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Muon Collider: Machine-Detector Interface (MDI)

Daniele Calzolari^{*} on behalf of the IMCC & MuCol MDI WG Muon Collider Annual Meeting 2025

> *CERN (SY-STI-BMI) INFN sezione di Padova



Introduction





- Machine-Detector Interface (MDI) objectives:
 - Quantify beam-induced background (BIB) and propose mitigation for $\sqrt{s} = 3 \& 10 \text{ TeV}$.
 - Deliver an interaction-region (IR) design compatible with detector operation.
- Could profit from previous US MAP studies (N. Mokhov et al): MAP design served as starting point.
- This talk:
 - Muon Collider IR and MDI geometries
 - Beam-Induced Background sources: muon decay, incoherent pair production, halo losses
 - Radiation load to the detector area
 - Nozzle optimization strategy

How to deal with the beam-induced background?

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Sources of beam-induced background



	Description	Relevance as background
Muon decay	Decay of stored muons around the collider ring $\mu^{\pm} \rightarrow e^{\pm} v \overline{v}$	Dominating source
Synchrotron radiation by stored muons	Synchrotron radiation emission by the beams in magnets near the IP (including IR quads → large transverse beam tails)	Small
Muon beam losses on the aperture	 Halo losses on the machine aperture, can have multiple sources, e.g.: Beam instabilities Machine imperfections (e.g. magnet misalignment) Elastic (Bhabha) μμ scattering Beam-gas scattering (Coulomb scattering or Bremsstrahlung emission) Beamstrahlung (deflection of muon in field of opposite bunch) 	Can be significant (although some of the listed source terms are expected to yield a small contribution like elastic μμ scattering, beam-gas, Beamstrahlung)
Coherent e ⁻ e⁺ pair production	Pair creation by real [*] or virtual photons of the field of the counter-rotating bunch	Expected to be small (but should nevertheless be quantified)
Incoherent e ⁻ e ⁺ pair production	Pair creation through the collision of two real* or virtual photons emitted by muons of counter-rotating bunches	Significant



Interaction region lattices







Final focusing region: decay e⁺/e⁻







Radiation load to the final focusing magnets



- Limiting factor: total ionizing dose (TID) in organic materials insulation, spacers etc.)
- **Design target: 5-10 MGy/y** \rightarrow **50 MGy** during the collider lifetime.
- We assume an operational time of 1.2×10^7 s / year with 5-10 years operation.
- The damage is cumulative. In case of extended collider use lower limits must be taken.

Table: radial build for superconducting magnets							
Shield radial build	Thickness (mm)						
beam screen	0.01						
shield	2.53						
shield support +thermal insulation	1.1						
cold bore	0.3						
insulation (kapton)	0.05	Froi	nt mask				
clearance + liquid helium	0.01	l in t	ungsten				
Sum	4						

Table: radia	FLUKA			
Name	L [m]	Shield thickness [cm]	Coil aperture (radius) [cm]	Peak TID [MGy/y]
IB2	6	4.53	16	1.3
IB1	10	4.53	16	3.1
IB3	6	4.53	16	4.9
IQF2	6	2.53	14	7.7
IQF2_1	6	2.53	13.3	4.6
IQD1	9	2.53	14.5	1.1
IQD1_1	9	2.53	14.5	3.7
IQF1B	2	2.53	10.2	6.4
IQF1A	3	2.53	8.6	3.6

2.53

IQF1

3

3.5

7



Power load to the final focusing magnets



0.4

0.6

1.6

2.0

2.2

3.0

8.0

12.9

10.2

- Limiting factor: total power to the cold mass
- **Design target:** 1/2% of the radiated power in the arcs, more margin in the IR?
- Decay product total power in the MDI around 160 kW \rightarrow up to 15 W/m in cold mass



Name

IB2

IB1

IB3

IQF2

IQF2 1

Power inPower perPowerL [m]element [W]meter [W/m]fraction [%]

13.5

30.3

47.8

77.2

61.3

Table: power load for each magnet in the final focus

6

10

6

6

6



Anatomy of decay-induced background







Anatomy of decay-induced background









Nozzle Design:

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- Tapered tungsten-alloy (INERMET180) structure with borated polyethylene core.
- Extends ~6 m from IP to intercept secondaries early.
- Optimized geometry minimizes photon fluences to calorimeters.

