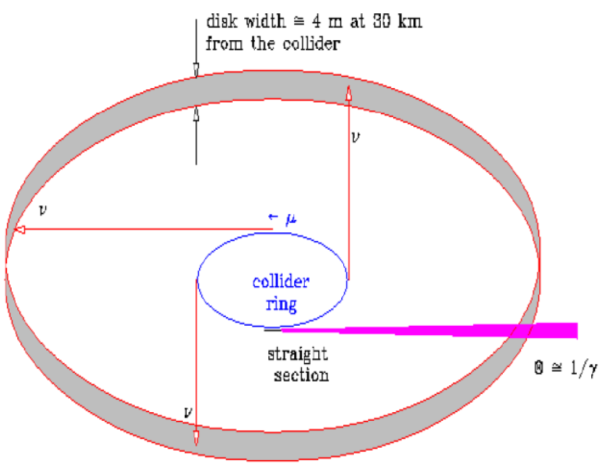
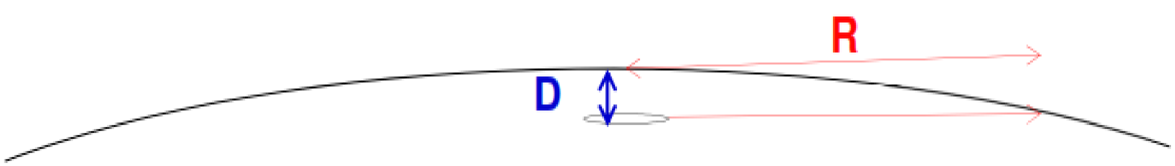
Tentative Muon Collider Parameters

Parameter	Symbol	unit			
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Average field	$\langle B \rangle$	T	7	10.5	10.5
Muons/bunch	N	10^{12}	2.2	1.8	1.8
Repetition rate	f_r	Hz	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	20
Longitudinal emittance	ϵ_L	MeVm	7.5	7.5	7.5
Transverse emittance	ϵ	μm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.07
IP betafunction	β	mm	5	1.5	1.07
IP beam size	σ	μm	3	0.9	0.63

Neutrino Flux at a Distance from Collider Ring (1)

Intense highly collimated neutrino beams, created from muon decays in the ring and various straight sections of high-energy $\mu^+\mu^-$ colliders (MC), can cause – to the surprise of many - radiation problems even at very large distances from the machine.





$$R = \sqrt{2R_{earth}D}$$

The more energetic decay neutrinos emanate radially outward from the collider ring at angles with respect to the muon direction of order

$$\theta_\nu = 1/\gamma_\mu = m_\mu/E_\mu \simeq 10^{-4}\ /E_\mu[\mathrm{TeV}]$$

Neutrino Flux at a Distance from Collider Ring (2)

Neutrino flux and dose per neutrino at a given location from muon colliders (MC) grow with muon energy – keeping all other MC parameters the same - roughly as $\boldsymbol{E_\mu^3}$ due to (each responsible for a factor of E_μ):

1. Increase with energy of the neutrino cross section
2. Grows of total energy deposited
3. Collimation of the decay neutrinos

This will impact strongly siting issues and cost of a high energy muon collider and needs to be taken seriously in evaluating long-term averaged neutrino flux and resulting dose.

Developed by NM & AVG in 1996 a weighted neutrino interaction generator for the MARS Monte Carlo code permitted detailed simulations of the interactions with matter of neutrinos and of their progeny in and around MC capable to modeling neutrinos in the energy range from 10 MeV to 10 TeV.

Neutrino-Interaction Model in MARS15 (1)

