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MILESTONE REPORT

CONSOLIDATED PARAMETERS

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Abstract:

This document is comprised of a collection of consolidated parameters for the key parts of the muon collider. These consolidated parameters follow on from the October 2024 Preliminary Parameters Report. Attention has been given to a high-level consistent set of baseline parameters throughout all systems of the complex, following a 10 TeV center-of-mass design. Additional details of the designs contributing to this baseline design are featured in the appendix. Likewise, explorative variations from this baseline set can be found in the appendix. The data is collected from a collaborative spreadsheet and transferred to overleaf.

MuCol Consortium, 2025

For more information on MuCol, its partners and contributors please see <https://mucol.web.cern.ch/>

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1 Introduction

This document contains updated parameters for the MuCol study. This is the third and final iteration of the parameters, and is developed from the preliminary parameters report of 2024 [1] and tentative parameters report of 2023 [2].

This consolidated collection of parameters considers a high-level baseline overview for a 10 TeV centre-of-mass collider, and the resulting parameters of each sub-system. Additional details from the baseline parameter set are written in detail within the appendix. The appendix also contains variations on designs and site-based parameters that have been developed bottom-up by the teams that work on the different parts of the complex and different technologies. These parameters are already the fruit of the R&D of each team, or the goals that the team considers realistic based on their expertise and studies carried out so far.

1.1 Muon Collider Design

The design effort focuses on a high energy stage at 10 TeV with a luminosity of $18 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This would match approximately the physics reach of a 100 TeV energy FCC-hh design.

Whilst it is possible to reach this through intermediary stages, such as with a 3 TeV collider, or a lower-luminosity 10 TeV collider, this report only considers the final product.

1.2 Structure of the Document

The high-level baseline parameters are listed in Section 1.3 followed by parameters for each subsystem split by section. Figure 1.1 demonstrates the present systems and subsystems of the complex, starting with the proton driver (blue) in Section 2, passing through to the front end (purple) in Section 3, the ionization cooling (pink) in Section 4, acceleration (light red) in Section 5 and finally the collider ring (red) in Section 6. The Detector and Machine-Detector Interface (MDI) designs are described in Section 7 and 8 respectively. Details of underlying technologies are given in subsequent sections, including magnets (Section 9) and RF cavities (Section 10). Collective effects throughout the complex are described in Section 11, and the radiation shielding and protection considerations throughout the complex are described in Section 12 and 13 respectively. Finally details of the demonstrator cooling cell can be found in Section 14. The appendix of this report contains additional details of the lattice designs of each section, including system variations, such as site-specific designs.

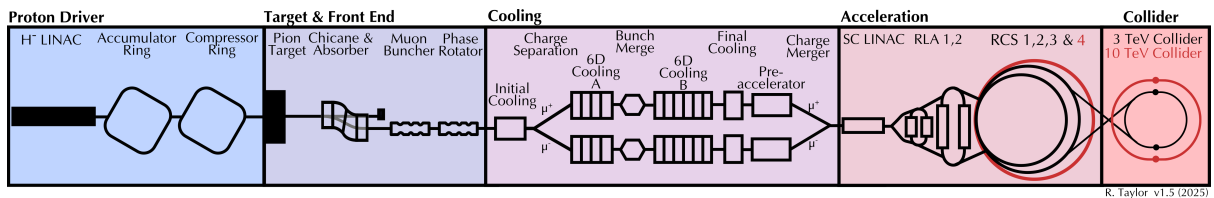


Fig. 1.1: Simplified overview of the proton driver and muon collider accelerator complex.

1.3 Top-Level Parameters

The top-level parameters for the Muon Collider are shown in Table 1.1. These are the ideal design specifications that each subsystem aims to achieve. The parameters have been adapted as of the ESPPU

update [3], whereby the baseline collider arc peak field is 14 T, based on feedback within the magnet community. This provides a 12% linear scaling to the circumference and estimated luminosity.

Table 1.2 provides an overview of the whole complex, with the key numbers including the length and outgoing beam energy for each system. It also indicates the required transmission performance per system to achieve the target transmission values. An additional estimate of transmission and emittance is provided in Table 1.3, based on the current efficiency of each simulated system.

The total estimated muon charge after the front-end and cooling is 2.5×10^{12} , which is less than the required 3.6×10^{12} . We aim to increase the transmission in the different subsystems to achieve this. In addition, we are studying a variation of the muon production target design with an increase proton beam power of up to 4 MW, the design of which is featured in Appendix C.2. These two approaches should enable us to reach the bunch charge target in the collider ring.

A commentary on the assumptions in the luminosity calculations is in Appendix A.1. Additional information on the decay throughout the facility is in Appendix A.2.

We notice that the transverse emittance target seems to be in reach, if further studies confirm the preservation along the accelerator chain. For the longitudinal emittances that indications are that we might be able to achieve a better value than the target. However, at this moment we do not change the target for the collider ring and accelerator chain to better understand the boundaries. The better value thus serves as a margin and we will later review how to integrate it into the design.

Parameter	Symbol	Unit	Baseline
Centre-of-mass energy	E_{cm}	TeV	10
Target integrated luminosity	$\int \mathcal{L}_{\text{target}}$	ab^{-1}	10
Estimated luminosity	$\mathcal{L}_{\text{estimated}}$	$10^{34} \text{cm}^{-2} \text{s}^{-1}$	18
Collider circumference	C_{coll}	km	11.4
Collider arc peak field	B_{arc}	T	14
Luminosity lifetime	N_{turn}	turns	1363
Muons/bunch	N	10^{12}	1.8
Repetition rate	f_{r}	Hz	5
Beam power	P_{coll}	MW	14.4
RMS longitudinal emittance	$\varepsilon_{\parallel}$	eVs	0.025
Norm. RMS transverse emittance	$\varepsilon_{\perp}$	μm	25
IP bunch length	σ_z	mm	1.5*
IP betafunction	β	mm	1.5*
IP beam size	σ	μm	0.9
Protons on target/bunch	N_{p}	10^{14}	5
Proton energy on target	E_{p}	GeV	5

Table 1.1: Consolidated target parameters for a muon collider at 10 TeV. The estimated luminosity refers to the value that can be reached if all target specifications can be reached, including beam-beam effects. *Relaxed β options are displayed in Table 6.1

Subsystem	Energy Out	Length	Tar. ε_T um	Tar. ε_L eV ms	Target Transm. %	Target Cumulative Transm. %	Target μ^- /bunch 10^{12}
	GeV	m					
Proton Driver	5 (p^+)	1500			–		500 (p^+)
Front End	0.17	150	17000	16.0	9	100.0	45
Charge Sep.	0.2	12	17000	16.0			
Rectilinear A	0.2	363	1240	0.6			
Bunch Merge	0.13	134	5130	3.5			
Rectilinear B	0.124	424	300	0.5			
Final Cooling	0.005	100	22.5	22.9			
Pre-Acc.	0.25	140	22.5	22.9	8	8	3.6
LINAC	1.25	500					
RLA1	5	o500			90	7.3	3.3
RLA2	62.5	o2400			92.6	6.7	3.0
RCS1	314	o5990			90	6.1	2.7
RCS2	750	o5990			90	5.5	2.5
RCS3	1500	o10700			90	4.9	2.2
3 TeV Collider	1500	o4500			–	–	2.2
RCS4	5000	o35000	25	25.2	90*	4.4	1.8
10 TeV Collider	5000	o11400	25	25.2	–	–	1.8

Table 1.2: Target beam parameters at the end of each section of the acceleration chain for the baseline muon collider. Lengths are approximate and o refers to the circumference. The 9% transmission in the front-end refers to the yields from Option 1 as per Table 3.2. For μ^+ the yield at the Front End is 12% but the additional charge will be reduced via collimation to provide the same bunch charge and beam-loading in both beams. *A 10% transmission budget is added to encompass potential additional losses throughout acceleration.

Subsystem	Est. ε_T um	Est. ε_L eV ms	Target Transm. %	Cumulative Estimated Transm.	Estimated μ^- /bunch 10^{12}
Proton Driver			–		500 (p^+)
Front End	17000	16.0	9	100.0	45
Charge Sep.	17000	16.0	95	95.0	42.8
Rectilinear A	1240	0.6	49.6	47.1	21.2
Bunch Merge	5130	3.5	78	36.8	16.5
Rectilinear B	300	0.5	28.6	10.5	4.7
Final Cooling	22.5	7.7	61.4	6.5	2.9
Pre-Acc.	22.5	7.7	86	5.6	2.5
LINAC					
RLA1			90	5.0	2.2
RLA2			92.6	6.7	2.1
RCS1			90	6.1	1.9
RCS2			90	5.5	1.7
RCS3			90	4.9	1.5
3 TeV Collider			–	–	1.5
RCS4	25	7.7 – 8.5	90	4.4	1.4
10 TeV Collider	25	7.7 – 8.5	–	–	1.4

Table 1.3: Estimated beam parameters at the end of each section of the acceleration chain, based on best-available simulations. Currently, the achieved muon transmission is lower than the target value and further improvement is expected. A 4 MW target (Appendix C.2) would provide almost twice as many muons at the beginning. Longitudinal emittance range assumes $\approx 10\%$ emittance growth throughout the acceleration complex.

2 Proton Driver

Main overview of the proton driver complex, for the 5 GeV, 2 MW option can be found in Table 2.1. Information on the parameter sets for the accumulator ring and compressor ring designs are in Table 2.2. The parameter set for the 10 GeV, 4 MW option can be seen in the appendix Table B.1. Accumulator ring and compressor ring designs for this alternative parameter set is in Table B.2.

Parameters	Unit	main
Final Energy	GeV	5
Repetition Rate	Hz	5
Max. source pulse length	ms	2.5
Max. source pulse current	mA	80
Source emittance	mm.mrad	0.25
Power	MW	2
Linac length	m	670
RF frequency	MHz	352, 704

Table 2.1: H- LINAC parameters for the baseline option considering 1) LINAC single use for muon production; 2) Chopping will later reduce the average current.

Parameters	Unit	Accumulator	Compressor
Energy	GeV	5	5
Circumference	m	180	314
Final rms bunch length	ns	120	2
Geo. rms. emit	π .mm.mrad	9.5	9.5
number of bunches		2	2
Number of turns		4167	41
RF voltage	MV	-	4
RF harmonic		-	2
initial mom. spread	%	0.025	0.025
final mom. spread	%	0.025	1.5
Protons on target	10^{14}	-	5

Table 2.2: Baseline Accumulator and Compressor parameters

3 Target & Front-End

The deep inelastic interactions of the proton beam with the target produces kaons and pions, which eventually decay into muons. To capture the produced particles and keep the emittance under control, the production target and the subsequent line has to be kept in a strong solenoidal magnetic field, which confines the charged particles along helical trajectories. The baseline case considers a graphite target as the most suitable option. This material allows operation at high temperatures and has a high thermal-shock resistance. Therefore the majority of studies performed to optimize the pion-yield and estimate the radiation load on the front-end magnets have taken this target as baseline. An overview of the proton driver parameters being used in the studies of the front-end target systems is shown in Table 3.1. Different ranges of these parameters have been considered in order to optimise both the physics and engineering design. Additional target geometries and higher power alternatives can be found in Appendix C.

To assess the most suitable conditions to operate the proton driver and to design the target, several

Parameters	Unit	Baseline	Range
Beam power	MW	2	1.5-3.0
Beam energy	GeV	5	2-10
Pulse frequency	Hz	5	5-50
Pulse intensity	p+ 10^{14}	5	3.7-7.5
Bunches per pulse		1	1-2
Pulse length	ns	2	1-2
Beam size	mm	5	1-7.5
Impinging angle	°	0	0-10

Table 3.1: Assumed beam from proton driver via carbon target used in studies

FLUKA simulations were conducted, calculating the muon and the pion yield in each setting. For this purpose, it was assumed that all the muon and pions going in the chicane can be captured if their momentum is below 500 MeV/c. The obtained yields are summarized as a function of beam energy in Table 3.2, assuming a transverse beam sigma of 5 mm and a graphite target rod with a radius of 15 mm.

Yield [10^{-2} GeV / p^+]	3	4	5	6	7	8	9	10
μ^+	2.8	2.6	2.4	2.3	2.2	2.1	1.9	1.9
μ^-	1.8	1.8	1.8	1.8	1.7	1.7	1.7	1.7
π^+	1.3	1.2	1.1	1.1	1	0.98	0.92	0.9
π^-	0.84	0.81	0.84	0.82	0.83	0.8	0.8	0.81

Table 3.2: Yield per unit energy proton beam [10^{-2} GeV / p^+]

4 Cooling

The cooling channel is defined from the end of the RF capture system to the beginning of acceleration. Five sub-systems are part of the cooling apparatus. Details of the sub-systems can be found in Appendix D.

1. Charge separation, which splits the positive and negative muon species into separate beamlines;
2. Rectilinear cooling (A and B lattices) which cools the beam in 6D phase space. Detailed parameters on each of these stages are in Appendix D.2;
3. Bunch merge after the A lattice which merges the microbunches produced by the front end into a single bunch;
4. Final cooling, which cools in 4D phase space and produces the final low transverse emittance beam, at the cost of a larger longitudinal emittance. Detailed parameters on this sub-system including design alternatives are in Appendix D.3;
5. Re-acceleration, which accelerates the low energy beam up to 339 MeV/c momentum which is 250 MeV kinetic energy. Potential performance for re-acceleration is estimated in Table D.21.

For this iteration, parameters are listed in Table 4.1 for the principal subsystems: rectilinear cooling and final cooling. This is for two alternative stagings: One with a shorter rectilinear cooling, finishing at stage 8 but with a longer final cooling. The other with a longer rectilinear cooling until stage 10, but with a shorter final cooling. A potential initial cooling stage is described in Section D.1. This system would be integrated prior to the charge separation.

	ε_T μm	ε_T <i>target</i> μm	ε_L mm	ε_L <i>target</i> mm	Mean p_z MeV/c	Transm. $\%$
End of charge separation	17000		46		288	95
6D Cooling end of Stage 8	260	300	1.86	1.5	200	14.9
End of Final Cooling	22.5	22.5	42 – 72	64	28	6.4
End of Reacceleration	22.5	22.5	64	64	339	5.8
	ε_T μm	ε_T <i>target</i> μm	ε_L mm	ε_L <i>target</i> mm	Mean p_z MeV/c	Transm. $\%$
End of charge separation	17000		46		288	95
6D Cooling end of Stage 10	140	300	1.56	1.5	200	10.5
End of Final Cooling	22.5	22.5	22	64	26.5	6.4
End of Reacceleration	22.5	22.5	22	64	339	5.8

Table 4.1: Beam parameters entering and leaving the cooling system for short-rectilinear (top) and long-rectilinear (bottom) options. The target emittances are listed. They are 10 % more demanding than the nominal emittances in the RCS and collider, allowing for some emittance growth at some point in the acceleration chain. Note: 64 mm = 0.0225 eVs

5 Acceleration

5.1 Low Energy Acceleration

The low energy acceleration chain brings the muon beams from 250 MeV after the pre-accelerator to 62.5 GeV for injection into the high energy acceleration chain described in Section 5.

Details of the Low Energy Acceleration systems are in Appendix E. They are composed of a single-pass superconducting LINAC outlined in Table E.1, followed by two recirculating linear accelerators (RLA), described in Table E.2.

RLA2 has a preliminary optics design. No optics design exists for LINAC and RLA1. Both RLAs have an assumed racetrack geometry. The transmission through RLA2 is 92.6%. The target transmission for LINAC and RLA1 is 90%, which corresponds to an effective average gradient of 4.1 MV/m.

5.2 High Energy Acceleration

Below is the main overview of the high energy acceleration system. Table 5.1 shows the general RCS parameters. We assume a survival rate of 90 % per ring and linear ramping only considering losses due to muon decay, even though these values are subject to further adjustments to optimize the RF and magnet powering parameters with respect to total costing, ramp shape, bunch matching, and the overall transmission of the entire chain. The lattice parameters based on the key parameters are shown in Table 5.2. The high energy acceleration parameters for site-based variations are summarized in Appendix F. Parameters for high energy acceleration performed with a fixed field accelerator are shown in Appendix F.2.

Recent longitudinal tracking studies in both RLA2 and RCS1 revealed an important longitudinal mismatch at injection into the high-energy acceleration chain at 62.5 GeV. This mismatch, mainly due to the important difference in the aspect ratios of the RF buckets, could be mitigated by lowering the RF frequency of RCS1, presently 1.3 GHz, closer towards the frequency of the accelerating sections at 352 MHz in RLA2.

To progress with the baseline optics study, an eightfold symmetry with eight long straight sections has

Parameter	Unit	RCS1	RCS2	RCS3	RCS4
Hybrid RCS	-	no	yes	yes	yes
Repetition rate	Hz	5	5	5	5
Circumference	m	5990	5990	10700	35000
Injection energy	GeV	63	314	750	1500
Extraction energy	GeV	314	750	1500	5000
Energy ratio		5.0	2.4	2.0	3.33
Assumed survival rate		0.9	0.9	0.9	0.9
Cumulative survival rate		0.9	0.81	0.73	0.66
Acceleration time	ms	0.34	1.10	2.37	6.37
Revolution period	μ s	20	20	36	117
Number of turns	-	17	55	66	55
Required energy gain/turn	GeV	14.8	7.9	11.4	63.6
Average accel. gradient	MV/m	2.44	1.33	1.06	1.83
Number of bunches		1	1	1	1
Inj. bunch population	10^{12}	2.7	2.4	2.2	2
Ext. bunch population	10^{12}	2.4	2.2	2	1.8
Beam current per bunch	mA	21.67	19.5	9.88	2.75
Peak RF power	MW	640	310	225	350
Vert. norm. emittance	μ m	25	25	25	25
Horiz. norm. emittance	μ m	25	25	25	25
Long. norm. emittance	eVs	0.025	0.025	0.025	0.025
Bunch length at injection	ps	31	22	18	14
Bunch length at ejection	ps	22	18	14	10
Straight section length	m	1012.4	536.4	793.6	4385.6
Length with pulsed dipole magnets	m	3654	2539	4366	20376
Length with steady dipole magnets	m	-	1115	2358	4257
Max. pulsed dipole field	T	1.8	1.8	1.8	1.8
Max. steady dipole field	T	-	10	10	16
Ramp rate	T/s	4232	3272	1519	565
Main RF frequency	GHz	1.3	1.3	1.3	1.3
Harmonic number		25900	25900	46300	151400

Table 5.1: RCS acceleration chain key parameters

been assumed. As this would be insufficient from the longitudinal beam dynamics point of view, due to the large energy gain per long straight section, alternative options are being investigated to either lower the momentum compaction factor of the lattice or to introduce more straight sections for acceleration. Both approaches would smooth the impact of the discrete energy kicks by the RF system.

The present assumption to reach a 90 % survival rate per RCS with an initial bunch intensity of $2.7 \cdot 10^{12}$ muons injected at 62.5 GeV simplified the preliminary choice of parameters given in this report. However, a global optimization of the beam transfer energies between the different RCS in the chain will be performed, with the objective to maximize the overall transmission for muons up to 1.5 TeV or 5 TeV. This optimization is also expected to adjust RF voltages, average accelerating gradients and horizontal apertures of all four synchrotrons. Of course, variations cannot be completely avoided in the upstream part of the chain due to the constraint of installing the first two RCS in the same accelerator tunnel.