BIB:

- Background mostly localized around the nozzle tip.
- Vertex detectors most exposed to electromagnetic background.
- Fluences up to 10⁴ e^{+/-} in the vertex detectors





Decay background: impact of lattice choices



Number of background particles entering Latest 10 TeV **Dipole chicane** Pure quads the detector as a function of the muon lattice version decay position: (v0.8) μ^+ beam, Latrice v0.8, $\sqrt{s} = 10$ TeV 10^{7} $t \in [-\infty, \infty]$ Decays inside nozzle (between IP and L*) $\in [-5, 15]$ ns 10^{6} contribute very little to the background But: increasing L* from 6 m to 10 m yields ${[}^{\rm I-m}_{\rm I} {]}^{\rm I-m}_{\rm I} {]}^{\rm I-m}_{\rm I-m} {]}^{\rm I$ only small improvement - O(few 10%) at the expense of a more complex lattice design **Decays inside triplet dominate** beam Decays in drift upstream of FF would background Can only be partially mitigate by lattice yield a non-negligible contribution but choice (e.g. dipolar component) can be strongly reduced by a dipole -150-100-50chicane z_{μ} [m] Nevertheless, the contribution remains non-zero



Decay background: muon component



Muon background from muon decay:

- Bethe-Heitler μ[±] originate from high-E γ; photonuclear reactions add extra contribution.
- They can be produced also in photonuclear interaction (delta baryion decaying in π)



Lethargy distribution of muons: trice v0.8, $\sqrt{s} = 10$ TeV



Number of background particles per muon decay position:





Decay background: muon component







Incoherent e-/e+ pair production



Incoherent pair production at 10 TeV

- Adds 20-30 % to e/γ load in |z| < 40 cm; but pairs are on average more energetic than decay induced background.
- Improved description of pair production by muon beams in the GUINEA-PIG event generator, with BIB sample circulated to the detector community





Halo losses



• Objective:

Estimate the *distribution* of beam halo losses in the Interaction Region (IR)

Methodology:

- Generate transverse coordinates using the covariance matrix (including optics and dispersion):
- x = L z, with $\Sigma = L L^{T}$
- Fix the normalized amplitude $Q = \sum z_i^2$
- Sample Q from a logarithmic distribution to enhance halo representation
- Track particles through the IR and record losses
- Results: around 10⁻² e[±]/cm² per bunch crossing. Muon losses in the FF shall be kept under 10⁻⁶ per bunch

Ratio of the probability of loss per Q in FF 0.5 0.4 0.3 0.0 0.2 0.1 0.9 0.0 10⁻⁹ 10⁻⁸ 10⁻⁷ 10⁻⁶ 10⁻⁵ 10⁻⁴ 10⁻³







Radiation damage in detector (10 TeV)



- Estimates include decay-induced background only (IMCC v0.8).
- Per year of operation, vertex up to MGy TID. Lower radiation on external detectors
- Calorimeter comfortably below existing limits.



Yearly 1 MeV n. eq. fluence in Si in MAIA detector



*For IMCC lattice version v0.8

Component	Dose [kGy]		1 MeV neutron-equivalent fluence (Si) [10 ¹⁴ n/cm ²]		Radiation damage
	MAIA	MUSIC	MAIA	MUSIC	estimates for 10 TeV
Vertex (barrel)	10	000		2.3	Includes only
Vertex (endcaps)	20	000		8	contribution of
Inner trackers (barrel)	7	70	4.5	4	decay-induced
Inner trackers (endcaps)	3	30	11.5	10	background!
ECAL	0.58	1.4	0.15	1	



Towards a nozzle optimization



- Objective:
 - Minimize the radiation load to the tracker detectors via shielding design.
- Nozzle tip:
 - It affects the radiation load in the innermost detector elements.
 - Parametric scan ongoing to identify mitigation strategies.





Conclusions



- Comprehensive MDI model in place for 10 TeV.
- Decay e[±] dominate; nozzle + lattice suppress by > 10⁶. BIB distribution simulated and shared with detector expert
- Incoherent pair production sample generated. Background simulated and propagated to detector experts.
- First estimation of halo losses proposed, with the aim of keeping beam losses in the FF below 10⁻⁶. No collimation system yet under consideration
- Material budgets in magnets for shielding proposed. Still conflicting with magnet & beam aperture requirements.
- Nozzle/lattice co-optimisation ongoing; 4th optics under consideration, more realistic nozzle options under scrutiny





Thank you!



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Recap of collider parameters



=10 TeV =3 TeV **Beam parameters** 1.5 TeV 5 TeV Muon energy Bunches/beam 1 Bunch intensity (at injection) 2.2×10^{12} 1.8×10^{12} Norm. transverse emittance 25 µm rad Repetition rate (inj. rate) 5 Hz **Collider ring specs** Circumference 4.5 km 10 km **Revolution time** 15.0 µs 33.4 µs Luminosity 10 ab⁻¹ **Target integrated luminosity** 1 ab⁻¹ Average instantaneous luminosity 2 x 10³⁴ cm⁻²s⁻¹ 2 x 10³⁵ cm⁻²s⁻¹ (5/10 yrs of op.)/ 1 x 10³⁴ cm⁻²s⁻¹ / 1 x 10³⁵ cm⁻²s⁻¹



See also parameter doc: https://cernbox.cern.ch/s/NraNbczzBSXctQ9



Workflow in the IMCC