The model serves to represent energy and angle of the particles emanating from a simulated interaction. These particles, along with the showers initiated by them, are then further processed by the MARS code which calculates, e.g., energy deposition, absorbed and effective dose as a function of location in a user specified geometry model. Effective dose – caused by charged particles from neutrino interactions - is calculated with particle- and energy-dependent quality factors taken into account. Muon and electron neutrinos and their antiparticles are included and distinguished throughout, which are represented in the decays from MC in roughly equal amounts. The MARS model identifies charged and neutral current deep inelastic neutrino and antineutrino interactions with nuclei as the dominant channels forming the main contributions to the dose from neutrino interactions. For the first channel (first row in the Table), total cross-sections σ in cm^2 are assumed to be $6.7\times 10^{-39} E_\nu$ per nucleon with E in GeV for neutrino and a half of that for antineutrino. The differential cross section is

$$\frac{d\sigma}{dx\,dy} = \frac{G^2 x s}{2\pi}\left(Q(x) + (1-y)^2\,\overline{Q}(x)\right)$$

where $x=-q^2/2M\nu$ with q the momentum transfer, M the nucleon mass and ν the energy loss of the neutrino in the lab, $y=\nu/E_\nu$, G is the Fermi coupling constant, s is the total energy in the center of mass, and $Q(x)$ represents quark (antiquark) momentum distributions inside the nucleon.

Neutrino-Interaction Model in MARS15 (2)

For the neutral current deep inelastic neutrino and antineutrino interactions with nuclei (second row in the Table), total cross-sections σ in cm^2 are taken as $2.2 \times 10^{-39}\, E_\nu$ per nucleon with E in GeV for neutrino and $1.35 \times 10^{-39}\, E_\nu$ for antineutrino. The differential cross section is built similarly to that as for the charged current deep inelastic neutrino and antineutrino interactions.

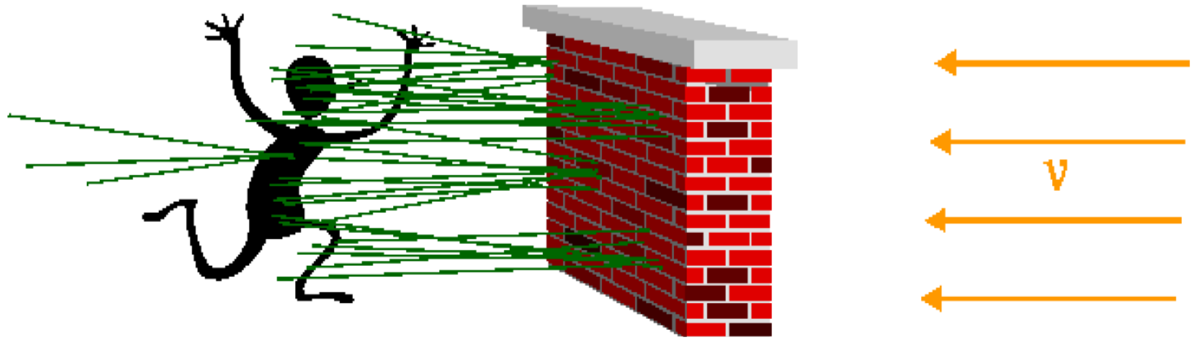
Besides that, the model accurately describes neutrino-nucleon elastic and quasi-elastic scattering (rows 3-5), interactions with atomic electrons (rows 6-7) and coherent elastic scattering (row 8 in the Table). In latter, a Pauli formfactor of quark – topological fluctuation of QCD vacuum - is included (as a weight) to discourage small $|q^2|$ insufficient to liberate a nucleon or promote the nucleus to an excited state.

Table 1: *Neutrino Interactions*

$\nu_\mu N$	$\to$	$\mu^+ X$	$\overline{\nu}_\mu N$	$\to$	$\mu^- X$	Charged current deep inelastic
$\nu_\mu N$	$\to$	$\nu_\mu X$	$\overline{\nu}_\mu N$	$\to$	$\overline{\nu}_\mu X$	Neutral current deep inelastic
$\nu_\mu p$	$\to$	$\mu^+ n$	$\overline{\nu}_\mu n$	$\to$	$\mu^- p$	Elastic and quasi-elastic scattering
$\nu_\mu p$	$\to$	$\nu_\mu p$	$\overline{\nu}_\mu p$	$\to$	$\overline{\nu}_\mu p$	Elastic and quasi-elastic scattering
$\nu_\mu n$	$\to$	$\nu_\mu n$	$\overline{\nu}_\mu n$	$\to$	$\overline{\nu}_\mu n$	Elastic and quasi-elastic scattering
$\nu_\mu e^-$	$\to$	$\nu_\mu e^-$	$\overline{\nu}_\mu e^-$	$\to$	$\overline{\nu}_\mu e^-$	*Neutrino-electron* – almost negligible
$\nu_\mu e^-$	$\to$	$\nu_e \mu^-$				
$\nu_\mu A$	$\to$	$\nu_\mu A$	$\overline{\nu}_\mu A$	$\to$	$\overline{\nu}_\mu A$	Coherent elastic scattering