Parameter	Unit	RCS1	RCS2	RCS3	RCS4
Fill ratio dipole	%	61	61	62.8	70.4
Cells per arc		17	17	29	36
Number of arcs		8	8	8	8
Cell length	m	36.6	40.1	42.7	106.3
Total Arc length	m	4977.6	5453.6	9906.4	30614.4
Arc Ratio	-	0.83	0.91	0.93	0.87
Relative path length difference	10^{-6}	0	5.1	0.9	1
Horizontal aperture	mm	91.3	83.4	49.7	88.6
Vertical aperture	mm	24.8	21.6	21.1	21.1
Transition gamma		31.02	33.36	55.85	68.78
Momentum compaction factor	10^{-4}	10.4	9.0	3.2	2.1
Horizontal tune (ring)		41.02	39.56	64.54	82.40
Vertical tune (ring)		42.36	36.08	62.44	81.43
Mean horizontal beta	m	36.54	35.42	38.31	97.94
Mean vertical beta	m	38.31	36.02	37.84	92.75
Horizontal natural chromaticity (ring)		-60.91	-53.96	-86.58	-112.94
Vertical natural chromaticity (ring)		-61.11	-46.88	-82.11	-102.39

Table 5.2: RCS acceleration chain lattice parameters

6 Collider

The present work concentrates on the design of a 10 TeV center-of-mass collider. The aim is to maximize the luminosity to the two possible experiments, introduced in Section 7. The basic luminosity assumptions (in Section A.1) are extrapolations from lower energy starting with a relative rms momentum spread of $\sigma_\delta = 1 \cdot 10^{-3}$. Together with the longitudinal emittance, this fixes the rms bunch length $\sigma_z = 1.5$ mm and the $\beta^* = 1.5$ mm to the same value, such that the hour glass luminosity reduction factor $f_{hg} = 0.758$ starts to become significant. Maximization of the luminosity requires to choose the shortest possible circumference C compatible with feasibility of the magnets (average bending field assumed to be $\bar{B} \approx 10.48$ T leading to $C \approx 10$ km). Note that extrapolation of parameters to higher energies lead to very large chromatic effects further increasing with energy.

The main parameters are described in Table 6.1, which contains a set of target parameters which meet the performance of Table 1.1. The set of relaxed parameters considers a lattice with reduced beta oscillations and chromatic aberrations, to study imperfections and the effects of movers.

The radial build of arc dipoles is described in Table 6.2. The radial build assumes a radiation shielding thickness of 3 cm, which can be accepted from a cryogenics point of view if the operating temperature is 20 K. The estimated heat load and radiation damage in arc dipoles is summarized in Table 12.3.

¹Luminosities for Gaussian beams with hour glass reduction factor and without beam-beam effect. Multiturn beam simulations with the correct lattice and tunes are needed in addition to first single pass simulations resulting in a modest luminosity increase.

²The approximate circumference depends on the maximum achievable dipole field. The current lattice design assumes a collider arc peak field of 16 T, but will likely be updated later to reduce the field to 14 T. This change should not significantly affect the optics and will mainly result in an increased collider circumference.

³Assuming constant bending field of 16 T. The exact value will depend on the detailed lattice design and likely be lower.

⁴Assuming that only the synchrotron radiation losses have to be compensated. Some margin and no particular frequency requirements as long as the RF voltage does not vary too much over the bunch length of few 10s of ns.

Parameter	Unit	version	
		relaxed	target
Center of mass energy	TeV	10	
Geometric Luminosity ¹	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	5.77	19.2
Beam energy	TeV	5	
Relativistic Lorentz factor		47322	
Circumference ²	km	≈ 10	
Dist. of last magnet to IP	m	6	
Repetition rate	Hz	5	
Bunch intensity (one bunch per beam)	10^{12}	1.80	
Injected beam power per beam	MW	7.2	
Normalized transverse rms emittance	μm	25	
Longitudinal norm. rms emittance	eVs	0.025	
Relative rms momentum spread	10^{-3}	0.3	1
RMS bunch length in space	mm	5	1.5
RMS bunch length in time domain	ns	.017	0.005
Twiss betatron function at the IP	mm	5	1.5
Energy loss per turn ³	MeV	≈ 27.2	
Integrated RF gradient ⁴	MV	30	

Table 6.1: Assumptions for the main parameters used in the design of a 10 TeV muon collider.

Parameter	Unit	Thickness	Outer radius
Beam aperture	mm	23.49	23.49
Coating (copper)	mm	0.01	23.5
Radiation absorber (tungsten alloy)	mm	30	53.5
Shielding support and thermal insulation	mm	11	64.5
Cold bore	mm	3	67.5
Insulation (Kapton)	mm	0.5	68
Clearance to coils	mm	1	69

Table 6.2: Collider arcs, coil inner aperture. For options using low temperature superconductor, i.e. at 3 TeV, the shielding thickness should be 40 mm and the other parameters changed accordingly.

7 Detectors

The design of the detector for $\sqrt{s} = 10$ TeV follows the concept already developed for $\sqrt{s} = 3$ TeV with modifications to account for the higher energy. Two distinct detector concepts are presented, MAIA (Muon Accelerator Instrumented Apparatus) and MUSIC (MUon System for Interesting Collisions), to fully exploit the two interaction points of the collider. Both designs share a similar structure, a cylinder 11.4 m long with a diameter of 12.8 m. The main detector components are:

- Tracking system
- Electromagnetic calorimeter (ECAL)
- Hadron calorimeter (HCAL)
- A superconducting solenoid
- A muon sub-detector

The origin of the space coordinates is the beam interaction point at the center of the detector. The z -axis

Requirement	Baseline		Aspirational
	$\sqrt{s} = 3 \text{ TeV}$	$\sqrt{s} = 10 \text{ TeV}$	
Angular acceptance	$ \eta < 2.5$	$ \eta < 2.5$	$ \eta < 4$
Minimum tracking distance [cm]	~ 3	~ 3	< 3
Forward muons ($\eta > 5$)	–	tag	$\sigma_p/p \sim 10\%$
Track $\sigma_{p_T}/p_T^2 [\text{GeV}^{-1}]$	4×10^{-5}	4×10^{-5}	1×10^{-5}
Photon energy resolution	$0.2/\sqrt{E} [\text{GeV}]$	$0.2/\sqrt{E} [\text{GeV}]$	$0.1/\sqrt{E} [\text{GeV}]$
Neutral hadron energy resolution	$0.5/\sqrt{E} [\text{GeV}]$	$0.4/\sqrt{E} [\text{GeV}]$	$0.2/\sqrt{E} [\text{GeV}]$
Timing resolution (tracker) [ps]	$\sim 30 - 60$	$\sim 30 - 60$	$\sim 10 - 30$
Timing resolution (calorimeters) [ps]	100	100	10
Timing resolution (muon system) [ps]	~ 50 for $ \eta > 2.5$	~ 50 for $ \eta > 2.5$	< 50 for $ \eta > 2.5$
Flavour tagging	b vs c	b vs c	b vs c , s -tagging
Boosted hadronic resonance ID	h vs W/Z	h vs W/Z	W vs Z

Table 7.1: Preliminary summary of the “baseline” and “aspirational” targets for selected key metrics, reported separately for machines taking data at $\sqrt{s} = 3$ and 10 TeV. The reported performance targets refer to the measurement of the reconstructed objects in physics events after, for example, background subtraction and not to the bare detector performance.

follows the direction of the clockwise-circulating μ^+ beam, the y -axis is parallel to gravity acceleration, and the x -axis is defined as perpendicular to both the y and z axes.

Table 7.1 summarises the baseline and aspirational performance and acceptance targets for the muon collider detectors. Table 7.2 summarises the detector parameters sub-system by sub-system for the two concepts. While the tracking system has a similar structure, the MAIA detector has the solenoid just after the tracker, before the ECAL while MUSIC places the solenoid magnet between ECAL and HCAL.

7.1 Tracking System

The tracking detector is composed of the vertex and tracker sub-detectors, both of them structured in barrels and end-caps. The barrels consist of sensor modules arranged in cylindrical configurations with varying lengths and radii, whose axes align with the beamline, covering the central region of the detector. The endcaps are annuli centered on the z axis, with variable distance from the interaction point and radii which cover the forward part of the detector. The major characteristics of this sub-system are described in Table 7.3.

The vertex detector is close to the interaction point in order to allow a good resolution on track impact parameter. The building blocks of the barrel detection layers are rectangular staves of sensors, arranged to form a cylinder, while the endcaps are constituted by trapezoidal modules of sensors, arranged as “petals” to form a disk. The MAIA detector has 5 layers, with the first two structured as a double layer, while MUSIC has 5 distinct layers. The length of the MUSIC barrel is 26 cm, which is double that of MAIA.

The barrel layers of the vertex detector have silicon pixels of size $25 \times 25 \mu\text{m}^2$, and thickness 50 μm .

The inner and outer trackers are based on the same technology for MAIA and MUSIC, single layer of silicon macro-pixels sensors of 100 μm thickness.

Detector Concept	MuColl $\sqrt{s} = 3 \text{ TeV}$	MUSIC $\sqrt{s} = 10 \text{ TeV}$	MAIA $\sqrt{s} = 10 \text{ TeV}$
Inner Trackers			
$R_{\min} - R_{\max} \text{ [mm]}$	30 – 1486	29 – 1486	30 – 1486
$z_{\min} - z_{\max} \text{ [mm]}$	0 – 2190	0 – 2190	0 – 2190
Angular Acceptance [$^{\circ}$]	10 – 170	10 – 170	10 – 170
X/X_0	0.3	0.1	0.1
L/L_0	0.1	0.04	0.04
EM Calorimeters			
$R_{\min} - R_{\max} \text{ [mm]}$	1500 – 1702	1690 – 1960	1857 – 2125
$z_{\min} - z_{\max} \text{ [mm]}$	2307 – 2210	2307 – 2577	2307 – 2575
Angular Acceptance [$^{\circ}$]	10 – 170	10 – 170	10 – 170
X/X_0	26 – 32	33 – 38	40 – 42
L/L_0	1.2 – 1.5	1.4 – 1.7	1.8 – 1.9
Hadron Calorimeters			
$R_{\min} - R_{\max} \text{ [mm]}$	1740 – 3330	2902 – 4756	2125 – 4113
$z_{\min} - z_{\max} \text{ [mm]}$	2539 – 4129	2579 – 4434	2575 – 4562
Angular Acceptance [$^{\circ}$]	10 – 170	10 – 170	10 – 170
X/X_0	82 – 87	89 – 116	100 – 114
L/L_0	8.8 – 9.3	9.5 – 12.5	10.9 – 12.3
Muon Systems			
$R_{\min} - R_{\max} \text{ [mm]}$	4461 – 6450	4806 – 6800	4150 – 7150
$z_{\min} - z_{\max} \text{ [mm]}$	4179 – 5638	4444 – 5903	4565 – 6025
Angular Acceptance [$^{\circ}$]	10 – 170	10 – 170	10 – 170
Solenoid			
$R_{\min} - R_{\max} \text{ [mm]}$	3483 – 4290	2000 – 2807	1500 – 1857
$z_{\min} - z_{\max} \text{ [mm]}$	0 – 4129	0 – 2500	0 – 2307
X/X_0	–	18	6
L/L_0	–	2.7	1.4
$B_z \text{ [T]}$	3.6	5	5
Nozzles			
$R_{\min} - R_{\max} \text{ [mm]}$	10 – 600	10 – 550	10 – 550
$z_{\min} - z_{\max} \text{ [mm]}$	60 – 6000	60 – 6000	60 – 6000

Table 7.2: Detector parameters for the MuColl (v1), MUSIC (v2) and MAIA (v0) concepts. Values that are left empty ("–") are not relevant for the specific detector. X/X_0 and L/L_0 are for a particle travelling from the nominal beam interaction point (IP). The origin of the space coordinates is the IP. The z -axis has direction parallel to the beam pipe, the y -axis is parallel to gravity acceleration and the x -axis is defined as perpendicular to both the y and z axes.

7.2 Calorimeter System

The calorimeter system is composed of the electromagnetic (ECAL) and hadronic (HCAL) sub-detectors. A summary of the main characteristics are in Tables 7.4 and 7.5.

The MAIA ECAL configuration is inspired by CLIC. It consists of a dodecagonal barrel and two endcap systems. It is composed of 50 alternating layers of Tungsten as absorber material 2.2 mm thick and Si sensor as active material with $5.1 \times 5.1 \text{ mm}^2$ silicon detector cells. It is located outside of the superconducting solenoid.

The MUSIC ECAL, has the same geometry as MAIA's, but is positioned immediately after the tracking

	Vertex Detector	Inner Tracker	Outer Tracker
Sensor type	pixels	macro-pixels	macro-pixels
Barrel Layers	5	3	3
Endcap Layers (per side)	4	7	4
Cell Size	$25\text{ }\mu\text{m} \times 25\text{ }\mu\text{m}$	$50\text{ }\mu\text{m} \times 1\text{ mm}$	$50\text{ }\mu\text{m} \times 10\text{ mm}$
Sensor Thickness	$50\text{ }\mu\text{m}$	$100\text{ }\mu\text{m}$	$100\text{ }\mu\text{m}$
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	$5\text{ }\mu\text{m} \times 5\text{ }\mu\text{m}$	$7\text{ }\mu\text{m} \times 90\text{ }\mu\text{m}$	$7\text{ }\mu\text{m} \times 90\text{ }\mu\text{m}$

Table 7.3: Assumed spatial and time resolution for MAIA and MUSIC Tracking Detector sub-systems. There is no resolution difference between the barrel and end-cap regions. The first layer of the Vertex barrel and all Vertex endcap layers of MAIA are implemented as double layers.

system and within the superconducting solenoid. It is a semi-homogeneous longitudinally-segmented calorimeter based on lead-fluoride (PbF_2) crystals read out by Silicon Photomultipliers. It represents a modern design approach that aims to combine the intrinsic high-energy resolution of homogeneous calorimeters with the longitudinal segmentation typically found in sampling calorimeters.

MAIA and MUSIC currently share the same technology for HCAL. It consists of a dodecagonal barrel and two endcap systems, structured in alternating layers of iron absorber 20 mm thick and plastic scintillating tiles with cell size $30 \times 30\text{ mm}^2$, 75 layers in MAIA and 70 in MUSIC. It allows the reconstruction of hadronic jets and helps in particle identification, to separate hadrons from leptons and photons.

	Electromagnetic Calorimeter	Hadron Calorimeter
Cell type	Silicon - Tungsten	Iron - Scintillator
Cell Size	$5.1\text{ mm} \times 5.1\text{ mm}$	$30.0\text{ mm} \times 30.0\text{ mm}$
Sensor Thickness	0.5 mm	3.0 mm
Absorber Thickness	2.2 mm	20.0 mm
Number of layers	50	75

Table 7.4: Cell and absorber sizes in the MAIA calorimeter systems, describing both the barrel and end-cap regions.

	Electromagnetic Calorimeter	Hadron Calorimeter
Cell type	PbF_2 crystal	Iron - Scintillator
Cell Size	$10\text{ mm} \times 10\text{ mm} \times 40\text{ mm}$	$30.0\text{ mm} \times 30.0\text{ mm}$
Sensor Thickness	-	3.0 mm
Absorber Thickness	-	20.0 mm
Number of layers	6	70

Table 7.5: MUSIC calorimeter systems, describing both the barrel and end-cap regions.

7.3 Muon System

The current configuration of the two detector concepts does not include a magnetic field outside the calorimetric system, so the role of the muon detector must be reconsidered. In particular, for high-energy muons, new methods based on machine learning, which combine tracking detector and calorimeter information, could be employed. In this case, the muon detector would primarily serve to identify that the particle is a muon.

8 Machine-Detector Interface

This section contains the main overview of the Machine-Detector Interface (MDI). An overview of the detectors can be found in Section 7. An indication of the ionization dose and neutron-equivalent fluence of both detector geometries can be found in Table 8.1. The results for the vertex detector, the inner tracker, as well as the electromagnetic calorimeter correspond to one year of operation, assuming 1.2×10^7 seconds of operation (139 days). The studies considered only muon decay, while neglecting the contribution of collision products and beam halo losses. The results were computed for IR lattice version 0.8.

Table 8.2 indicates the species of secondary particles that enter the detectors. Additional information and variations can be found in Appendix G.

Unit	Dose kGy		1 MeV neutron-equivalent fluence in Si 10^{14} n/cm ²	
	MAIA	MUSIC	MAIA	MUSIC
Vertex (barrel)	900		2	
Vertex (endcaps)	1800		7	
Inner trackers (barrel)	61		4	3.5
Inner trackers (endcap)	26		10	8.8
ECAL	0.51	1.2	0.13	0.8

Table 8.1: Maximum values of the ionizing dose and the 1 MeV neutron-equivalent fluence (Si) in the MAIA and MUSIC detectors. All values are per year of operation (10 TeV) and include only the contribution of muon decay. The updated values assume a collider ring circumference of 11.4 km.

Particle type	Particles entering detector	Threshold
Photons	1.0×10^8	100 keV
Neutrons	1.1×10^8	0.01 meV
Electron/positrons	1.2×10^6	100 keV
Muons	1.1×10^4	100 keV
Charged hadrons	4.0×10^4	100 keV

Table 8.2: Number of secondary particles (muon decay) entering the detector volume (10 TeV). Only particles above the threshold values were included. The multiplicities include only the contribution of one beam and correspond to one bunch crossing.

9 Magnets

The below table summarizes the latest studies of the most challenging magnets of the muon collider. The main performance targets and target ranges (i.e., not yet to specification) of the most challenging magnets of the muon collider are shown Table 9.1. Though these targets are bound to adapt as the study proceeds, they already provide a good basis to feedback on beam optics and accelerator performance, and to identify outstanding issues to be addressed by future work and dedicated R&D. The whole accelerator complex functions in steady state, apart from the fast ramped magnets in the rapid cycling synchrotrons. Specific details on the 6D cooling solenoids can be found in Appendix H.

Complex Unit	Magnet	No.	Aper. [mm]	Length [m]	Field [T]	Grad. [T/m]	Ramp rate [T/s]	Temp. [K]
Target, capture	Solenoid Coils	23	1380	$\approx 0.4 - 0.8$	2 – 20		SS	20
6D cooling	Solenoid Coils	≈ 6000	90-1500	0.08 – 0.5	2 – 17		SS	4.2-20
Final cooling	Solenoid Coils	20	50	0.5	>40		SS	4.2
RCS	NC dipole	≈ 1500	30x100	5	± 1.8		4200	300
	SC dipole	≈ 2500	30x100	1.5	10		SS	4.2-20
Collider arc	Dipoles	≈ 1050	140	5	14*		SS	
	CF	≈ 628	140	5 – 10	4 – 8	$\pm 100 - \pm 150^*$	SS	4.2-20
IR	quadrupoles	≈ 20	100 - 280	5 – 10		$\pm 110 - \pm 330^{**}$	SS	4.2-20

Table 9.1: Summary of main magnet development targets. For the collider magnet values marked with a * slightly higher values are assumed in the lattice design but no important changes are expected adjusting to the specified performances. The values marked with ** correspond to the lattice design but might be too high for the magnets; the lattice design will be updated accordingly. Specific configurations still need to be evaluated and this is a work in progress. CF stands for combined-function magnets.

10 RF Cavities

The RF parameters which should be considered in the design are listed in Table 10.1. In the other sub-systems of the muon cooling complex: capture, bunch merge, final cooling, etc many different RF frequencies are necessary. It is recommended to keep these RF frequencies as high as reasonable possible from the beam dynamics point of view, since the size of the achievable gradient scales approximately as $\sqrt{(f_{RF})}$.

Further details on the designs of the 6D cooling cavities and the RCS cavities can be found in Appendix I.

Proton driver						
LINAC	RF frequencies	MHz	352	704		
Muon cooling complex						
	RF frequencies	MHz	352	704	1056	
6D Cooling Channels	Max accelerating field (conservative)	MV/m	22	30	30	
	Max accelerating field (optimistic)	MV/m	35	50	50	
Acceleration complex						
	RF frequencies	MHz	352	704	1056	
LINAC	Max accelerating field (conservative)	MV/m	20	25	30	
	Max accelerating field (optimistic)	MV/m	30	38	45	
	RF frequency	MHz		704	1056, 1300	
RCS	Max accelerating field (conservative)	MV/m		25	30	
	Max accelerating field (optimistic)	MV/m		38	45	

Table 10.1: RF frequencies and gradients to be used in the beam dynamics studies.

11 Impedance

This section is devoted to beam intensity limitations that could be encountered in the different machines due to collective effects.

11.1 Impedance model for the Rapid Cycling Synchrotrons

Impedance models for the four RCS of the acceleration chain were developed. The Rapid Cycling Synchrotrons (RCS) will be comprised of many RF cavities to provide the large acceleration voltage needed to reach the muon survival target, as developed in Section 5. It is assumed that the RCS 1, 2, 3 and 4 have respectively 700, 380, 540 and 3000 cavities. Because of their number, the cavities are expected to be a large contributor to the RCS impedance model. The models assume that superconducting TESLA cavities [4] are used for the RF system, and include the High-Order Modes (HOMs) generated by these cavities [5]. Additional details on the RCS impedance models, including the HOMs parameters for a single cavity, are reported in the Appendix, Table K.1.

The RCS parameters relevant for the impedance and coherent stability simulations are reported in Table 11.2.

A second important contributor to the impedance model of the RCS is the normal conducting magnets vacuum chamber. Because of the high ramping rate, a large eddy current would appear if a fully metallic chamber was used [6]. A ceramic chamber with a thin metallic coating on the inner surface would therefore be used [7]. Its dimension and characteristics are reported in Table 11.1.

Parameter	Unit	Value
Inner dimension width, height	mm, mm	30, 20
Inner RF shield (copper stripes) thickness	um	500
Copper resistivity at 300 K	nΩ m	17.9
Ceramic thickness	mm	5
Ceramic type		HA-997
Outer dimension width, height	mm, mm	40, 30

Table 11.1: RCS normal conducting magnets vacuum chamber used in simulations

Parameter	Unit	Value
Average Twiss beta horizontal/vertical	m	50, 50
Chromaticity Q' horizontal/vertical		+20, +20
Transverse damper	turns	20
Maximum transverse offset admissible	um	100
Detuning from octupoles horizontal/vertical	m ⁻¹	0, 0

Table 11.2: RCS Collective Effects Parameters used in simulations.

11.2 Impedance model for the 10 TeV collider ring

In the 10 TeV collider ring, the main impedance source would be the resistive-wall contribution from the magnets' vacuum chamber. To protect the superconducting magnet coils from muon decay induced heating and radiation damage, a tungsten shield is proposed to be inserted in the magnet cold bore as detailed in Section 12 and described in Ref. [8].

Previous parametric studies performed with Xsuite and PyHEADTAIL showed that a minimum chamber radius of 13 mm, together with a copper coating on the inner diameter are required to ensure coherent transverse beam stability. The current dipole magnet radial build detailed in Table 6.2 foresees a 23.5 mm inner radius, with a 10 μm copper coating. The vacuum chamber properties used for the

impedance model computation are summarized in Table 11.3.

Parameter	Unit	Value
Chamber geometry		circular
Chamber length	m	10000
Copper coating thickness	μm	10
Copper resistivity at 300 K	$\text{n}\Omega\text{ m}$	17.9
Tungsten resistivity at 300 K	$\text{n}\Omega\text{ m}$	54.4
Chamber radius (from magnet radial build)	mm	23
Min. chamber radius required (50-turn damper)	mm	13

Table 11.3: 10 TeV collider parameters for impedance model simulations.

Transverse coherent beam stability simulations were performed with Xsuite [9] and PyHEADTAIL, including the effect of muon beam decay [10]. The beam parameters used for these simulations are summarized in Table K.3.

11.3 Impedance models in cooling

Studies are ongoing to understand impedance models and other collective effects in the cooling stages. These are challenging, due to the extra step of studying these behaviours within the absorbers. In addition, the beam conditions change significantly through each stage. The beam-loading, wakefields, space-charge and inter-beam scattering in the 6D cooling and final cooling lattices listed in Section D will be modelled with RF-Track [11].

12 Radiation Shielding

The below tables summarize the latest studies of radiation shielding in the muon collider for two particular systems: The target solenoids considering proton impact on a Graphite target; and magnets in the collider arcs and interaction regions due to muon decay.

12.1 Radiation load on the target superconducting solenoids

Generic radiation load studies for the superconducting solenoid were performed by means of FLUKA Monte Carlo simulations. A 5 GeV proton beam with a beam sigma of 5 mm and a beam power of 2 MW was assumed to impinge on a graphite target rod (see Table C.3 for the target dimensions). The target was centered along the beam axis and therefore no dependence on the azimuthal angle can be expected. The simulation results for the coils are presented in Table 12.1, showing the maximum displacement per atom (DPA) per year and the maximum yearly absorbed dose. The studies were carried out for different target shielding thicknesses and shielding compositions. The shielding inner radius in the area of the target vessel is fixed at 17.8 cm. The gap between the shielding outer radius and the magnet coils is always kept at 7.5 cm. The shielding outer radius can be read from the table by subtracting 7.5 cm from the magnet coils' inner radius. The target shielding was either assumed to be made of pure tungsten or tungsten with an outer, neutron-absorbing layer made of water combined with boron-carbide.

Tungsten + Water + Boron-Carbide			
Coil inner radius	Shielding thickness around the target	DPA/year [10^{-3}]	Dose [MGy/year]
60 cm	(B)W 31.2 cm + H ₂ O 2 cm + B ₄ C 0.5 cm + W 1 cm	1.70 ± 0.02	10.0 ± 0.3
65 cm	W 36.2 cm + H ₂ O 2 cm + B ₄ C 0.5 cm + W 1 cm	0.90 ± 0.02	5.6 ± 0.2
70 cm	W 41.2 cm + H ₂ O 2 cm + B ₄ C 0.5 cm + W 1 cm	0.49 ± 0.01	3.1 ± 0.1
75 cm	W 46.2 cm + H ₂ O 2 cm + B ₄ C 0.5 cm + W 1 cm	0.29 ± 0.01	1.9 ± 0.1
80 cm	W 51.2 cm + H ₂ O 2 cm + B ₄ C 0.5 cm + W 1 cm	0.16 ± 0.01	1.0 ± 0.1
85 cm	W 56.2 cm + H ₂ O 2 cm + B ₄ C 0.5 cm + W 1 cm	0.09 ± 0.01	0.6 ± 0.1

Table 12.1: Radiation load on the target superconducting magnet coils in terms of the maximum displacement per atom (DPA) and the maximum absorbed dose per year of operation for various shielding configurations.

12.2 Muon decay in the collider ring

The radiation-induced power load and radiation effects in collider equipment are dominated by the products of muon decay. While decay neutrinos yield a negligible contribution to the radiation load on the machine, the decay electrons and positrons induce secondary particle showers, which dissipate their energy in the surrounding materials. A continuous shielding is therefore needed, which dissipates the induced heat and protects the superconducting magnets against long-term radiation damage. Shielding studies for muon colliders have been previously carried out within MAP [12, 13, 14]. In particular, the shielding must:

- prevent magnet quenches,
- reduce the thermal load to the cryogenic system (by reducing the heat load to the cold mass of magnets),
- prevent magnet failures due to the ionizing dose in organic materials (e.g. insulation, spacers) and atomic displacements in the superconductor.

The assumed beam parameters and operational scenarios for the radiation studies are summarized in Table 12.2.

	Units	3 TeV	10 TeV
Particle energy	TeV	1.5	5
Bunches/beam		1	1
Muons per bunch	10^{12}	2.2	1.8
Circumference	km	4.5	11.4
Muon decay rate per unit length	$10^9 \text{ m}^{-1} \text{ s}^{-1}$	4.9	1.8
Power ($e^\pm$)/meter	kW/m	0.411	0.443
Operational years	years	5 – 10	
Operational time per year (average)	days	139	
Operational time per year (average)	seconds	1.2×10^7	

Table 12.2: Parameters for radiation studies (collider ring) with 14 T arc peak field. The number of decays consider the contribution of both beams.

In order to estimate the required shielding thickness for a 10 TeV collider, generic shielding studies for the arc magnets were performed with FLUKA [15, 16]. The studies considered only muon decay,

whereas other source terms (e.g. beam halo losses) still have to be addressed in the future. Table 12.3 summarizes the calculated power load and radiation damage in collider ring magnets as a function of the radial absorber thickness (10 TeV collider). For simplicity, the FLUKA simulation model consisted of a generic string of 16 T dipoles, each six meters long; the drift regions between dipoles were assumed to be 20 cm long.

	Unit	20 mm	30 mm	40 mm
Beam aperture	mm	23.5	23.5	23.5
Outer shielding radius	mm	43.5	53.5	63.5
Inner coil aperture	mm	59	69	79
Absolute power penetrating tungsten absorber	W/m	16.2	7	3.5
Fractional power penetrating tungsten absorber	%	3.7	1.6	0.8
Peak power density in coils	mW/cm ³	5.5	1.8	0.6
Peak dose in Kapton insulation (1 year)	MGy	9.3	2.9	1.1
Peak dose in coils (1 year)	MGy	7.5	2.5	0.9
Peak DPA in coils (1 year)	10 ⁻⁵ DPA	1.4	1.0	0.8

Table 12.3: Power load and radiation damage in collider ring arc magnets (10 TeV) as a function of the radial tungsten absorber thickness. The power penetrating the shielding does not include neutrinos, since they are not relevant for the radiation load to the machine; the percentage values are given with respect to the power carried by decay electrons and positrons. The results include the contribution of both counter-rotating beams.

In the interaction region, which accommodates the final focus magnets and a chicane for background reduction, more radiation is expected to arrive on the machine elements. This is a consequence of the long straight section between the chicane and the chromaticity correction section, which leads to a build-up of decay products. As a consequence, the radial shielding thickness generally needs to be larger than in the arcs in order to remain below critical dose levels. Moreover, the beam size in this section is substantially larger than the one in the arc sections, therefore increasing the aperture requirements.

In Table 12.4, the different IR magnets and the corresponding ionizing dose is reported. Thicker shielding elements are required for the first three dipoles than for the final focus quadrupoles.

In case of 5 years of operation, the dose would remain below 40 MGy in all magnets, which is considered acceptable. However, the dose would become too high for 10 years of operation, exceeding even 70 MGy for one of the final focus quadrupoles (IQF2). Therefore, in case of an extended operational period, even more stringent requirements on the shielding would be required.

Name	L [m]	Beam aperture (radius) [cm]	Coil aperture [cm]	Peak TID [MGy/y]
IB2	6	10	16.0	1.1
IB1	10	10	16.0	2.7
IB3	6	10	16.0	4.3
IQF2	6	10	14.0	6.8
IQF2_1	6	9.3	13.3	4.0
IQD1	9	10.5	14.5	1.0
IQD1_1	9	10.5	14.5	3.2
IQF1B	2	6.2	10.2	5.6
IQF1A	3	4.6	8.6	3.2
IQF1	3	3	7.0	3.1

Table 12.4: Cumulative ionizing dose in final focus quadrupoles and chicane dipoles located in the insertion region (lattice version 0.8).

13 Radiation Protection

The decay of muons in the collider ring produces very energetic neutrinos that have a non-negligible probability to interact far away from the collider in material near to the Earth’s surface, producing secondary particle showers. The goal is to ensure that this effect does not entail any noticeable addition to natural radiation and that the environmental impact of the muon collider is negligible, i.e. an effective dose of the order of $10 \mu\text{Sv/year}$, similar, for instance, to the impact from the LHC. For the environmental impact assessment, detailed studies of the expected neutrino and secondary-particle fluxes are being performed with FLUKA. The latter can be folded with the realistic neutrino source term taking into account the collider lattice to predict the effective dose and to design suitable methods for mitigation and demonstration of compliance.

The results of the FLUKA simulations are shown in Tables 13.1 and 13.2 for the 1.5 TeV and 5 TeV muon beams. These results are expressed in terms of dose kernel parameters, i.e. peak and lateral width of the effective dose profile at different baseline distances from the muon decay position.

Distance	μ^-		μ^+	
	Peak eff. dose [pSv/decay]	σ [m]	Peak eff. dose [pSv/decay]	σ [m]
5 km	$2.09 \cdot 10^{-7}$	0.17	$2.19 \cdot 10^{-7}$	0.16
10 km	$6.57 \cdot 10^{-8}$	0.32	$6.56 \cdot 10^{-8}$	0.32
15 km	$3.28 \cdot 10^{-8}$	0.47	$3.34 \cdot 10^{-8}$	0.46
20 km	$1.98 \cdot 10^{-8}$	0.60	$1.99 \cdot 10^{-8}$	0.60
40 km	$5.42 \cdot 10^{-9}$	1.17	$5.49 \cdot 10^{-9}$	1.17
60 km	$2.53 \cdot 10^{-9}$	1.71	$2.51 \cdot 10^{-9}$	1.71
80 km	$1.44 \cdot 10^{-9}$	2.29	$1.42 \cdot 10^{-9}$	2.29
100 km	$9.20 \cdot 10^{-10}$	2.85	$9.21 \cdot 10^{-10}$	2.84

Table 13.1: Effective dose kernel parameters in [pSv/decay] of neutrino-induced radiation within soil at different baseline distances from the muon decay, for a muon beam energy of 1.5 TeV. The peak dose per muon decay and the lateral width of the dose profile (σ) have been derived from Gaussian fits of the FLUKA results.

The neutrino flux density arising from the collider ring arcs is expected to be reduced to a negligible level by deforming the muon beam trajectory, achieving a wide-enough angular spread of the neutrinos.

Distance	μ^-		μ^+	
	Peak eff. dose [pSv/decay]	σ [m]	Peak eff. dose [pSv/decay]	σ [m]
5 km	$1.57 \cdot 10^{-5}$	0.05	$1.63 \cdot 10^{-5}$	0.05
10 km	$4.86 \cdot 10^{-6}$	0.10	$5.38 \cdot 10^{-6}$	0.10
15 km	$2.54 \cdot 10^{-6}$	0.15	$2.70 \cdot 10^{-6}$	0.14
20 km	$1.56 \cdot 10^{-6}$	0.19	$1.55 \cdot 10^{-6}$	0.20
40 km	$4.80 \cdot 10^{-7}$	0.37	$4.62 \cdot 10^{-7}$	0.38
60 km	$2.33 \cdot 10^{-7}$	0.54	$2.22 \cdot 10^{-7}$	0.55
80 km	$1.38 \cdot 10^{-7}$	0.71	$1.31 \cdot 10^{-7}$	0.73
100 km	$9.16 \cdot 10^{-8}$	0.87	$8.63 \cdot 10^{-8}$	0.90
200 km	$2.55 \cdot 10^{-8}$	1.64	$2.30 \cdot 10^{-8}$	1.75
300 km	$1.11 \cdot 10^{-8}$	2.52	$1.07 \cdot 10^{-8}$	2.56

Table 13.2: Effective dose kernel parameters in [pSv/decay] of neutrino-induced radiation within soil at different baseline distances from the muon decay, for a muon beam energy of 5 TeV. The peak dose per muon decay and the lateral width of the dose profile (σ) have been derived from Gaussian fits of the FLUKA results.

Wobbling of the muon beam within the beam pipe would be sufficient for 1.5 TeV muon beam energy. At 5 TeV muon beam energy, the beam line components in the arcs may have to be placed on movers to deform the ring periodically in small steps such that the muon beam direction would change over time.

Figure 13.1 shows how neutrino fluxes emerge from different elements of the collider lattice. The long straight sections surround the IP regions result in very intense, but localized neutrino fluxes which are directed to unpopulated areas with the careful collider placement. To estimate the doses from the neutrinos

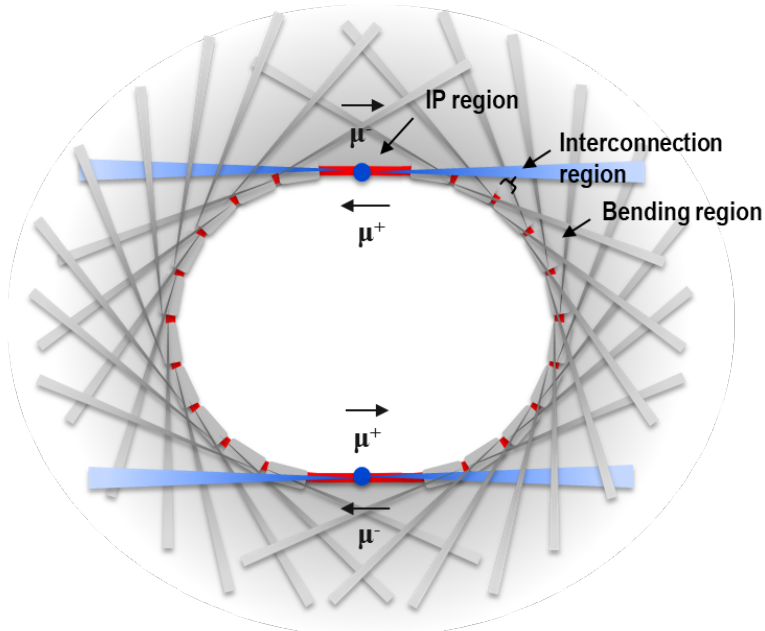


Fig. 13.1: Conceptual view of the collider ring elements contributing to the neutrino fluxes emitted by the collider.

emerging from the interconnection and the bending regions, realistic yet conservative exposure scenarios were investigated, including building structures below and above the ground. The most conservative

geometry considered are two consecutive underground rooms that are aligned along the neutrino flux path. The resulting neutrino induced dose distributions for the interconnection and the bending regions are illustrated in Figs 13.2 and 13.3, respectively. Assuming a conservative annual exposure scenario with a 100% occupancy in the two underground rooms would lead to a respective effective dose for various relevant distances as given in Tables 13.4 and 13.3.

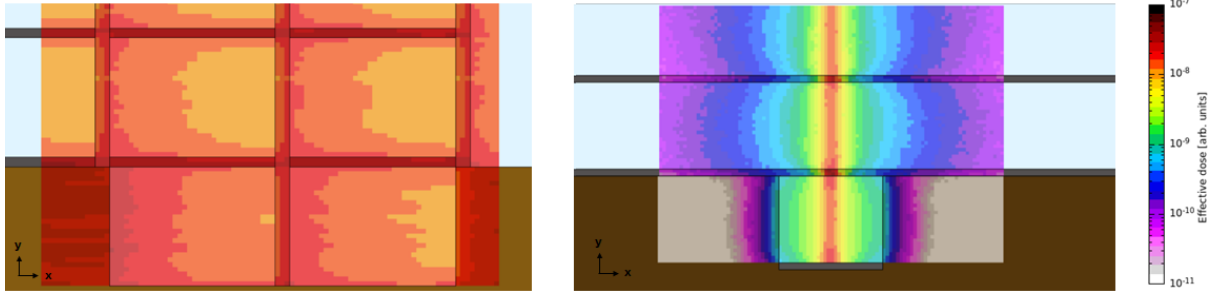


Fig. 13.2: Side (left) and cross-sectional view (right) of the effective dose (in arb. units) for an underground building structure exposed to the neutrino flux from the decay of negative muons in an interconnection region, after the vertical deformation by the movers.

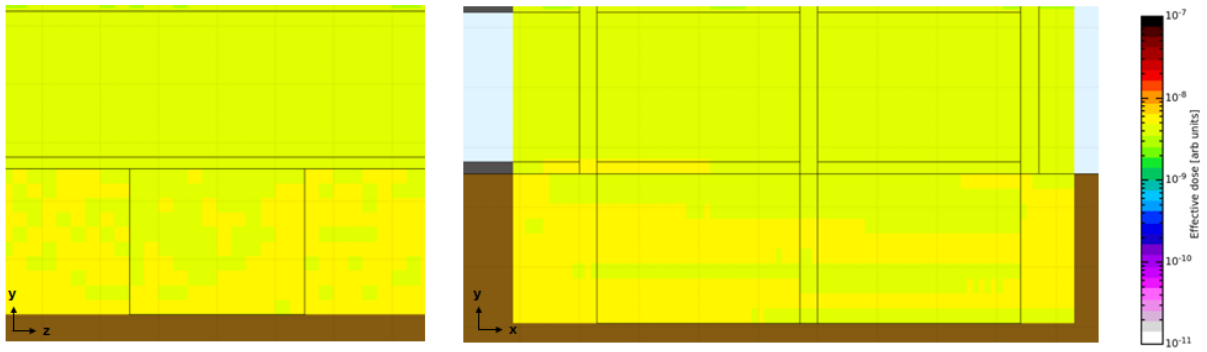


Fig. 13.3: Side (left) and cross-sectional view (right) of the effective dose (in arb. units) for an underground building structure exposed to the neutrino flux from the decay of negative muons within a bending region, after the vertical deformation by the movers.