“Neutrino” Dose around Muon Colliders

Extremely low interaction and scattering probabilities mean that neutrinos travel essentially in a straight line and survive over enormous distances. Much like neutrons and gammas, neutrinos by themselves cause little or no biological damage but instead create charged particles which in turn deposit their energy in tissue to be interpreted as dose “due to neutrinos”.
“Neutrino” dose is by charged particles generated by neutrinos upstream a human.

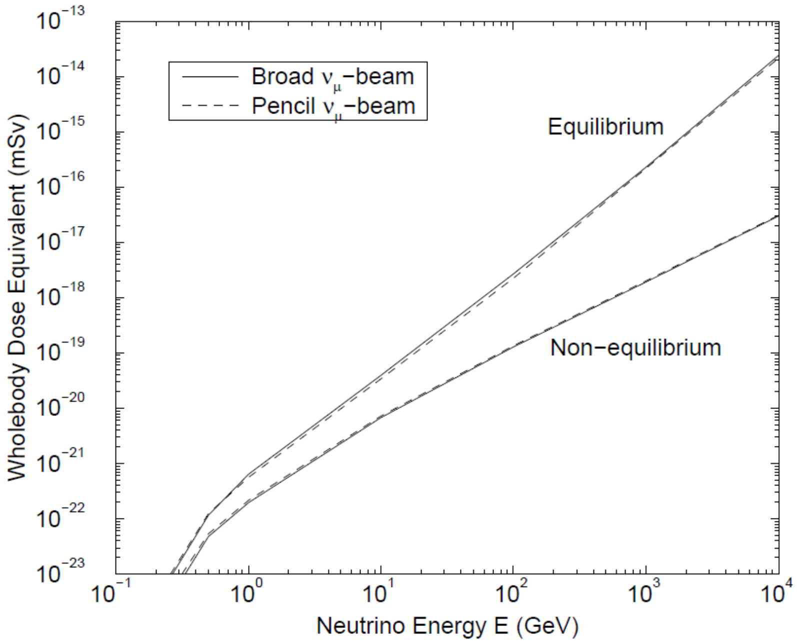


Therefore:

- Small effect for anyone above ground or/and above ground building
- Noticeable effect inside a basement swimming pool
- Unacceptably high effect, e.g., for a person lying in a basement room for extended period