Table 13.3 shows the dose contribution from a bending section, for which the collider is approximated as an ideal circle of 1.36 km radius. As can be seen in Fig. 13.3, the vertical smearing effect of the movers is overlapped with the horizontal bending of the muon beam resulting in neutrino flux uniformly distributed in the plane perpendicular to the neutrino direction. It was found that the neutrino-induced dose from a bending section is approximately proportional to the square of the muon beam energy.

The dose evaluation for a straight section in an interconnection region is shown in Table 13.4. Assuming 1 m of a straight section length, the values for a single beam are comparable with the summed numbers of a bending section shown in Table 13.3. Due to overlaps, the dose from a bending section always has to take into account a contribution from both beams, while an interconnection straight section generally contributes from a single beam. More studies are needed to understand possible overlaps of neutrino fluxes emerging from the interconnection regions of a realistic collider lattice.

	μ^-	μ^+	Summed
Distance [km]	Avg eff. dose [pSv m/decay]	Avg eff. dose [pSv m/decay]	[pSv m/decay]
15	1.37×10^{-9}	1.38×10^{-9}	2.75×10^{-9}
20	7.70×10^{-10}	7.79×10^{-10}	1.55×10^{-9}
30	3.43×10^{-10}	3.47×10^{-10}	6.90×10^{-10}
40	1.93×10^{-10}	1.95×10^{-10}	3.88×10^{-10}
60	8.58×10^{-11}	8.67×10^{-11}	1.73×10^{-10}
80	4.82×10^{-11}	4.88×10^{-11}	9.70×10^{-11}
100	3.09×10^{-11}	3.12×10^{-11}	6.21×10^{-11}
200	7.72×10^{-12}	7.81×10^{-12}	1.55×10^{-11}
300	3.43×10^{-12}	3.47×10^{-12}	6.90×10^{-12}

Table 13.3: Effective dose in [pSv m/decay] of neutrino-induced radiation for an underground building structure at different baseline distances from the muon decay after the vertical deformation by the movers is applied. The muon beam energy is 5 TeV and the neutrinos are assumed to emerge from a bending magnet inside the collider arcs, where the mover system is employed. The dose unit comes from the convention where the quoted numbers have to be only multiplied by decays/meter/year to obtain the annual dose. The bending section length is already embedded in the calculation.

	μ^-	μ^+
Distance [km]	Avg eff. dose [pSv/decay]	Avg eff. dose [pSv/decay]
15	6.55×10^{-9}	6.66×10^{-9}
20	4.74×10^{-9}	4.88×10^{-9}
30	3.04×10^{-9}	3.14×10^{-9}
60	1.32×10^{-9}	1.35×10^{-9}
100	6.55×10^{-10}	6.58×10^{-10}

Table 13.4: Effective dose in [pSv/decay] of neutrino-induced radiation for an underground building structure at different baseline distances from the muon decay after the vertical deformation by the movers is applied. The muon beam energy is 5 TeV and the neutrinos are assumed to emerge from a collider straight section inside the arcs, where the mover system is employed.

14 Demonstrators

The Muon Cooling Demonstrator Programme will be an essential component of the muon collider R&D programme. Muon cooling is required in order to deliver the required luminosities but it is a technology that has not been fully proven.

The muon cooling demonstrator will demonstrate

- Successful integration of cooling equipment.
- Operation of the cooling equipment with beam.
- Delivery of required beam physics performance.

Delivery of the demonstration of muon cooling will require a programme of R&D to understand and mitigate risks surrounding construction of the cooling lattice. The principle issues are:

1. The cooling cell has RF cavities and solenoids in close proximity. Solenoid fields are known to induce RF breakdown which must be understood in detail.

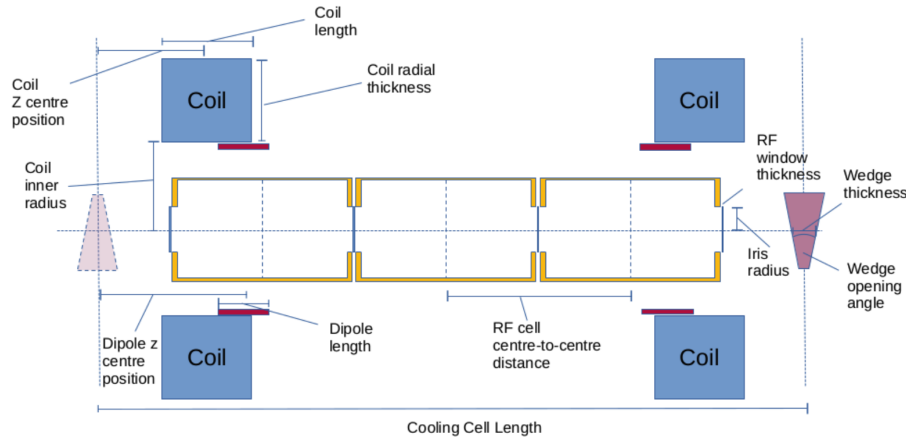


Fig. 14.1: Cooling Cell Schematic showing individual elements.

2. Warm-cold interfaces between adjacent RF cavities and solenoids require careful attention to thermal management.
3. Integration of ancillary equipment such as vacuum, RF power and beam instrumentation may be very challenging to implement in such a compact lattice.
4. Beam instrumentation must enable suitable commissioning of the equipment. For the beam demonstration in particular, where muon rates may be low compared to conventional beams, suitable instrumentation must still be implemented.
5. The integrated facility must be operable in a routine manner.

In order to deliver this, a staged R&D programme is envisaged, with each stage demonstrating the technology more fully:

1. Several RF test stands will be constructed to understand the limits to RF gradient that can be achieved in the presence of high-field solenoids.
2. A one-cell module will be implemented in order to test the operation of RF cavities in an operational magnetic environment.
3. A multi-cell module will be implemented to demonstrate integration of absorber, RF and magnets.
4. The multi-cell module will be operated with beam in order to demonstrate commissioning and operation of the cooling equipment with beam.
5. A cooling line comprising several cooling modules will be implemented to demonstrate beam physics performance.

The Collaboration has adopted the terminology in Fig. 14.1 to designate the elements of a cooling cell. The chosen cooling cell to implement is related to the B5 rectilinear cooling cell. Several important design differences have been implemented compared to B5. The Demonstrator cooling cell parameters are chosen as a compromise between cost and technical challenge. The design will inform subsequent design of the muon collider cooling system.

The cooling channel would be composed of a series of cooling cells grouped into vacuum vessels, as shown in Fig 14.2. The cooling performance for two different cooling channel lengths is listed in Tab. 14.1, while the main parameters of the most recent demonstrator cell layout are reported in Tab. 14.2.

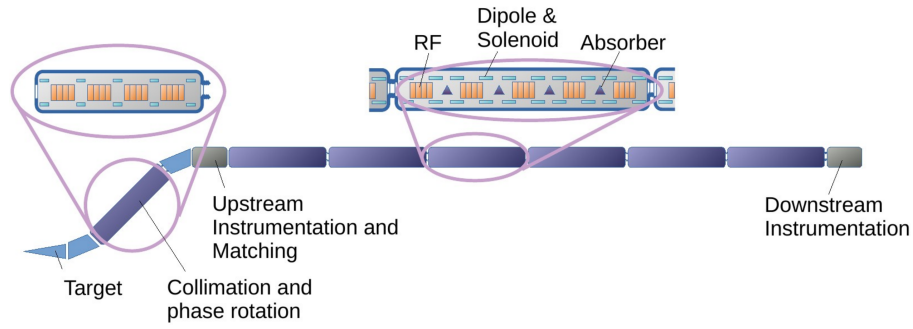


Fig. 14.2: Cooling demonstrator conceptual layout.

Simulated cooling performance	Unit	Start value	End value (50 m)
Transverse emittance	mm	1.85	1.46
Longitudinal emittance	mm	3.20	2.81
Transmission	%	100	95.4

Table 14.1: Simulated cooling performance.

Parameter	Unit	Value	
Cooling Cell Length	mm	1000	
Beam Physics			
Momentum	MeV/c	200	
Twiss beta function	mm	130	
Dispersion in X	mm	-61.5	
Dispersion in Y	mm	-19.7	
Beam Pipe Radius	mm	81.6	
Solenoid Parameters			
	Unit	Value	Tol
B0	T	7	0.2
B0.5	T	0	0.016
B1	T	1	0.02
B2	T	0	0.4
Coil Geometry			
Parameter	Unit	Coil 1	Coil 2
Geometry	–	B5-DEMO-MAG-2.4	
Inner Radius	mm	285	185
Length	mm	211	63.4
Radial Thickness	mm	76.2	71.7
Z Centre Position	mm	251.8	88.1
Pancake length	mm	12	12
Spacer length	mm	7.9	13.7
Number pancakes	–	11	3
Current Density	A/mm ²	403.5	632.3
RF Cavity			
Centre-to-centre distance	mm	177.5	
Gradient E0	MV/m	30	
Iris Radius	mm	60	
Number of RF Cells		3	
Frequency	GHz	0.704	
Synchronous Phase	degree	20	
Window Thickness	mm	0.1	
Wedge			
Material		LiH	
Opening Angle	degree	10	
Thickness	mm	20	
Alignment		Horizontal	
Dipole			
Length	mm	100	
Polarity		+ - - +	
Field	T	0.2	
Z Centre Position	mm	160	
Field Direction		Vertical	

Table 14.2: Cooling Cell Table

Appendices

A Appendix: Top-Level Parameters

Additional parameters relating to the Muon Collider staging options can be found in Table A.1.

Parameter	Symbol	Unit	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3	10
Target integrated luminosity	$\int \mathcal{L}_{\text{target}}$	ab^{-1}	1	10
Estimated luminosity	$\mathcal{L}_{\text{estimated}}$	$10^{34} \text{cm}^{-2} \text{s}^{-1}$	2.1	18
Collider circumference	C_{coll}	km	4.5	11.4
Collider arc peak field	B_{arc}	T	11	14
Luminosity lifetime	N_{turn}	turns	1039	1363
Muons/bunch	N	10^{12}	2.2	1.8
Repetition rate	f_{r}	Hz	5	5
Beam power	P_{coll}	MW	5.3	14.4
RMS longitudinal emittance	$\varepsilon_{\parallel}$	eVs	0.025	0.025
Norm. RMS transverse emittance	$\varepsilon_{\perp}$	μm	25	25
IP bunch length	σ_z	mm	5	1.5
IP betafunction	β	mm	5	1.5
IP beam size	σ	μm	3	0.9
Protons on target/bunch	N_{p}	10^{14}	5	5
Proton energy on target	E_{p}	GeV	5	5

Table A.1: Target parameters for a muon collider for Stage 1 at 3 TeV and Stage 2 at 10 TeV. The estimated luminosity refers to the value that can be reached if all target specifications can be reached, including beam-beam effects.

A.1 Luminosity assumptions

The luminosity of the muon collider is estimated taking into account several effects. The beams will perform collisions with the bunch charges N decreasing with time t following

$$N(t) = N_0 \exp\left(-\frac{t}{\gamma\tau}\right) \quad (\text{A.1})$$

It should be noted that in the 10 TeV machine after 200 ms still about 15% of the charge remain, which corresponds to 2% of the integrated luminosity. One can inject a new bunch without removing the old one. However, for the current luminosity estimate, we assume that the beam is being removed. In contrast, for the radiation load on the detector and arcs as well as the neutrino flux, we assume that the bunch is not being removed. The hourglass effect reduces the luminosity by a factor 0.76 for round beams with the beta-function and the rms bunch length being equal, as can be easily estimated analytically. The beam-beam forces on the other hand increase the luminosity since the beams focus each other, this requires simulations since the disruption parameter is of the order of 1. A simple estimate of the combination of both effects is produced by running the muon version of GUINEA-PIG using the target beam parameters. The calculation is performed assuming a longitudinally "round" beam, i.e. all particles are distributed with equal density in the space

$$\left(\frac{\Delta E}{\sigma_E}\right)^2 + \left(\frac{\Delta z}{\sigma_z}\right)^2 \leq 2^2 \quad (\text{A.2})$$

The beam-beam enhancement factor varies with the bunch charge, and reaches up to 24% at 10 TeV and full charge. We perform the integration over time and find

$$\mathcal{L} \approx 1.86 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \quad (\text{A.3})$$

The result depends on the actual charge distribution in the bunch, the full model is being developed. However, using other longitudinal profiles with the same RMS bunch length, such as Gaussian distributions or a constant charge profile yield very similar results. We thus use

$$\mathcal{L} \approx 1.8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \quad (\text{A.4})$$

For the 3 TeV parameters the disruption is higher.

The above luminosity can be roughly estimated analytically using the following assumptions:

- One bunch of μ^+ is colliding against one bunch of μ^- (as for the same total number of particles, it is more efficient to have all the particles in one bunch),
- Densities are uncorrelated in the three planes,
- Gaussian distributions in the transverse planes,
- Same parameters for both bunches,
- Round (transverse) beam,
- No crossing angle,
- No transverse offset,
- Ignoring the beam-beam enhancement.

The Muon Collider luminosity formula is typically written as

$$L = \frac{N_0^2 f_0 \gamma}{4\pi \beta^* \epsilon_n} F_{\text{HG}}(\beta^*/\sigma_z) F_{\text{decay}} \quad , \quad (\text{A.5})$$

where N_0 is the initial number of muons colliding, f_0 is the revolution frequency, β^* is the beta function at the interaction point, ϵ_n is the normalised transverse emittance and σ_z is the rms longitudinal beam size. Furthermore, $F_{\text{HG}}(\beta^*/\sigma_z)$ describes the usual hourglass effect while F_{decay} is a new term specific to the muons due to their decay and replenishment. For the first term, assuming that $\beta^* = \sigma_z$ yields $F_{\text{HG}}(1) = 0.76$. For the second term, as the muons decay rapidly and new muons arrive with the repetition frequency $f_r = 1/T_r$, the number of muons needs to be averaged such that

$$\langle N^2 \rangle = \frac{1}{T_r} \int_0^{T_r} (N_0 e^{-\frac{t}{\gamma \tau_{\mu 0}}})^2 dt = N_0^2 F_{\text{decay}} \quad , \quad (\text{A.6})$$

with

$$F_{\text{decay}} = \frac{f_r \gamma \tau_{\mu 0}}{2} [1 - e^{-\frac{2}{f_r \gamma \tau_{\mu 0}}}] \quad . \quad (\text{A.7})$$

It is worth reminding that this scheme assumes that there is no muon beam once the new injection arrives, either because muons decayed or because the remaining ones were kicked out. Therefore, the luminosity

can be written fully as:

$$L = \frac{N_0^2 f_0 \gamma}{4\pi \beta^* \epsilon_n} F_{\text{HG}}(\beta^* / \sigma_z) \frac{f_r \gamma \tau_{\mu 0}}{2} [1 - e^{-\frac{2}{f_r \gamma \tau_{\mu 0}}}] \quad . \quad (\text{A.8})$$

Once applying the aforementioned assumption that $\beta^* = \sigma_z$,

$$L = \frac{c}{8\pi^2} \frac{N_0^2}{\epsilon_n \epsilon_1} B_{\text{avg}} \gamma \frac{\sigma_E}{E} F_{\text{HG}}(1) \frac{f_r \gamma \tau_{\mu 0}}{2} [1 - e^{-\frac{2}{f_r \gamma \tau_{\mu 0}}}] \quad . \quad (\text{A.9})$$

Here we define $\epsilon_1 [\text{eVs}] = \sigma_t \frac{\sigma_E}{E} E$ and $B_{\text{avg}} R = \frac{p}{e}$, where B_{avg} is the average dipolar magnetic field, R is the average machine radius, p is the muon momentum and e is the elementary charge. Doing the numerical application with the baseline parameters of Table A.1 ($N_0 = 1.8 \times 10^{12}$, $\epsilon_n = 25 \mu\text{m}$, $\epsilon_1 = 0.025 \text{ eVs}$, $B_{\text{avg}} = 10.5 \text{ T}$, $E = 5 \text{ TeV}$, $\frac{\sigma_E}{E} = 0.1 \%$, $F_{\text{HG}}(1) = 0.76$, $f_r = 5 \text{ Hz}$, $\beta^* = \sigma_z = 1.5 \text{ mm}$), yields $L \approx 18.8 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Assuming that one year of run corresponds to $1.2 \times 10^7 \text{ s}$ leads to $L_{\text{int}}(1 \text{ year}) \approx 2.2 \text{ ab}^{-1}$. This means that 10 ab^{-1} can thus be reached in ~ 5 years (or ~ 2.5 years with two detectors), which should give enough margin for further design and technology studies and a realistic ramp-up of the luminosity.

It is also interesting to normalise the luminosity per beam power, with $P_{\text{beam}} [\text{W}] = E [\text{J}] \times N_0 \times f_r [\text{Hz}]$, which yields the following:

$$\frac{L}{P_{\text{beam}}} = \frac{1}{8\pi^2 m_{\mu 0} c} \frac{N_0}{\epsilon_n \epsilon_1} B_{\text{avg}} \frac{\sigma_E}{E} F_{\text{HG}}(1) \times F_{\text{energy}} \quad , \quad (\text{A.10})$$

where

$$F_{\text{energy}} = \frac{\gamma \tau_{\mu 0}}{2} [1 - e^{-\frac{2}{f_r \gamma \tau_{\mu 0}}}] \quad . \quad (\text{A.11})$$

Plotting F_{energy} , the only factor dependant on energy, Fig. A.1 is obtained, from which three conclusions can be drawn. First, the derived luminosity formula of Eq. A.9, gives the same result as the linearised one in Eq. A.5 (i.e. neglecting the exponential term linked to the muon decay) with the IMCC assumptions ($E = 5 \text{ TeV}$ and $f_r = 5 \text{ Hz}$). Second, these linearised assumptions would however not be true for higher energies and/or higher repetition rates, as the energy factor F_{energy} converges towards $1/f_r$. Third, the (linear) luminosity formula can be recovered by using more than one bunch per beam, but then in this case we cannot consider our initial assumption of one bunch of μ^+ colliding against one bunch of μ^- .

Let's consider an integer n and average N^2 over nT_r instead of T_r . This leads to:

$$\langle N^2 \rangle = \frac{1}{nT_r} \int_0^{nT_r} (N_0 e^{-\frac{t}{\gamma \tau_{\mu 0}}})^2 dt = N_0^2 F_{\text{decay}}(n) \quad , \quad (\text{A.12})$$

with

$$F_{\text{decay}}(n) = \frac{f_r \gamma \tau_{\mu 0}}{2n} [1 - e^{-\frac{2n}{f_r \gamma \tau_{\mu 0}}}] \quad . \quad (\text{A.13})$$

To conclude: for any energy and repetition rate, one can choose a n such that the exponential term becomes negligible. One then just has to inject the bunches in n different buckets and one recovers the

usual luminosity formula (without the exponential term). However, in this case all the beam studies should be performed with these n bunches of μ^+ colliding against n bunches of μ^- . If multiple bunches are stored, a collider design may be implemented with additional interaction points leading to an increase in the physics capability of the facility beyond the baseline assumptions.

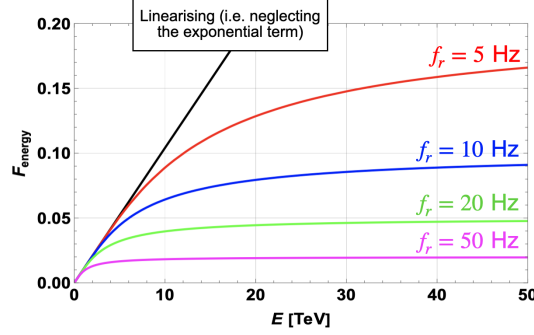


Fig. A.1: Normalised luminosity per muon beam power as a function of the muon beam energy, assuming that (only) one bunch of μ^+ collides with one bunch of μ^- . This is a worst-case scenario; in reality additional bunches will be stored if F_{decay} becomes significant.

A.2 Muon Decays

Within the main document of Table 1.3, the total transmission of the muon beams throughout the muon collider complex has been listed. These values include both the losses due to decays and the losses due to beam dynamics effects. The transmission loss solely due to decays can be safely predicted as it depends only on the energy of the beam, and the length of each system the beam travels through. This is significant as it dictates the maximum intensity which is physically possible for a perfect system. In addition it allows for an integrated understanding of which systems contribute the most significant decay losses.

System	Energy In GeV	Energy Out GeV	Lengths m	Turns	Transm. %	Cumul. Transm. %	Total Length m
Front End	0.121	0.200	150	1	90.5	90.5	150
Rectilinear A	0.200	0.162	363	1	80.3	72.7	513
Rectilinear B	0.162	0.124	487	1	70.6	51.3	1000
Final Cooling	0.124	0.005	100	1	86.0	44.2	1100
Pre-Accelerator	0.005	0.250	245	1	77.5	34.2	1345
LINAC	0.25	1.250	500	1	89.7	30.7	1845
RLA1	1.25	5	800	4.5	81.5	25.0	2645
RLA2	5	62.5	2430	4.5	92.6	23.2	5075
RCS1	62.5	314	5990	17	90.0	20.9	11065
RCS2	314	750	5990	55	90.0	18.8	17055
RCS3	750	1500	10700	66	90.0	16.9	27755
RCS4	1500	5000	35000	55	90.0	15.2	62755
Collider	5000	5000	10000	1000	72.6	11.0	72755

Table A.2: Transmission due to only decays assuming linear change in energy.

Table A.2 shows the transmission for each system only due to decays, which is represented graphically in Figure A.2. The total length logarithmically represents the path the muon takes, which is the length of

the system multiplied by the number of turns the beam takes. It is clear that the rate of decay increases most significantly throughout the cooling system.

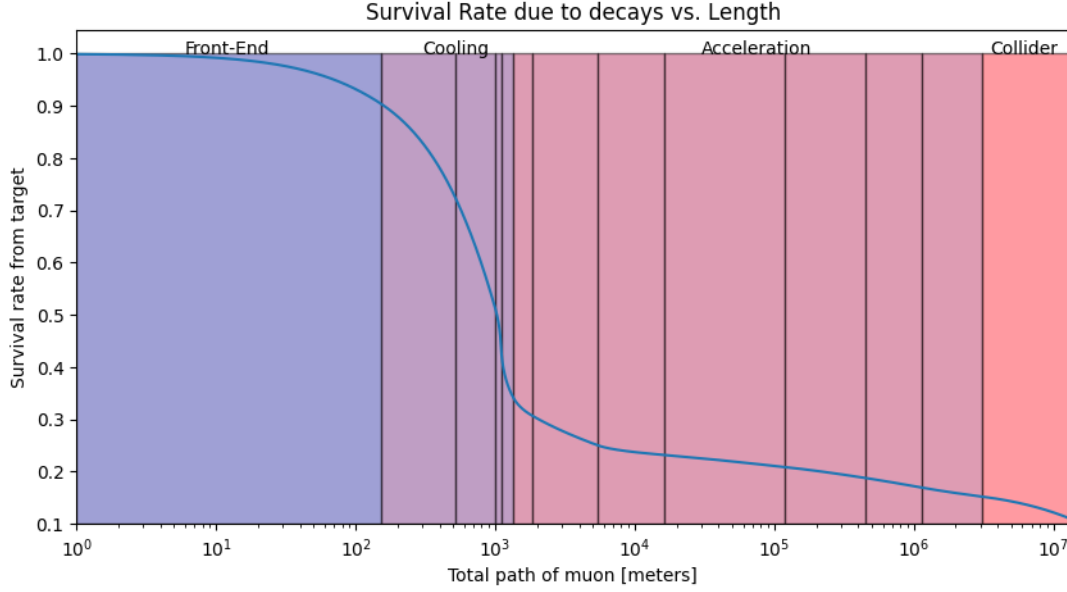


Fig. A.2: Decrease in survival rate throughout the complex only due to decays, estimated from energy and lengths of each system

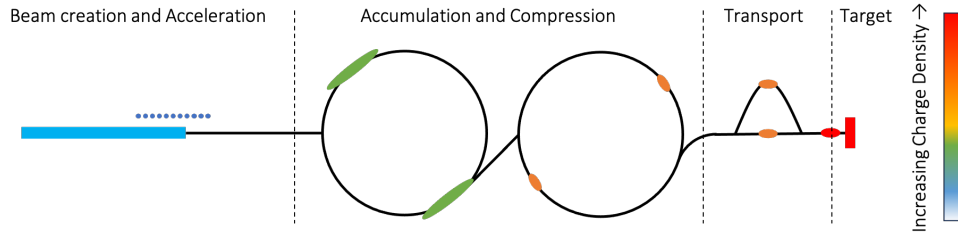
B Appendix: Proton Driver

This section is devoted to the Proton Complex parameters choice. The proton driver of a future Muon Collider is required to deliver a proton-beam of at least 2 MW at a repetition rate of 5 Hz to the pion-production target. The proton-beam energy must be in the multi-GeV range in order to maximize the pion yield. In addition, a particular time structure consisting of a single very short bunch, with a rms pulse length on the order of 2 ns, is needed to allow the muon beam to be captured efficiently in the cooling section. The proton bunch parameters are intimately connected and constrained by beam loading and longitudinal acceptance in the downstream muon accelerator systems and by the acceptance (in time, energy, and power) of the target and pion capture system. The study for the proton complex focused on two different options, the first considers a 5 GeV proton beam with a power of 2 MW and the high-level parameters are listed in 2.1 and 2.2, and the second considers a higher energy and higher power proton beam of 10 GeV and 4 MW, and the parameters are listed in Tables B.1 and B.2. These two options are equivalent to the luminosity scaling options.

Figure B.1 is a schematics of the baseline for the proton complex for both energy options presented. A full energy linac delivers a pulse of H^- to an accumulator ring, after that the pulses are transferred to a compressor ring and rotated longitudinally in order to reach the 2 ns rms bunch length. After the compressor a recombination transport line merge the bunches, which are 2 for now for both cases, and delivers a final single bunch to the target.

Table B.1: H- LINAC parameters for a final energy of 10 GeV.

Parameters	Unit	main
Final Energy	GeV	10
Repetition Rate	Hz	5
Max. source pulse length	ms	5.0
Max. source pulse current	mA	80
Source emittance	mm.mrad	0.25
Power	MW	4
Linac length	m	1200
RF frequency	MHz	352, 704

**Fig. B.1:** Schematic of the baseline design for the Proton Complex.**Table B.2:** Alternative Accumulator and Compressor parameters for a 10 GeV beam.

Parameters	Unit	Accumulator	Compressor
Energy	GeV	10	10
Circumference	m	300	628
Final rms bunch length	ns	120	2
Geo. rms. emit	π .mm.mrad	9.5	9.5
number of bunches		2	2
Number of turns		4167	67
RF voltage	MV	-	4
RF harmonic		-	2
initial mom. spread	%	0.025	0.025
final mom. spread	%	0.025	0.6
Protons on target	10^{14}	-	5

B.1 High power Linac

The linear accelerator is the first stage of any hadron accelerator complex. The LINAC generates the initial transverse and longitudinal beam emittances and energy spread, defining the beam quality for the next stages of acceleration, accumulation and compression. For a project like the Muon Collider, where the repetition rate is low, a high-energy high-power LINAC can be a versatile machine that can serve many other purposes including (and not restricted to) neutrino factories and nuclear science experiments.

The main parameters for a Muon Collider LINAC based injector are listed in Tables 2.1 and 2.2 consisting of two options that will drive the final power of the facility. Additional components required for the proton driver includes a H^- source for charge-exchange injection, and a low-energy chopper. Fig. B.2 presents a chopping scheme for each of the options where the source current is set at 80 mA and a pulse length from the source pulse length of either 2.5 or 5.0 ms is needed.

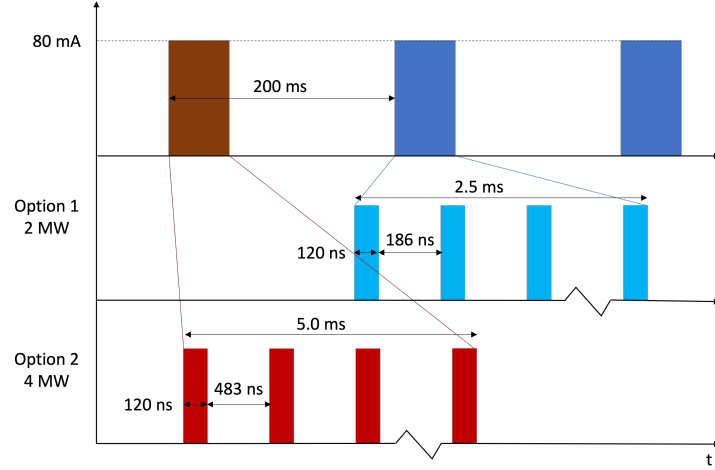


Fig. B.2: Possible Chopping scheme for the LINAC considering a double bunch option for both final energies.

A study on the losses in the high energy section of a full energy LINAC for both options was carried out [17]. The main contributor is black body radiation losses which indicates that the warm sections outside cryomodules and the transfer line to the accumulator ring will have to be cooled to temperatures below 200 K in order to maintain the losses within acceptable levels.

B.2 Accumulator

In order to test the stability and possible accumulation schemes for the beam coming from the LINAC we used two lattices developed for the Neutrino Factory at CERN [18, 19] and based on the parameters listed in Tables 2.2 and B.2. For both final energies no instabilities are seen throughout the turns needed for accumulation. The total tune spread due to space charge forces is 0.15 for the 5 GeV (2 MW) option and less than 0.05 for the 10 GeV (4 MW) option.

B.3 Compressor

The role of the compressor ring is to transform the 120 ns bunch from the accumulator into a 2 ns bunch, keeping the same bunch intensity. This is done by injecting a longitudinally 'mismatched' bunch into a synchrotron ring with RF cavities.

The current design is inspired by the lattice for short proton bunches for a neutrino factory, which combines a large slippage factor for a fast rotation with a minimized dispersion for a realistic ring aperture [20]. This is achieved by capping the maximum positive dispersion by adding negative bends. A lattice for the 5 GeV and 10 GeV options exists and simulations including 3D space charge are under way in order to optimized the longitudinal rotation, working points and final emittances.

B.4 Next Steps

A new lattice for the linac including cavities with higher geometrical beta ($\beta_g = 1$) we developed and the simulations show a good transport. New calculation on intra-beam stripping of H^- ions for the new lattice was carried out and no major show stopped could be identified, losses are well within the 1 W/m

loss budget.

New simulations for the accumulator for the 5 GeV case is also under way where 3D space charge will be used in order to confirm that no major problems are encountered during accumulation.

An alternative compression idea is under study, in this idea there is no need for an accumulator lattice and the current compressor ring is used for final compression. During the simulation for the compression with RF for the 5 GeV case, significant beam emittance blow-up was observed at the end of compression and is under investigation.

C Appendix: Target & Front-End

1. The target and solenoid (transverse) capture system, initially with field 15–20 T tapering to 1–2 T, the baseline parameters of which are in Table 3.1. Further information in Section C.1 for the baseline design, and Section C.2 for the higher-power option;
2. Extraction line for the spent proton beam in Section C.3.2;
3. Solenoid chicane and proton absorber, in Section C.3.1;
4. Longitudinal drift;
5. Sequence of RF cavities for bunching, in Section C.4;
6. Further sequence of RF cavities for rotating in energy-phase space, also in Section C.4.

C.1 2 MW Target and solenoid

Pions are produced by sending protons onto a graphite target immersed in a strong magnetic field. Solenoid parameters are listed in Table 9.1. In the MAP design, resistive magnets (RC1–RC5) were considered, however IMCC is developing a full HTS-based alternative. The target and target systems are under design, thus no details regarding the expected operation temperature, mechanical response and life-time are listed here.

Moreover, small discrepancies exist in the components dimensions reported in this chapter, particularly between pion/muon yield studies and design and engineering calculations.

Information on the radiation load on the target solenoids is within Section 12.1.

C.1.1 Production target engineering parameters

As depicted in Table C.1, the target system is divided into production target, target vessel, target shielding, target shielding vessel, proton beam window and muon beam window. The auxiliary services for cooling of the target and shielding are equally part of the target system and are listed in Table C.2. For both tables, the main dimensions, key material considerations and important design and integration features are summarized.

The baseline for a 2 MW-class target consists of a solid graphite target. The graphite rod is housed within a double-walled vessel filled with a static helium atmosphere. This helium confinement facilitates the initial stage of heat removal from the graphite rod through natural convection, while raising the sublimation temperature of the graphite when compared to a vacuum environment and providing a non-erosive heat transfer medium. Forced convection cooling is then applied through the vessel's double wall using a 10 bar helium flow.

	Material	Box dimensions DxL [mm]	Integration
Production Target	Isostatic Graphite	D30 x L800	Rod supported with transverse CFC supports attached to cylindrical frame
Target Vessel	Titanium Grade 5	D346 x L920	Located in the bore of the Target shielding vessel.
Proton Beam Window	Beryllium	D220 x L0.25	
Muon Beam Window	Titanium Grade 5	D240 x L1	Welded on the vessel
Target Shielding	Tungsten	D x L2000	Inside Shielding Vessel. Multiple pie-like blocks stacked together with guiding rods.
Target Shielding Vessel	Stainless-Steel	D1218 x L2065	Supported by transversal beam across the cryostat of the solenoid.

Table C.1: Baseline engineering parameters of the carbon target system

Cooling Unit	Coolant	Type	Mass Flow kg/s	Pressure bar	Integration
Target	Helium	Static / Natural convection	-	1	Surrounding target rod enclosed by windows and target vessel.
Target Vessel	Helium	Forced convection	0.5	10	Inside double wall target vessel. Routing upstream via the Solenoid bore.
Beam window	Helium	Forced convection	0.005	1	Double layer window
Target Shielding	Helium	Forced convection	0.33	2	Inside Target shielding Vessel. Routing upstream via the Solenoid bore.

Table C.2: Baseline engineering parameters of the carbon target auxiliary systems for 2MW.

Titanium is a suitable candidate for the target vessel due to its low density (reduced interaction with produced pions and muons) and good thermal-shock resistance. However, it is required to use beryllium in proton and muon windows to guarantee a peak power density of approximately 800 W/cm^3 and yearly DPA around 0.5. On the contrary, adopting titanium would increase these values by an order of magnitude.

The target vessel is surrounded by a helium-cooled, heavy tungsten shield, which reduces power deposition and radiation damage to the solenoid materials to acceptable levels. For details on the radiation shielding, see Section 12. The target proximity shielding is housed inside a large stainless-steel vessel, extending from just upstream of the target to around 2 meters downstream. The large size and weight, combined with the need to efficiently extract heat from each tungsten block, resulted in proximity shielding composed of multiple pie-shaped tungsten segments, perforated in specific locations to either guide helium flow or allow for the insertion of longitudinal rods to hold the assembly together. The shielding vessel also hosts a water layer to moderate the neutrons.

Both the cooling and instrumentation routing for the target systems are handled via the upstream side of the assembly.

Downstream of the target and its cooled shielding assembly, the shielding is made of tungsten and has an aperture following the parabolic shape defined in the MAP studies.

C.1.2 Target radial build

A preliminary target radial build has been defined and is shown in Table C.3. This build takes into account a 700 mm inner-radius solenoid coil, the baseline target system dimensions as described in Table C.1, and the required shielding configuration with a water and Boron-Carbide neutron-absorbing layers (Table 12.1). The discrepancy in thickness of tungsten shielding between Table C.3 and Table 12.1

is explained by the need to integrate other components in the prior as part of the exercise to engineer the entire target-solenoid cryostat.

Component	Material	r_i [mm]	r_e [mm]	Δr [mm]
Solenoid coils	HTS	700	-	-
Insulation	Insulation	690	700	10
Vacuum	Vacuum	670	690	20
Thermal shield	Copper & Water	651	670	19
Vacuum	Vacuum	631	651	20
Inner supporting tube	Stainless-steel	619	631	12
Vacuum	Vacuum	609	619	10
Outer Target shielding	Tungsten	599	609	10
Neutron absorber	Boron Carbide	594	599	5
Target shielding and neutron moderator	Stainless-steel	589	594	5
	Water	569	589	20
	Stainless-steel	564	569	5
	Tungsten	179	564	385
	Stainless-steel	174	179	5
Vacuum	Vacuum	173	174	1
Target vessel	Titanium	168	173	5
	Helium	155	168	13
	Titanium	150	155	5
	Helium	15	150	135
Target	Graphite	0	15	15

Table C.3: Target System radial build for a graphite target.

C.2 4 MW Target and solenoid

Additional studies on the higher-power 4 MW target option have been performed assuming the initial proton beam of Table C.4. The engineering parameters for such a target are shown in Table C.5, and the cooling in Table C.6.

Parameters	Unit	Baseline
Beam power	MW	4
Beam energy	GeV	10
Pulse frequency	Hz	5
Pulse intensity	p+ 10^{14}	5
Bunches per pulse		1
Pulse length	ns	2
Beam size	mm	5 or 7.5
Impinging angle	°	0

Table C.4: Alternative beam from proton driver via carbon target for the 4 MW beam

	Material	Box dimensions DxL [mm]	Integration
Production Target	Isostatic Graphite	D30 x L800	Rod supported with transverse CFC supports attached to cylindrical frame
Target Forced Convection Inner Vessel	Titanium Grade 5	D42 x L920	Inner vessel to force annular convection. Supported with the Outer vessel
Target Vessel	Titanium Grade 5	D346 x L920	Located in the bore of the Target shielding vessel.

Table C.5: Engineering parameters for carbon target for alternative option of 4MW

Cooling Unit	Coolant	Type	Mass Flow kg/s	Pressure bar
Target	Helium	Forced convection	0.2-0.36	10

Table C.6: Baseline engineering parameters of the carbon target auxiliary systems for 4MW.

C.3 Front-End

C.3.1 Chicane and proton absorber

The target solenoid is followed by a solenoid chicane which is terminated by a thick beryllium cylinder. The cylinder absorbs low energy remnant protons which would otherwise irradiate equipment downstream of the chicane. The concept was initially introduced in [21] and initial parameters were defined. Further discussion was made in [22]. In particular, the former study assumed 1.5 T solenoid fields, while the MAP and latter study considered 2 T solenoid fields in this region. The latter study also noted that a large proportion of undecayed pions were stopped in the proton absorber which negatively impacted the muon yield.

Table C.7 shows the current design parameters for the chicane and the proton absorber.

Parameters	Unit	Value
Chicane bend angle	degree	15
Chicane radius of curvature	m	22
Proton absorber material	-	Be
Proton absorber thickness	m	0.1
Chicane field	T	1.5

Table C.7: Chicane and proton absorber parameters

C.3.2 Spent proton beam extraction

A non-negligible fraction of the primary protons do not have an inelastic nuclear collision in the production target and escape from the graphite rod. At these energies, the protons are not bent significantly by the chicane and would be lost on the chicane aperture. In absence of a mitigation strategy, the energy carried by these particles would lead to a high power deposition density in the normal-conducting chicane solenoids. In addition, a high cumulative ionizing dose and displacement damage would be reached within a short operational time. It is therefore necessary to extract the spent protons from the front-end and steer them onto an external beam dump.