Dose to a Human Body *vs* Neutrino Energy

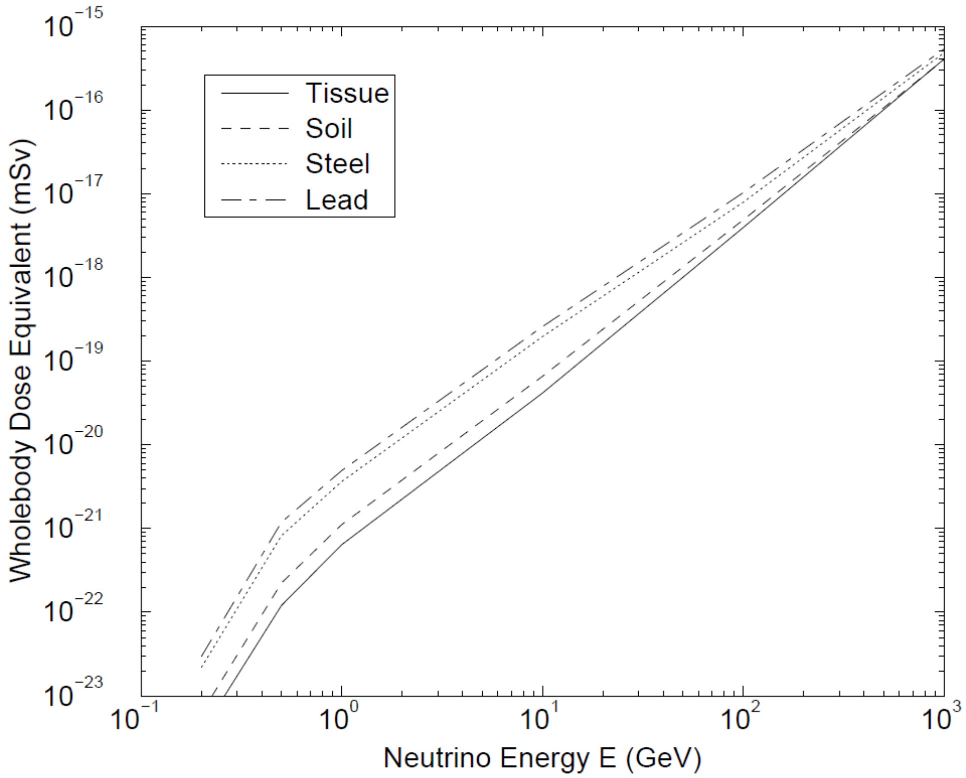
- Total whole-body effective dose in a bare seated person (**non-equilibrium**) and in one embedded in infinite soil (**equilibrium**).
- The whole-body dose is a factor of 2 lower than the maximum dose, because a neutrino flux footprint could be smaller than typical human directions.
- The equilibrium dose is achieved after 3-4 m of soil or concrete at all neutrino energies considered here.
- Instead of providing shielding, the presence of soil/concrete upstream enhances the dose by a factor of 1000 in the TeV region as compared to the case with no shielding.



Annual off-site limits:

DOE	**1 mSv = 100 mrem**
FNAL	**0.1 mSv = 10 mrem**
Europe	**0.01 mSv = 1 mrem**

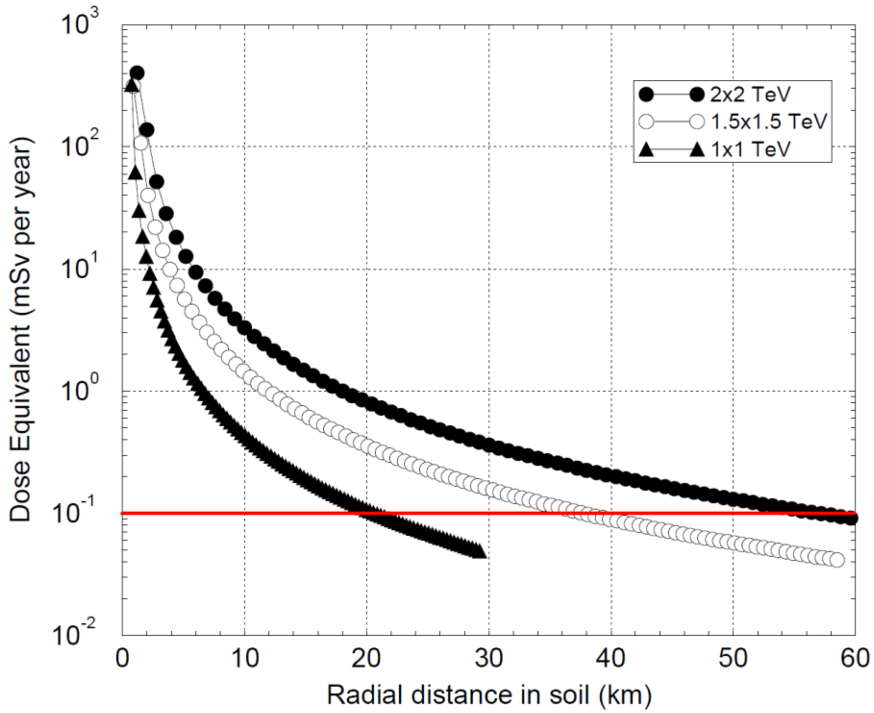
Neutrino-Induced Dose *vs* Upstream Material