Earlier studies explored a possible solution of injecting the proton beam at different angles into the front-end, with an extraction channel envisaged in a gap between the superconducting magnets upstream of the chicane. This concept proved to be unfeasible due to geometrical aspects and the increase of the radiation load to the superconducting coils. As an alternative solution, the spent proton beam could be

extracted in the middle of the chicane, by using solenoids with different diameters in order to create a gap for the high-energy protons. Shower simulation studies showed that such an extraction channel in the chicane needs to have a transverse size of a few tens of centimeters, which is challenging for the magnet design. In addition, an internal radiation shielding would be needed to protect the coils from particles, which are still lost in the chicane. The chicane design studies are presently still ongoing.

Parameters	Unit	
Num. micro bunches		21
Longit. emittance	mm	46
Transv. emittance	um	17000
Positive muon yield	1/GeV per p+	0.024
Negative muon yield	1/GeV per p+	0.018

Table C.8: Outgoing muon beam

C.4 Buncher & Phase Rotator

The buncher is comprised of a sequence of RF cavities. The cavity frequency is chosen to match the distance between nominal RF bunches, so that it varies along the length of the buncher. The phase is purely bunching.

In the phase rotator, cavities are dephased so that the low energy tail of the beam sees an accelerating gradient and the high energy front of the beam sees a decelerating gradient.

Cavities are placed in a two-cavity LINAC with 0.25 m separation between adjacent cavity pairs. Each cavity in the pair is independently phased. Transversely, the beam is contained in a 2 T field.

D Appendix: Cooling

D.1 Initial Cooling

The Helical FOFO Snake (HFOFO) is a design for initial (pre-charge separation) 6D cooling of both signs of muon in a single channel. The HFOFO lattice is composed of alternating-polarity, inclined solenoids, as well as RF cavities and LiH wedge absorbers. Periodic rotations about both the x- and z-axes are applied to the solenoids, as defined by the pitch and roll angles respectively. The effect of these rotations is the generation of a rotating dipole field which enables charge-agnostic focusing. A “matching section” comprising the first nine solenoids, characterized by unique parameters, is necessary to induce the hallmark helical orbits particles execute in the HFOFO channel. The subsequent portion of the channel, referred to here as the “steady-state,” is built from repeated periods of six units corresponding to six periodic solenoid rotations (where a unit is defined as a set of one solenoid, the RF cavity within it, and the wedge absorber placed after it).

Table D.1 contains those parameters which vary along the channel — that is, the rotations of solenoids in the matching and steady-state sections, in addition to the RF gradient. In Table D.2, a list of parameters which are consistent for the entire channel is given, including the solenoid geometries and further descriptions of the RF system.

The set of six repeated z-rotations (described by roll angles) of solenoids in the steady-state channel are given in Table D.3, as are the angles of the repeated wedge absorber rotations (about the z-axis).

Position of unit in lattice	Coil pitch [deg]	Coil roll [deg]	RF gradient [MV/m]
1	0	0	20
2	0	0	20
3	0.0886	-122.4	20
4	0.1246	-23.6	20
5	0.0863	122.3	20
6	0.0817	-102.0	25
7	0.0969	25.3	25
8	0.1672	137.8	25
9	0.1226	-97.0	25
10-end	0.14	periodic (see additional table)	25

Table D.1: HFOFO full-channel variable parameters for matching (units 1–9) and steady-state (units 10–end) sections.

Parameter	Unit	Value
Number of solenoids per period		6
Period length	mm	4200
Number of periods per channel		30
Coil length	mm	300
Coil inner radius	mm	420
Coil outer radius	mm	600
Spacing between coil centers	mm	700
RF frequency	MHz	325
RF length	mm	249
GH ₂ density	g/cm ³	0.014

Table D.2: HFOFO full-channel constant parameters for matching and steady-state sections.

Position of unit in period	Periodic coil rolls [deg]	Periodic wedge angles [deg]
1	240	-26.97
2	0	93.03
3	120	213
4	240	333
5	0	453
6	120	573

Table D.3: HFOFO periodic parameters.

Finally, Table D.4 provides performance results from present G4beamline simulations of HFOFO. The emittances have been calculated using the ICOOL *emitcalc* script. Notably, these simulations use a MAP-era beam file containing only positive muons — though further studies are ongoing to assess the performance and acceptance of the design with more modern input beams. Corrections may be in order to adequately compare the performance to that of other designs.

	N_{total}	$N_{150 < p < 350 \text{ MeV}}$	$\varepsilon_{\perp} [\text{m}]$	$\varepsilon_L [\text{m}]$
Initial	11452	7666	0.01604	5.748
Final	5348	5139	0.003595	2.908
	47% transmission	67% transmission	Factor of 4.46	Factor of 1.98

Table D.4: HFOFO performance (with MAP-era μ^+ beam). Emittances calculated with *emitcalc*.

D.2 Baseline Rectilinear Cooling

The rectilinear cooling section consists of a number of solenoid magnets with dipole field superimposed. In the MAP design the dipole field was achieved by means of introducing a tilt in the solenoids but separate dipoles are proposed for this IMCC design. The rectilinear cooling lattice described below is stored in the MuonCollider-WG4 GitHub group, `rectilinear` repository as release (branch) `2024-09-27_release` and described in [23].

The solenoid field is approximately sinusoidal with a period given by the cell length L so that $B_z(z, r = 0) = B_{\text{peak}} \sin(2\pi z/L)$. Cells in the Rectilinear B lattices are increasingly non-sinusoidal, with a component $B_z(z, r = 0) = B_{\text{peak}} \sin(4\pi z/L)$ that gets stronger further down the B lattice. The peak B_z listed in Table D.6 is the peak field on the axis of the solenoid. Fields may be higher in the conductor volume.

RF cavities are modelled as perfect cylindrical pillbox cavities operating in TM010 mode. Several RF cavities are included within each cell. A thin conductive window electromagnetically seals the RF cavities so that the pillbox model is an adequate approximation to the real cavity field and the cavities can be assumed to be independently phased. The RF gradient listed in Table D.7 is the peak gradient.

Updates for the A and B stages of the rectilinear cooling system have been developed, comprising of 10 "B-type" stages, denoted S1 through S10 that yields improved performance over the MAP lattice listed above and has been designed using 352 MHz RF and harmonics. The performance is summarised in Table D.5.

Hardware parameters are described in Table D.6. In this lattice, the dipoles were simulated as a magnet independent of the solenoids which were not tilted and the dipole field is listed.

	ε_T mm	ε_L mm	ε_{6D} mm ³	Stage Transmission	Cumulative Transmission %
Start	16.96	45.53	13500		100
A-Stage 1	5.17	18.31	492.60	75.2	75.2
A-Stage 2	2.47	7.11	44.03	84.4	63.5
A-Stage 3	1.56	3.88	9.59	85.6	54.3
A-Stage 4	1.24	1.74	2.86	91.3	49.6
Bunch merge	5.13	9.99	262.5	78.0	38.7
B-Stage 1	2.89	9.09	76.07	85.2	33.0
B-Stage 2	1.99	6.58	26.68	89.4	29.4
B-Stage 3	1.27	4.05	6.73	87.5	25.8
B-Stage 4	0.93	3.16	2.83	89.8	23.2
B-Stage 5	0.70	2.51	1.32	89.4	20.7
B-Stage 6	0.48	2.29	0.55	88.4	18.2
B-Stage 7	0.39	2.06	0.31	92.8	17.0
B-Stage 8	0.26	1.86	0.13	87.9	14.9
B-Stage 9	0.19	1.72	0.06	85.2	12.7
B-Stage 10	0.14	1.56	0.03	87.1	11.1

Table D.5: Rectilinear cooling performance in terms of emittance reduction (transverse, longitudinal and 6D) and transmission per stage.

	Cell Length m	Stage Length m	Pipe Radius cm	Max. B_z On-Axis T	Int. B_y Tm	$\beta_\perp$ cm	D_x mm	On-Axis Wedge Len. cm	Wedge Angle deg
A-Stage 1	1.8	104.4	28	2.5	0.102	70	-60	14.5	45
A-Stage 2	1.2	106.8	16	3.7	0.147	45	-57	10.5	60
A-Stage 3	0.8	64.8	10	5.7	0.154	30	-40	15	100
A-Stage 4	0.7	86.8	8	7.2	0.186	23	-30	6.5	70
B-Stage 1	2.3	50.6	23	3.1	0.106	35	-51.8	37	110
B-Stage 2	1.8	66.6	19	3.9	0.138	30	-52.4	28	120
B-Stage 3	1.4	84.0	12.5	5.1	0.144	20	-40.6	24	115
B-Stage 4	1.2	66.0	9.5	6.6	0.163	15	-35.1	20	110
B-Stage 5	0.8	44.0	6	9.1	0.116	10	-17.7	12.5	120
B-Stage 6	0.7	38.5	4.5	11.5	0.087	6	-10.6	11	130
B-Stage 7	0.7	28.0	3.75	13	0.088	5	-9.8	10	130
B-Stage 8	0.65	46.15	2.85	15.8	0.073	3.8	-7	7	140
B-Stage 9	0.65	33.8	2.3	16.6	0.069	3	-6.1	7.5	140
B-Stage 10	0.63	29.61	2.0	17.2	0.069	2.7	-5.7	6.8	140

Table D.6: Rectilinear cooling cell hardware in terms of cell geometry, solenoid fields, dipole fields and wedge geometry

	RF Frequency MHz	Num. RF	RF Length cm	RF Gradient MV/m	RF phase deg
A-Stage 1	352	6	19	27.4	18.5
A-Stage 2	352	4	19	26.4	23.2
A-Stage 3	704	5	9.5	31.5	23.7
A-Stage 4	704	4	9.5	31.7	25.7
B-Stage 1	352	6	25	21.2	29.9
B-Stage 2	352	5	22	21.7	27.2
B-Stage 3	352	4	19	24.9	29.8
B-Stage 4	352	3	22	24.3	31.3
B-Stage 5	704	5	9.5	22.5	24.3
B-Stage 6	704	4	9.5	28.2	22.1
B-Stage 7	704	4	9.5	28.5	18.4
B-Stage 8	704	4	9.5	27.1	14.5
B-Stage 9	704	4	9.5	29.7	11.9
B-Stage 10	704	4	9.5	24.9	12.2

Table D.7: Rectilinear cooling cell RF parameters. 0° phase is bunching mode.

	Beam Size σ_x (σ_y) Cell Center (max) mm	Beam Size σ_x (σ_y) Cell Start (min) mm
A-Stage 1	48.6 (35.4)	38.6 (47.2)
A-Stage 2	25 (22.1)	23.9 (23.6)
A-Stage 3	15.6 (15.4)	15.7 (14.6)
A-Stage 4	13 (11.9)	12.6 (12)
B-Stage 1	28.4 (27.5)	23.9 (23.3)
B-Stage 2	20 (20.3)	19.5 (17.4)
B-Stage 3	16.4 (16.3)	12.3 (11.2)
B-Stage 4	13.5 (13.9)	8.9 (7.9)
B-Stage 5	9.8 (10)	6.2 (5.8)
B-Stage 6	8.6 (8.4)	3.9 (3.8)
B-Stage 7	7.7 (7.6)	3.3 (3.2)
B-Stage 8	5.8 (5.6)	2.3 (2.3)
B-Stage 9	5.2 (5.1)	1.7 (1.8)
B-Stage 10	4.7 (4.2)	1.4 (1.4)

Table D.8: Rectilinear cooling cell beam size at the start and center of the beam. Horizontally (and vertically).

D.2.1 Low-Stress Rectilinear Cooling

Upon review of the above solenoids, the radial stress was calculated, as shown in Table H.1. In response to this, a low-stress lattice option has been produced, the performance of which is displayed in Table D.9. The cell details in each stage is listed in Table D.10, and the resulting RF cavity parameters are in Table D.11.

VARIANT Low Stress	ε_T mm	ε_L mm	ε_{6D} mm ³	Stage Transmission	Cumulative Transmission
Start	16.96	45.53	13500		100
A-Stage 1	4.977	17.83	447.3	72.6	72.6
A-Stage 2	2.486	7.06	44.24	82.8	60.1
A-Stage 3	1.609	3.616	9.604	84.1	50.6
A-Stage 4	1.247	1.74	2.863	87.4	44.2
Bunch merge	5.13	9.99	262.5	78	34.6
B-Stage 1	2.892	9.239	77.77	85.3	29.5
B-Stage 2	2.025	6.418	26.96	90.9	26.8
B-Stage 3	1.214	3.972	5.943	87.2	23.4
B-Stage 4	0.8987	3.021	2.476	91.6	21.4
B-Stage 5	0.6868	2.528	1.224	90	19.3
B-Stage 6	0.4683	2.29	0.5099	85.3	16.5
B-Stage 7	0.3642	2.035	0.2718	88.4	14.5
B-Stage 8	0.2659	1.843	0.1307	84.5	12.3
B-Stage 9	0.1839	1.725	0.0586	81.4	10
B-Stage 10	0.1404	1.554	0.03027	82.7	8.3

Table D.9: New lattice with larger gaps and less solenoid stress. Rectilinear cooling performance in terms of emittance reduction (transverse, longitudinal and 6D) and transmission per stage.

VARIANT Low Stress	Cell Length m	Stage Length m	Pipe Radius cm	Max. B_z On-Axis T	Int. B_y Tm	$\beta_\perp$ cm	D_x mm	On-Axis Wedge Len. cm	Wedge Angle deg
A-Stage 1	1.9	110.2	28	2.5	0.095	72	-60	30	80
A-Stage 2	1.3	132.6	16	3.6	0.141	47	-56	21.5	100
A-Stage 3	0.9	80.1	10	5.5	0.152	31	-40	15	100
A-Stage 4	0.76	101.08	8	6.9	0.172	23	-35	14	110
B-Stage 1	2.2	50.6	23	3.3	0.118	34	-52	37	110
B-Stage 2	1.8	66.6	19	4	0.144	28	-52	28	120
B-Stage 3	1.5	90	12.5	4.9	0.144	19	-41	24	115
B-Stage 4	1.25	68.75	9.5	5.9	0.151	15	-35	20	120
B-Stage 5	0.85	45.9	6	8.8	0.110	10	-18	12.5	120
B-Stage 6	0.8	43.2	4.5	10.7	0.080	6	-10	11	130
B-Stage 7	0.8	32	3.8	11.5	0.078	5	-9.8	10	130
B-Stage 8	0.78	39	3	12.9	0.064	4	-7.1	7	140
B-Stage 9	0.78	40.56	2.3	13.5	0.059	3.5	-6.1	7.5	140
B-Stage 10	0.78	31.98	2	14.1	0.059	3.1	-5.7	6.8	140

Table D.10: New lattice with larger gaps and less solenoid stress. Rectilinear cooling cell hardware in terms of cell geometry, solenoid fields, dipole fields and wedge geometry

VARIANT Low Stress	rf frequency MHz	Number of rf cells	rf cell length cm	rf gradient MV/m	rf phase deg
A-Stage 1	352	6	20	25.7	19.9
A-Stage 2	352	4	20	26	23.6
A-Stage 3	704	5	10	31.6	22.2
A-Stage 4	704	4	10	31.6	23.7
B-Stage 1	352	6	22	22.5	32.8
B-Stage 2	352	5	22	23.6	27.1
B-Stage 3	352	4	22	23.2	25.5
B-Stage 4	352	3	22	24.1	27.9
B-Stage 5	704	4	10	27	26.4
B-Stage 6	704	4	8	31.8	25.6
B-Stage 7	704	4	8	31.3	22.7
B-Stage 8	704	4	8	25.9	15.9
B-Stage 9	704	4	8	23.8	15.4
B-Stage 10	704	4	8	24.3	13.6

Table D.11: New lattice with larger gaps and less solenoid stress. Rectilinear cooling cell RF parameters. 0° phase is bunching mode.

D.3 Final cooling

There are three lattice options for the final cooling in development. Each correspond to the initial conditions of the 6D cooling lattice before it. The first assumes MAP parameters of $\varepsilon_T=300\ \mu\text{m}$, $\varepsilon_L=1.5\ \text{mm}$. The second takes the beam from the B8 stage of the IMCC rectilinear cooling $\varepsilon_T=260\ \mu\text{m}$, $\varepsilon_L=1.8\ \text{mm}$, and the third takes the beam from the B10 stage of $\varepsilon_T=140\ \mu\text{m}$, $\varepsilon_L=1.5\ \text{mm}$.

D.3.1 Final Cooling - from MAP initial conditions

The final cooling lattice from MAP initial conditions is made of 10 high field solenoids, which alternate in polarity each cell, represented in Figure D.1. 10 matching low-field solenoids are placed between the two high-field solenoids, which have space sufficient to fit RF pillboxes, required to reach the kinetic energies and energy spreads referenced in Table D.12.

The absorbers are modelled as a constant pressure of $70.8\ \text{kg/m}^3$, which is unrealistic given the beam intensities towards the end of the final cooling lattice [24]. For this reason, the density x length is represented in Table D.12.

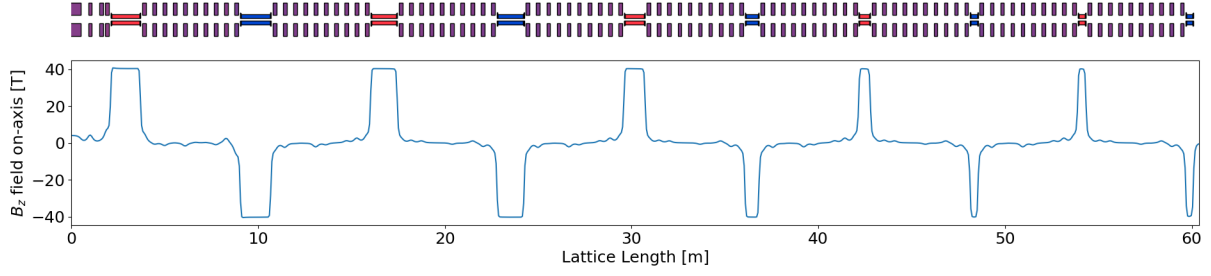


Fig. D.1: Geometric overview of the Final Cooling lattice from MAP parameters, including B_z field-on-axis. Red for +40 T solenoids, blue for -40 T solenoids, and purple for low-field matching solenoids. Correct relative inner and outer radii.

Cell No Unit	ε_T mm	ε_L mm	KE MeV	σKE MeV	$\rho L(H_2)$ kg/m ²	L_{sol} m	B_z T	T (loss) %	T (decay) %
0	0.300	1.5							1.00
1	0.247	1.88	123.49	5.42	90.4	1.52	40	100.0	0.99
2	0.203	2.28	123.34	5.82	93.8	1.57	-40	100.0	0.96
3	0.165	2.83	100.41	5.25	78.2	1.35	40	100.0	0.91
4	0.126	3.98	85.49	5.07	80.6	1.38	-40	100.0	0.85
5	0.103	5.13	74.48	5.66	57.8	1.06	40	100.0	0.77
6	0.087	6.73	51.82	4.36	30.9	0.68	-40	100.0	0.67
7	0.060	11.82	32.01	2.40	21.4	0.54	40	95.1	0.55
8	0.045	20.76	18.28	1.30	7.4	0.34	-40	99.7	0.43
9	0.032	39.25	17.94	1.25	8.4	0.36	40	96.4	0.32
10	0.0222	71.72	14.70	1.21	6.4	0.33	-40	89.8	0.20

Table D.12: Overview of final cooling design from MAP initial conditions

D.3.2 Final Cooling - from B8

Updated final cooling lattices were designed based on the output beam emittance from the 6D cooling lattices described in Section D.2. The overall cell layout follows the configuration shown in Figure D.1, except that the 0°-phase RF cavities used for phase rotation have been removed. Table D.13 summarizes the output and cumulative emittances at the end of each stage, with the initial emittance taken from B-Stage 8 in Table D.5. At the end of the cooling channel, the transverse emittance is reduced to 22.4 μm , satisfying the luminosity requirement, while the longitudinal emittance reaches 43 mm, which remains below the current requirement of the acceleration system. The main hardware parameters of the absorber, magnet, and RF system are listed in Tables D.14 and D.15. The peak magnetic field is kept below 42 T, and the RF frequency gradually decreases along the channel to match the increasing bunch length, as shown in Table D.16.

Stage	ε_T mm	ε_L mm	ε_{6D} mm ³	Cumulative transmission %
Start	0.26	1.8	0.12	100
Stage 0	0.21	2.5	0.11	99.6
Stage 1	0.16	5.2	0.14	90.1
Stage 2	0.12	8.7	0.13	79.8
Stage 3	0.095	10.3	0.098	72.5
Stage 4	0.063	15.1	0.064	65.5
Stage 5	0.041	22.7	0.039	55.5
Stage 6	0.032	32	0.035	52
Stage 7	0.0224	42.68	0.022	42.7

Table D.13: Short rectilinear final cooling cell performance parameters (latest version)

Stage	Stage length (m)	Peak on-axis Bz (T)	LH absorber length (m)	$\rho L(H_2)$ (kg/m ²)
Stage 0	2.754	33.6	0.692	48.99
Stage 1	5.195	-36	0.397	28.11
Stage 2	5.401	35.5	0.135	9.56
Stage 3	4.268	-41.8	0.053	3.75
Stage 4	5.204	40.9	0.043	3.04
Stage 5	6.836	-41.3	0.018	1.27
Stage 6	5.17	38.4	0.012	0.85
Stage 7	5.565	-43.4	0.014	0.99

Table D.14: Short rectilinear final cooling cell magnet lattice parameters (latest version)

Stage	Frequency MHz	Number of RF cells	Maximum gradient MV/m	Phase °	RF cell length m
stage 0		0			
stage 1	142.9	5	9.2	26	1.25
stage 2	67.3	6	5	18.7	1.5
stage 3	52.7	3	4.9	50.2	0.75
stage 4	29.8	10	1.7	15.7	2.5
stage 5	15.3	14	1.5	23	3.5
stage 6	10	10	1.3	28.3	2.5
stage 7	8	11	1.2	40.9	2.75

Table D.15: Short rectilinear final cooling cell RF parameters. 0° phase is bunching mode. (latest version)

Stage	Final Pz	Final energy spread	Final $c\sigma_t$
Units	MeV/c	MeV	c
Start	135	3.9	0.04932
Stage 0	95.4	5.3	0.06703
Stage 1	65	3.7	0.2813
Stage 2	53	2.1	0.4926
Stage 3	46.2	2.4	0.6547
Stage 4	36.1	1.8	1.074
Stage 5	31	1.7	1.465
Stage 6	30	1.7	2.492
Stage 7	28	1.6	3.307

Table D.16: Short rectilinear final cooling cell beam longitudinal parameters (latest version)

D.3.3 Final Cooling - From B10

Another final cooling lattice was also designed based on the output emittance from B-Stage 10. As shown in Table D.17, this design reduces the transverse emittance to 23 μm , while the longitudinal emittance increases to 22 mm, which is nearly a factor of two smaller than that in Table D.13. This improvement results from the smaller initial transverse emittance, which allows for fewer cooling stages (absorbers) and therefore less beam-length growth caused by passage through the absorbers. The main hardware parameters of the absorber, magnet, and RF system are listed in Tables D.18 and D.19, and the corresponding longitudinal beam parameters are given in Table D.20.

Stage	ε_T mm	ε_L mm	ε_{6D} mm ³	Cumulative transmission %
Start	0.14	1.5	0.03	100
Stage 0	0.12	1.9	0.03	99.5
Stage 1	0.08	5.2	0.034	90.6
Stage 2	0.053	7.7	0.023	77.9
Stage 3	0.041	10.9	0.019	71.9
Stage 4	0.029	15.7	0.014	66.8
Stage 5	0.023	22.1	0.012	61.4

Table D.17: Long rectilinear final cooling cell performance parameters (latest version)

Stage	Stage length (m)	Peak on-axis Bz (T)	LH absorber length (m)	$\rho L(H_2)$ (kg/m ²)
Stage 0	2.035	40	0.183	12.96
Stage 1	4.656	-29.3	0.255	18.05
Stage 2	4.628	39.4	0.055	3.89
Stage 3	3.89	-41	0.02	1.42
Stage 4	4.124	39.6	0.015	1.06
Stage 5	5.068	-42.7	0.0092	0.65

Table D.18: Long rectilinear final cooling cell magnet lattice parameters (latest version)

Stage	Frequency MHz	Number of RF cells	Maximum gradient MV/m	Phase °	RF cell length m
stage 0		0			
stage 1	131.8	6	6.6	14.5	1.5
stage 2	56.3	5	4.4	31.4	1.25
stage 3	25.5	6	2.9	17.4	1.5
stage 4	14.8	7	1.7	45.6	1.75
stage 5	11.5	9	1.3	41.3	2.25

Table D.19: Long rectilinear final cooling cell RF parameters. 0° phase is bunching mode. (latest version)

Stage Units	Final Pz MeV/c	Final energy spread MeV	Final $c\sigma_t$ c
Start	95	3.35	0.04794
Stage 0	79.2	4.1	0.08625
Stage 1	46.8	2.6	0.2489
Stage 2	37.1	2.1	0.6356
Stage 3	31.5	1.1	1.044
Stage 4	28.3	1.3	1.481
Stage 5	26.5	1.2	2.247

Table D.20: Long rectilinear final cooling cell beam longitudinal parameters (latest version)

D.4 Pre-accelerator

No pre-accelerator design exists. Table D.21 gives estimations of design and performance based on induction LINAC technology.

Injection Energy MeV	Extraction Energy MeV	Pulse Length ns	Transmission %	Linac Length m
5	250	15	86	140

Table D.21: Pre-Accelerator (Induction Linac) - see for example RADLAC-1

E Appendix: Low Energy Acceleration

The low energy acceleration chain brings the muon beams from 250 MeV after the pre-accelerator to 62.5 GeV for injection into the high energy acceleration chain described in Section 5.

It is composed of a single-pass superconducting LINAC outlined in Table E.1, followed by two recirculating linear accelerators (RLA), described in Table E.2.

RLA2 has an preliminary optics design. No optics design exists for LINAC and RLA1. Both RLAs have an assumed racetrack geometry. The transmission through RLA2 is 92.6%. The target transmission for LINAC and RLA1 is 90%, which corresponds to an effective average gradient of 4.1 MV/m.

	CryoModule 1	CryoModule 2
Initial energy [GeV]	0.255	–
Final energy [GeV]	–	1.25
Frequency [MHz]	88 / 264	88 / 264
RF gradient [MV/m]	5 / 8	5 / 8
Passes	1	1

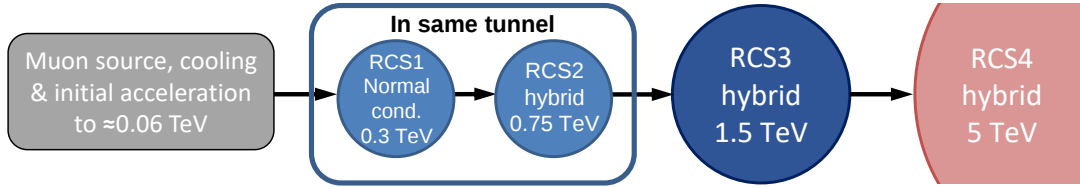
Table E.1: Parameters describing the single-pass LINAC that follows the final cooling section.

	RLA1		RLA2	
Initial energy [GeV]	1.25		5	
Final energy [GeV]	5		63	
Energy gain per pass	0.85		13.5	
Frequency [MHz]	352	1056	352	1056
No. SRF cavities	40	4	300	40
RF length [m]	68	3.44	510	34.4
RF gradient [MV/m]	15	25	15	25
Passes	4.5		4.5	
Linac length [m]	–		2 x 915	
Arc lengths [m]	–		$\approx 8 \times 438$	

Table E.2: Multi-pass recirculating LINACs

F Appendix: High Energy Acceleration

As described in [25], an option for the chain of four rapid cycling synchrotrons (RCS) foresees to accelerate two counter-rotating bunches at a repetition rate of 5 Hz in stages of 0.30 TeV (RCS1), 0.75 TeV (RCS2) and 1.5 TeV (RCS3) to inject into the 3 TeV collider ring, or 5 TeV (RCS4), to inject to the 10 TeV collider ring. This scenario is based on the US Muon Acceleration Program (MAP) [26, 27] and applied for a general Greenfield site. The high-energy stage of the accelerator chain with four RCS is illustrated in Fig. F.1. Corresponding site-specific parameter designs can be found in Section F.1. Alternative Fixed Field Accelerator options can be found in Section F.2.

**Fig. F.1:** Schematic of the chain of rapid cycling-synchrotrons for the high-energy acceleration complex. From [25].

The first two RCS share the same tunnel, meaning that they have the same circumference and layout [28]. The bending in the first RCS is provided by normal conducting magnets. The RCS2 to RCS4 are planned as hybrid RCSs where normal conducting magnets cycling from $-B_{nc}$ to $+B_{nc}$ are interleaved with strong fixed-field, superconducting magnets. Within this section, NC magnets are referred to as *pulsed*, and the SC magnets are referred to as *steady*. This is to reflect the alternative magnet technologies required for the hybrid RCS. This combination allows for a large energy swing with a high average bending field to minimize the travel distance of the muons and thus their decay losses. The absolute value of magnetic field in the normal-conducting dipoles does not exceed ± 1.8 T at injection and extraction for all RCSs to avoid saturation of the magnet yoke. For the hybrid RCS2 and RCS3, the magnetic field in the SC magnets is 10 T to provide a compromise between the magnet filling factor and magnet costs. To protect the SC magnets from decay products, the inner aperture of the SC magnets is larger with 10 T. Increasing the field to 16 T implies higher technological and financial cost without a significant improvement of the machine performance. In the case of RCS4 however, the average magnetic field in the accelerator is assumed to be 16 T as a higher magnetic field in the SC magnets helps to reduce the overall circumference and thus the muon decay and RF requirements. This requirement may evolve with

the optimization of the high-energy chain.

The number of synchrotron oscillations per turn is extreme [25], much larger than the conventional stability limit for stable synchrotron oscillations and phase focusing of $1/\pi$ in a synchrotron with one or few localized RF sections. To mitigate resulting beam losses, the RF system must be distributed over the entire RCSs. Tracking simulations on how the number of RF stations influences the longitudinal emittance have been performed. For the present design, the minimum number is around 32 RF stations for RCS1 and RCS4, and 24 stations for RCS2 and RCS3 [25].

It is worth noting that the longitudinal dynamics used values of momentum compaction factor for an RCS lattice design based on FODO cells. With a more defined optics design, this number might change and with it the basic parameters of the longitudinal beam dynamics such as the synchrotron tune, bucket area and energy acceptance, which are all a function of the momentum compaction factor.

Parameter tables

Table 5.1 shows the general RCS parameters, and Table 5.2 specifies lattice parameters. The first parameters for the fourth RCS to accelerate to 5 TeV are included but may evolve in the near future. We assume a survival rate of 90 % per ring and linear ramping only considering losses due to muon decay, even though these values are subject to further adjustments to optimize the RF and magnet powering parameters with respect to total costing, ramp shape, bunch matching, and the overall transmission of the entire chain.

F.1 Site-Based RCS Designs

Tentative parameter tables to guide future design efforts for the existing site options. Different assumptions were made for the magnet technologies.

F.1.1 RCS Layout at CERN

The RCS layout on the CERN site is based on the usage of the existing Super Proton Synchrotron (SPS) and Large Hadron Collider (LHC) tunnels to host the high-energy acceleration chain. To make a comparison with the greenfield study possible, the same assumptions for the injection energy and the injection bunch population were chosen. The survival rate over the whole RCS chain is assumed as 70%, only considering losses due to muon decay, while the individual survival rates of the rings were adjusted to achieve a high extraction energy from the last RCS. Table F.1 and F.2 for the site-based design correspond to Table 5.1 and 5.2 for the greenfield design respectively.

To avoid a complete redesign of the RCS optics for the CERN site-based high-energy acceleration chain, eight straight sections were assumed in each of the three RCS. A refined lattice would of course have to take into account that the existing accelerator tunnel of the SPS ring has a six-fold symmetry with only six long straight sections.

F.1.2 RCS Layout at FNAL

Tables F.3 and F.4 give tentative parameters for a four ring RCS layout for a Fermilab sited muon collider. A circumference of 6283 m is chosen for RCS1 and RCS2 to match that of the existing Tevatron tunnel, while a circumference of 15 500 m is chosen for RCS3 to fit within the Fermilab site boundary. The

Parameter	Unit	RCS SPS	RCS LHC1	RCS LHC2
Hybrid RCS	-	no	no	yes
Repetition rate	Hz	5	5	5
Circumference	m	6912	26659	26659
Injection energy	GeV	63	350	1600
Extraction energy	GeV	350	1600	3800
Energy ratio		5.6	4.6	2.4
Assumed survival rate		0.88	0.86	0.92
Cumulative survival rate		0.88	0.76	0.7
Acceleration time	ms	0.45	2.6	4.42
Revolution period	μ s	23	88.9	88.9
Number of turns		19	29	50
Required energy gain/turn	GeV	15.1	43.1	44
Average accel. gradient	MV/m	2.15	1.62	1.68
Number of bunches		1	1	1
Inj. bunch population	10^{12}	2.7	2.38	2.04
Ext. bunch population	10^{12}	2.38	2.04	1.88
Beam current per bunch	mA	18.75	4.29	3.675
Beam power	MW	803	523	462
Vert. norm. emittance	μ m	25	25	25
Horiz. norm. emittance	μ m	25	25	25
Long. norm. emittance	eVs	0.025	0.025	0.025
Bunch length at injection	ps	31	20	14
Bunch length at ejection	ps	20	14	10
Straight section length	m	1033.6	3989.4	4003
Length with pulsed dipole magnets	m	4075	18630	12808
Length with steady dipole magnets	m	-	-	5659
Injection pulsed dipole field	T	0.32	0.39	-1.8
Max. pulsed dipole field	T	1.8	1.8	1.8
Max. steady dipole field	T	-	-	10
Ramp rate	T/s	3280	541	810
Main RF frequency	GHz	1.3	1.3	1.3
Harmonic number		29900	115345	115345

Table F.1: Key acceleration Parameters for the CERN-site based RCS Acceleration Chain

circumference of 35 437 m of RCS4 was obtained by optimizing for an extraction energy of 5 TeV. This scenario is described in further detail, along with two other scenarios for the Fermilab RCS chain, in [29].

A slightly lower field of 1.75 T is assumed for pulsed magnets, while a higher field of 14 T is assumed for steady magnets.

Parameter	Unit	RCS1	RCS2	RCS3
Fill ratio dipole	%	59	70	70
Cells per arc		22	43	30
Number of arcs		8	8	8
Cell length	m	33.4	65.9	94.4
Total Arc length	m	5878.4	22669.6	22656
Arc Ratio	-	0.85	0.85	0.85
Relative path length difference	10^{-6}	0	0	1.5
Horizontal aperture	mm	76.5	43.9	76.8
Vertical aperture	mm	23.1	22.9	21
Transition gamma		40.92	82.62	59.04
Momentum compaction factor	10^{-4}	5.973	1.465	2.869
Horizontal tune (ring)		51.73	104.96	70.52
Vertical tune (ring)		51.56	103.86	69.93
Mean horizontal beta	m	32.95	72.15	87.39
Mean vertical beta	m	29.97	64.32	81.77
Horizontal natural chromaticity (ring)		-71.27	-150.52	-98.44
Vertical natural chromaticity (ring)		-64.63	-145.36	-87.87

Table F.2: Additional Lattice Parameters for the CERN-based RCS Acceleration Chain

Parameter	Unit	RCS1	RCS2	RCS3	RCS4
Hybrid RCS	-	no	yes	yes	yes
Repetition rate	Hz	5	5	5	5
Circumference	m	6283	6283	15500	35437
Injection energy	GeV	63.0	174	454	1541
Extraction energy	GeV	174	454	1541	5000
Energy ratio		2.756	2.614	3.394	3.245
Assumed survival rate		0.937	0.926	0.907	0.828
Cumulative survival rate		0.937	0.867	0.786	0.651
Acceleration time	ms	0.148	0.468	1.81	11.5
Revolution period	μ s	21.0	21.0	51.7	118
Number of turns		7.04	22.3	35.1	97.6
Required energy gain/turn	GeV	15.7	12.6	31.0	35.4
Average accel. gradient	MV/m	2.50	2.00	2.00	1.00
Number of bunches		1	1	1	1
Inj. bunch population	10^{12}	2.70	2.53	2.34	2.12
Ext. bunch population	10^{12}	2.53	2.34	2.12	1.76
Vert. norm. emittance	μ m	25.0	25.0	25.0	25.0
Horiz. norm. emittance	μ m	25.0	25.0	25.0	25.0
Long. norm. emittance	eVs	0.025	0.025	0.025	0.025
Straight section length	m	1478	1142	2067	2262
Length with pulsed dipole magnets	m	2496	2238	7811	21748
Length with steady dipole magnets	m	-	626	1792	5141
Injection pulsed dipole field	T	0.635	-1.75	-1.75	-1.75
Max. pulsed dipole field	T	1.75	1.75	1.75	1.75
Max. steady dipole field	T	-	14.0	14.0	14.0
Ramp rate	T/s	7553	7486	1931	303
Main RF frequency	GHz	1.30	1.30	1.30	1.30
Harmonic number		27246	27246	67213	153666

Table F.3: Key acceleration Parameters for the Fermilab-site based RCS Acceleration Chain

Parameter	Unit	RCS1	RCS2	RCS3	RCS4
Fill ratio dipole	%	33.1	34.2	51.6	72.3
Cells per arc		12	8	12	42
Number of arcs		12	12	12	6
Cell length	m	30.8	47.6	86.1	126
Transition gamma		38.2	24.7	35.7	60.4
Momentum compaction factor	10^{-4}	6.84	16.44	7.85	2.74

Table F.4: Additional Lattice Parameters for the Fermilab-based RCS Acceleration Chain

F.2 Fixed Field Acceleration

Milestone 17 [30] outlines the possibility of using vertical-excursion Fixed-Field Accelerator (vFFA) [31] rings as alternatives to one or more of the RCS rings, giving example parameters for RCS1 and RCS4 greenfield equivalents. These would provide the possibility for acceleration unconstrained by magnet ramp rates, removing issues for power conversion and storage, and enabling the construction of rings with full-superconducting magnet technology (thereby enhancing power efficiency). The relative isochronicity of the vFFA concept mitigates the need for frequency cycling in the RF systems, and enables the possibility of on-crest acceleration for an increased acceleration efficiency at a given RF voltage. Table F.5 lists the design parameters of these FFA rings alongside key parameters for comparison to the RCS equivalents.

However, the use of FFA arcs implies a closed orbit that moves as a function of energy. This increases requirements for element apertures. Milestone 17 presents a scheme for the implementation of dispersion suppressors to reduce the impact of this upon the RF systems. Depending on the specific execution of these schemes, further optimisation of the parameters in the included table could be possible to reduce peak fields and reduce the size of the machine by separating RF requirements from arc design requirements.

Table F.5: FFA alternative tentative parameters

Design Parameter	Symbol	Unit	vFFA1	vFFA4
Orbit radius at centre of F-magnet	r_0	m	953	5570
F-magnet bending angle	θ_F	rad.	0.01033	0.00786
Number of cells	N_c		790	1000
F-magnet half-opening angle	β_F	rad.	0.0015640	0.0019700
D-magnet half-opening angle	β_D	rad.	0.0011800	0.0011660
F-magnet orbit inclination	γ_F	rad.	0.252	-0.492
vFFA normalised field index	m	1/m	31.94	12.13
Comparison Parameter				
Circumference [m]		m	5990	35000
Injection Energy [TeV]		TeV	0.06	1.5
Extraction Energy [TeV]		TeV	0.3	5
Ramp Rate [T/s]		T/s	0	0
Vertical Excursion [m]		m	0.048	0.099
Relative path length difference			0	0
Peak Dipole Field On Orbit [T]		T	6.93	13.59
Peak Dipole Field (Good Field Region) [T]		T	12.52	29.04
Drift length [m]		m	1.18	1.03
Tune			(0.382, 0.079)	(0.460, 0.057)

G Appendix: Machine-Detector Interface

The beam-induced background arising from muon decay poses a significant challenge for the physics performance of a multi-TeV muon collider. The machine-detector interface relies on massive absorbers in close proximity to the interaction point (IP) to reduce the number of secondary particles reaching the detector. This section describes the geometrical features of the shielding and quantifies the flux of secondary background particles. In addition, the ionizing dose and displacement damage in different

parts of the detector are presented.