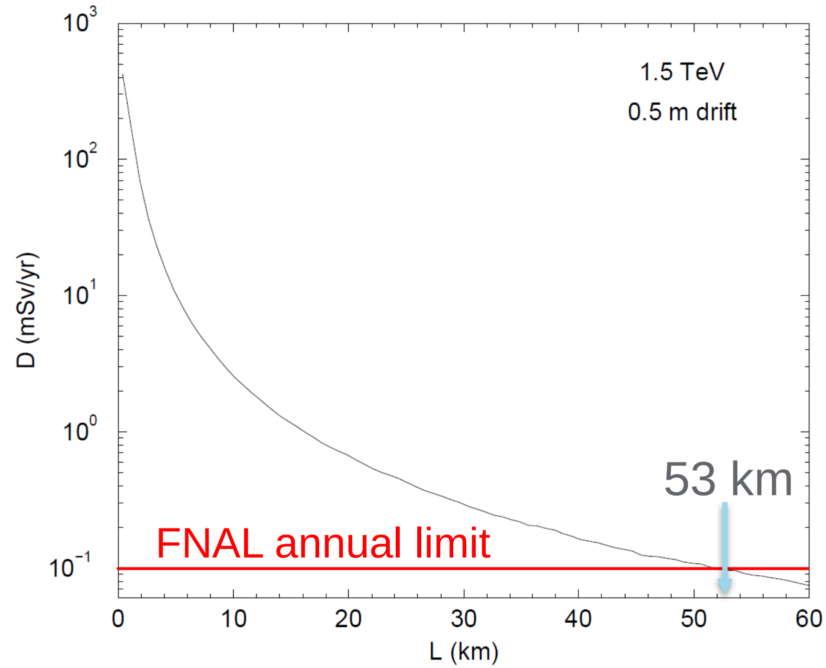


Whole-body dose in a 60-cm long tissue equivalent phantom embedded in infinite materials *vs* neutrino energy for a broad ν_{μ}-beam. Dose after a high-Z shielding is up to a factor of ten higher than that for a low-Z shielding at low neutrino energies, while the values converge in the TeV energy range.

At low energy, a larger fraction of the dose is delivered by (high quality factor) low energy neutrons whereas at high energy the electromagnetic component (with quality factor essentially unity) dominates.

Maximum Equilibrium Dose *vs* Distance in Soil





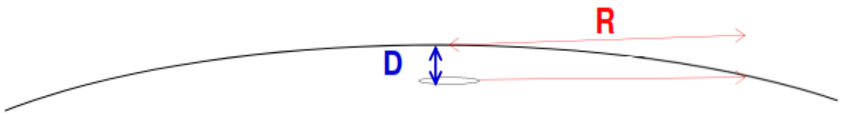
Around the 2, 3 and 4 TeV MC rings in the orbit plane with 1.2×10^{21} decays per year *vs* distance in soil from the ring center

1.5-TeV muon beam with 2.6×10^{16} decays/yr in a 0.5-m drift *vs* distance in soil downstream the drift.

Contribution from field-free regions (drifts, straight sections, etc.) becomes a serious one at high-energy muon colliders even with very short regions: at E_μ = 10 TeV, 0.1-m drift and10^{16} decays/yr ⟶ L=380 km

Seven Ways to Mitigate Neutrino Flux around Muon Colliders

Mitigation (1): Place Collider Deep Underground



$$R = \sqrt{2R_{earth}D}$$

	$\sqrt{s}$ (TeV)	0.5	1	2	3	4
	$N \times 10^{21}$	0.2	0.2	1.2	1.2	1.2
1 mSv	R (km)	0.4	1.1	6.5	12	18
	D (m)	≤ 1	≤ 1	3.3	11	25
0.1 mSv	R (km)	1.2	3.2	21	37	57
	D (m)	≤ 1	≤ 1	34	107	254

0.01 mSv/yr -> *D*=300 m for 3TeV case

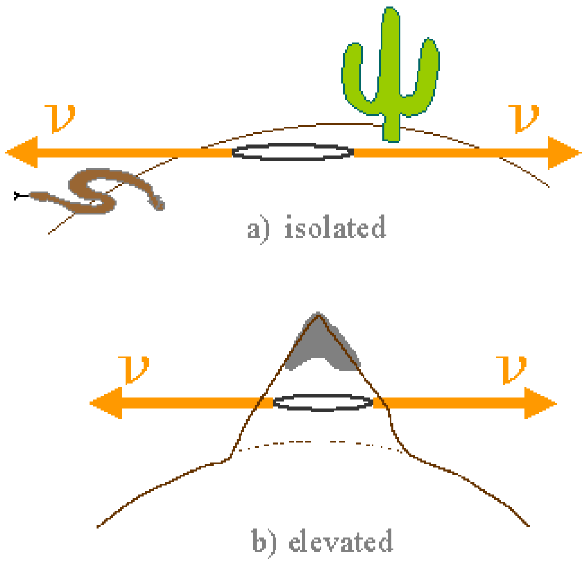
- Assuming suppressed contribution from field-free regions
- The Earth's curvature prevents this from being a generic solution
- There is also the regulatory question whether delivering an off-site dose above the limit at any depth underground or height above it is permissible

MARS-calculated depth *D* to reduce ν-induced long-term maximum dose at surface (at radial distance *R* from collider ring center) to DOE and Fermilab annual off-site limits at N decays/yr.

Note that simplified expressions derived by B. King in 1996-1998 give noticeably more conservative results compared to those from MARS full Monte Carlo. For example, for the 3-TeV case, depth to stay within 0.01 mSv/yr 1% of the DOE limit is 300 m (MARS) compared to the analytical 500 m (Ankenbrandt et al, 1999).

Mitigation (2): Isolated Site for multi-TeV MC

- Desert
- Mountain region
- Remote island



Mitigation (3): Minimize Field-Free Regions

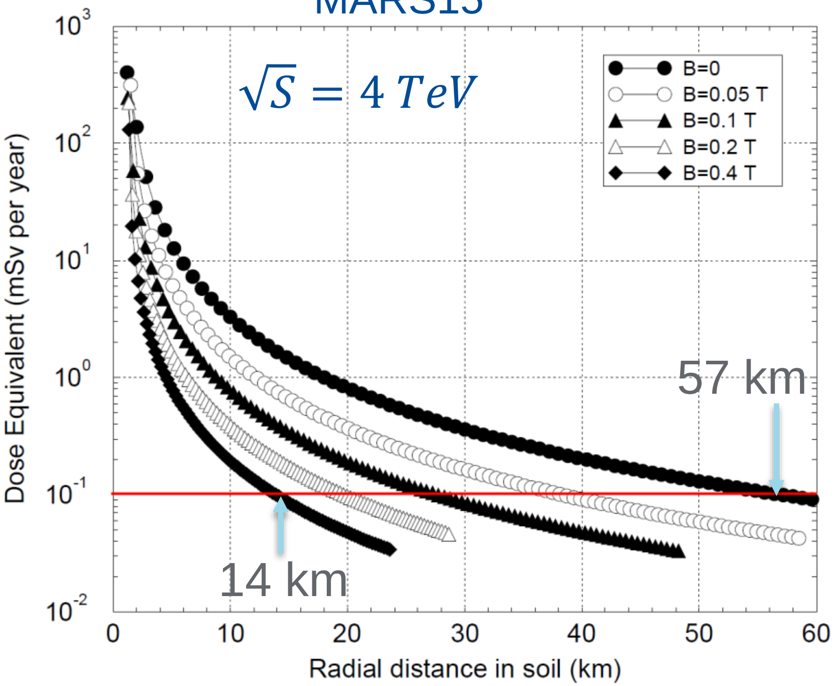
- Presence of a field of even a fraction of 1 T is enough to reduce the dose to a below-limit level
- The application of such a field over all RF and other components seems possible
- Straight sections could be shortened by using continuous combined function magnets

Mitigation (4-5): Beam Wobbling or/and Magnet Movers

4. Fast beam wobbling by systematic time-varying vertical wave field in the ring to disperse the strongly-directed neutrino flux (proposed by NM & CJJ at PAC1997 and studied in great details by NM&AVG in 2000)

5. Alternatively, large-stroke high-resolution magnet movers (proposed in 2021 at CERN)

MARS15



Mitigation (6-7): Reduce Muon Beam Intensity

6. Better cooling, *e.g.*, optical stochastic cooling, might reduce the emittances by several orders of magnitude, thus greatly reducing the muon beam currents
7. The focusing strength could be increased by the use of plasma or other exotic focusing method at IP