G.1 Nozzle geometry and material composition

The innermost part of the machine-detector interface consists of a nozzle-like shielding, which defines the inner detector envelope. The nozzle extends from the last magnet ($L^* = 6$ m) to almost the IP and must be made of a high- Z and high density material to shield efficiently the electromagnetic showers induced by the decay electrons and positrons. All studies carried out so far were based on the slightly modified nozzle geometry than the one developed within the Muon Accelerator Program (MAP) [32, 33]. Although the MAP nozzle was optimized for a center-of-mass energy of 1.5 TeV, it has been used as a starting point for the first 10 TeV studies (see, for example, Refs. [34, 35]).

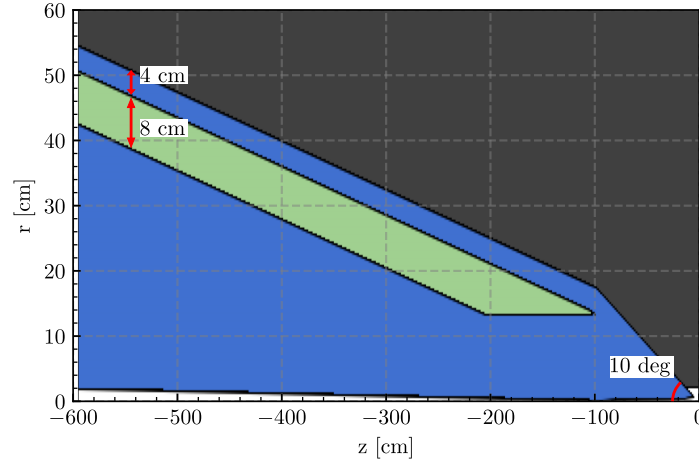


Fig. G.1: Left nozzle geometry dimensions. The blue layer is made of INNERMET180 (registered trademark), a heavy tungsten alloy, while the green one is composed of borated polyethylene.

z [cm]	r [cm]
Outer surface of nozzle	
595	55
100	17.57
6	1
Outer surface of the borated polyethylene layer	
595	51
100	13.57
Inner surface of the borated polyethylene layer	
595	43
204.49	13.47
100	13.47
Inner aperture of the nozzle	
595	1.78
100	0.3
15	0.6
6	1

Table G.1: Nozzle Dimensions

Figure G.1 illustrates the modified MAP nozzle geometry in the $z - r$ plane, where z is the beam axis

and r is the radial coordinate. The nozzle is assumed to have azimuthal symmetry around the z -axis. The figure shows only the nozzle on the left side of the IP; the second nozzle has the same shape but is mirrored with respect to the interaction point. The nozzle is assumed to consist mainly of INERMET180 (registered trademark), a tungsten-based alloy (blue color), with a layer of borated polyethylene on the outer surface (green color) to thermalize and absorb neutrons before they reach the detector. Using a tungsten alloy (instead of pure tungsten) is required to allow the manufacture of such shielding elements, however such a choice reduces slightly the shielding effectiveness of the nozzle due to the lower material density. The beam pipe connecting the two opposite nozzles is made of beryllium, with an internal radius of 2.3 cm and a thickness of 1 mm.

The nozzle tip is located at a distance of 6 cm from the IP. The inner aperture of the nozzle features three different angles, with an aperture bottleneck at 100 cm from the IP. In the region between 100 cm and the first magnet at 600 cm, the inner nozzle surface increases and is defined by the required beam clearance to avoid direct halo losses on the aperture. The outer surface of the nozzle follows a conical shape, with two different angles. Near the interaction point, the inclination amounts to 10 degrees, which determines the angular acceptance of the detector. All the space outside the nozzle and the central beam pipe can be occupied by the detector. The present setup is of conceptual nature, without yet considering engineering aspects or a possible support structure for the nozzle.

Table G.1 summarizes the coordinates of the inner aperture and outer surface of the nozzle, respectively. Table G.2 provides the material components of the nozzle.

Component	Density [g/cm ³]	Element	Atomic Fraction (mass fraction if negative)
EM Shower Absorber	18	W	-0.95
		Ni	-0.035
		Cu	-0.015
Neutron Absorber	0.918	H	0.5
		C	0.25
		B	0.25

Table G.2: Material composition of nozzle

G.2 Beam-induced background

The number of background particles entering the detector per bunch crossing depends on the nozzle geometry, the nozzle material composition and the interaction region layout. Table 8.2 summarizes the number of secondary electrons, positrons, photons and neutrons reaching the detector in a 10 TeV muon collider. The numbers were obtained with FLUKA Monte Carlo simulations, considering the nozzle introduced in the previous section. The bunch intensity was assumed to be 1.8×10^{12} muons. Only secondary particles with energies above a given threshold value were considered (see Table G.3).

Table G.3: Particle production and transport thresholds assumed in the background simulations.

Particle type	Threshold
Electrons, positrons and photons	100 keV
Hadrons and muons	100 keV
Neutrons	0.01 meV

The number of background particles presented in this section includes only the contribution from muon decay, which is expected to be the dominant source of beam-induced background. Other background sources can include muon halo losses on the aperture and incoherent electron-positron pair production.

G.3 Ionizing dose and displacement damage in detector

To evaluate the cumulative radiation damage in detector equipment, two quantities have been considered: the total ionizing dose and the 1 MeV neutron-equivalent fluence in Silicon. The former is a measure for the radiation damage in organic materials and compounds, while the latter is related to the displacement damage.

H Appendix: Magnets

Table 9.1 provides a summary of the magnet parameters for the study so far.

The short muon lifetime (2.2 μs at rest) and production of bright muon beams results in a unique set of demands for magnet technologies, including large-bore high-field solenoids, dipoles and quadrupoles, compact ultra-high-field solenoids, and very fast-ramping dipoles. Activities within the scope of the IMCC has led to the most advanced set of main magnet conceptual designs and performance parameters. These parameters are an evolution of previous studies, in particular the U.S. Muon Accelerator Program (MAP) [36], extending the performance space by considering recent advances in magnet technology.

This section will primarily consider the design challenges of the HTS 6D cooling solenoids, and the aperture-field developments of the collider dipoles and quadrupoles.

H.1 Cooling Solenoids

The overview of the cooling system parameters are in Section 4, which factors in our evolving understanding of acceptable solenoid parameter limits. We are presently performing analysis and optimization on this latest configuration. The 6D cooling section is crucial for producing a high-brightness muon beam, necessary for achieving the required luminosity at the interaction point. In this section the particles are cooled in the 6D phase space (position and momentum), the beam is focused and the bunch size is manipulated through the ionization cooling process.

H.1.1 Baseline 6D Cooling solenoids

In the current configuration, a total of 3054 solenoids are spread over a 0.85 km distance. There are 14 unique cell types, and 26 unique solenoid types. During the beam dynamics studies, we integrated a magnet design guide to constrain allowable magnet geometries and current densities based on key solenoid parameters (stresses σ , stored magnetic energy e_m , critical current density J_c). The limits are evaluated considering tape characteristics based on industrial production (Fujikura FESC-SCH ReBCO tape) [37]. The parameters and limits implemented (considering stand-alone, single solenoid operation) are: hoop stress, $\sigma_\theta < 300$ MPa; radial tensile stress, $\sigma_r < 20$ MPa; and stored magnetic energy density, $e_m < 150$ MJ/m³. The limits are identified from average single HTS tape characteristics with an adequate safety margin, ensuring a conservative approach given the considered homogenized coil representation. Additionally, a limit on the maximum current density was considered. The J_E values were compared to the critical current density J_c values from the measurements reported in [38], aiming

Cell	E_{Mag}	e_{Mag}	Coil	J_E	B_{peak}	σ_{Hoop} (Max.)	σ_{Radial} (Min.)	σ_{Radial} (Max.)
	(MJ)	(MJ/m ³)		(A/mm ²)	(T)	(MPa)	(MPa)	(MPa)
A1	5.4	21	A1-1	57.6	5.2	42	-8	0
A2	22.1	106.1	A2-1	149.5	11.6	194	-48	0
A3	5.0	49.5	A3-1	131.5	10.1	121	-25	0
A4	8.0	92.3	A4-1	193.2	13.8	225	-51	1
B1	9.1	49.8	B1-1	96.9	7.7	104	-24	0
B2	15.6	64.2	B2-1	102.1	9.2	131	-32	0
B3	36.9	105.9	B3-1	127.9	12.9	208	-57	0
B4	32.2	78.9	B4-1	103.0	10.6	281	-1	24
B4	32.2	78.9	B4-2	110.9	9.9	132	-49	1
B5	17.3	88.9	B5-1	179.6	14.7	295	-2	17
B5			B5-2	154.0	14.7	212	-57	1
B6	8.3	96.6	B6-1	214.4	15.3	339	-5	18
B6			B6-2	211.5	12.0	214	-6	6
B6			B6-3	212.7	12.4	162	-46	0
B7	8.2	87.7	B7-1	183.3	14.7	264	0	25
B7			B7-2	153.9	11.1	175	-4	10
B7			B7-3	210.3	13.2	180	-45	1
B8	8.8	92.1	B8-1	193.7	16.5	270	-6	38
B8			B8-2	202.1	15.4	270	-6	29
B8			B8-3	212.8	13.2	187	-50	0
B9	7.5	76.5	B9-1	256.4	17.2	281	0	37
B9			B9-2	88.4	10.0	95	-2	12
B9			B9-3	204.9	13.2	184	-46	0
B10	5.0	68.6	B10-1	326.8	19.2	378	0	49
B10			B10-2	146.1	11.1	105	-4	13
B10			B10-3	207.8	12.5	158	-43	1

Table H.1: Table of various parameters for 14 cell types and 26 unique solenoid types in the latest 6D cooling optics [23]. Values correspond to solenoids operating in their respective cells within a lattice. In bold, the parameters exceeding the considered design limits. The reported parameters will vary depending on the solenoid operational conditions (e.g., stand-alone or single cell operation).

at 2.5 K margin for HTS operating at 20 K. We report in Tab. H.1 the main parameters of each cooling cell type and unique solenoid type. These values are computed based on the lattice design within Section D.2.

Observing Tab. H.1, we find some solenoids exceed allowed design limits, primarily in terms of large hoop stresses (B6-1, B10-1) and tensile radial stresses (B4-1, B7-1, B8-1, B8-2, B9-1, B10-1). The most concerning solenoid is B10-1, with a hoop stress of 378 MPa, tensile radial stress of 49 MPa, and peak field on the coil of 19.2 T, exceeding its J_c by 114%. Critical to the solenoid configuration identified for the latest 6D cooling optics is the gap distance to the beam pipe and to the RF cavities. Following integration studies on the 6D cooling cell demonstrator, we found that larger gaps are needed to integrate the solenoids with RF cavities and absorbers within each cooling cell, making this solution not feasible from the point of view of cell integration. Therefore, another iteration of the design parameters is expected. The proposed solenoid configuration for the latest optic is thus a first step in the definition of

an integrated design, combining the beam optics requirements with a more comprehensive engineering design of the cooling cell solenoids. Further optimization will be needed, starting from the initial set of solenoids and integrating the inputs from the WP8 cell integration studies.

H.1.2 Low Stress 6D Cooling solenoids

Cell	E_{Mag} (MJ)	e_{Mag} (MJ/m ³)	Coil	J_E (A/mm ²)	B_{peak} (T)	σ_{Hoop} (Max.) (MPa)	σ_{Radial} (Min.) (MPa)	σ_{Radial} (Max.) (MPa)
A1	9.8	32.6	A1-1	68.6	6.4	66.1	-16.7	0.2
A2	38	72.7	A2-1	94.7	10.7	149.2	-40	0.7
A3	9.1	87.5	A3-1	168.5	11.9	188.4	-41.3	1.5
A4	13.1	83.9	A4-1	164.6	14	218.5	-49.6	5.6
B1	13.1	13.8	B1-1	32.1	5	33.5	-5.5	0.1
B2	25.4	31.3	B2-1	52.3	7.5	71.3	-14	0.2
B3	32.9	44.1	B3-1	84.6	8.2	154.3	-2.3	5.2
B3			B3-2	67.3	9.3	84.9	-22.3	0.3
B4	47.5	88	B4-1	115.2	9.2	231.5	-3.2	16.4
B4			B4-2	110.1	12.3	176	-52.7	1
B5	11.2	51	B5-1	141.6	12.2	220.1	-7	10.8
B5			B5-2	113.4	12	112.6	-32.9	3.5
B6	14.8	66.7	B6-1	183.4	13.8	276.3	-42.4	14.3
B6			B6-2	132.8	12.2	184.1	-161.3	7.9
B6			B6-3	136.3	10.8	106.5	-43.1	1.1
B7	10.8	47.8	B7-1	220.2	14.5	294.3	-26.4	13.8
B7			B7-2	113	9.4	127.8	-95.3	5.4
B7			B7-3	116.2	10.2	81.5	-26.4	1
B8	6.1	27.1	B8-1	221.6	15.3	293.3	-13.8	23.7
B8			B8-2	115.2	6.1	114.8	-17.4	6.6
B8			B8-3	78.6	6	23.2	-13.8	0.3
B9	15	48.9	B9-1	223	15.7	301.4	-64.4	28.8
B9			B9-2	107.3	7.7	192.3	-20.5	17.4
B9			B9-3	106.6	10.3	74.8	-64.9	0.7
B10	7.2	21.2	B10-1	254.6	16.5	333.6	-19.8	30.9
B10			B10-2	106.7	6.3	117.5	-18.9	8.8
B10			B10-3	65.6	8.3	30.2	-19.9	1.3

Table H.2: New lattice with larger gaps and reduced solenoid stress (low stress variant). In bold, the parameters exceeding the considered design limits.

The rectilinear cooling complex has an alternative lattice in Section D.2.1, with the aim of reducing the coil stresses and enlarge the gap distance between the solenoids and the other integrated cell systems (beam pipe, RF cavity, absorbers), in response to the investigation of Section H.1.1. The recalculated stresses are reported in Table H.2. In lattice operation, only three solenoids showed values exceeding the positive radial stress limit (B8-1, B9-1, B10-1), with B9-1 and B10-1 exceeding the hoop stress limit. This is expected, since these three magnets exhibit also the highest peak field values on coils (over 15 T) in a nested coil configuration. An improvement on the feasibility of the 6D cooling magnet configuration has been made in this alternative layout, with higher radial and axial gaps separating the different cell systems. A coil optimization is needed to further increase the gaps, considering the inputs from the

cooling cell demonstrator study, aiming also to lower the stresses in the last three B-type cells. This variant is not yet considered part of the baseline design due to its lower performance. Hence, further iterations in the design parameters for this lattice version are expected.

H.2 Collider Magnets

Section 6 presents the collider parameters, including the radiation shielding requirements from muon decay. To achieve a compact ring while allowing sufficient shielding, the ARC and Interaction Region (IR) magnets must feature **high magnetic fields and large apertures**.

The main arc magnets are **combined-function magnets** (dipole/quadrupole and dipole/sextupole) designed for magnetic fields up to **16 T** and **160 mm** aperture, though this exceeds current technological limits and requires further optimization. The **IR quadrupoles** are expected to reach magnetic fields up to **20 T** and apertures up to **200 mm**.

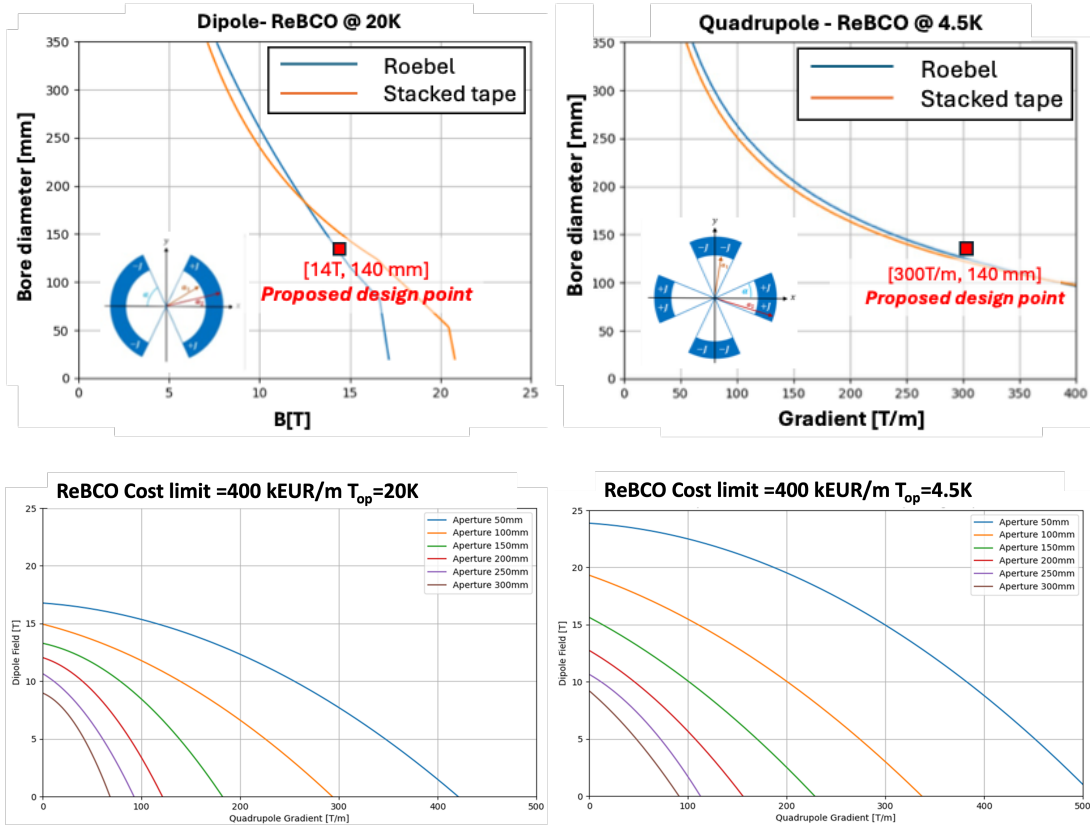


Fig. H.1: Performance upper-limit plots for ReBCO-based magnets. *Top left:* A–B plots for dipoles at 20 K. *Top right:* A–G plots for quadrupoles at 4.5 K. *Bottom:* B–G plots for combined-function magnets at 20 K (left) and 4.5 K (right).

Analytical evaluations based on **sector-coil geometries** were used to generate **performance limit plots** – A–B (aperture vs. field) for dipoles, A–G (aperture vs. gradient) for quadrupoles, and B–G (field vs. gradient) for combined-function magnets—considering **NbTi**, **Nb₃Sn**, and **ReBCO** superconductors.

- **NbTi (1.9 K):** inadequate due to low margins and high energy deposition.
- **Nb₃Sn (4.5 K):** viable up to 14 T, suitable for ~ 3 TeV machines but insufficient for some of the magnet performances required for the 10 TeV.

- **ReBCO**: best-performing option with high fields (10–20 K operation), presently considered as baseline, though R&D is needed to address **cost and quench protection** challenges.

If ReBCO costs are reduced by a factor 3–4, feasible designs could span **14–16 T** with **100–140 mm apertures** at operating temperature in the range 4.5 K - 20 K. For IR quadrupoles, operation at 4.5 K could enable up to **300 T/m gradients** with apertures up to **140 mm**.

A **semi-analytic design tool** has supported fast iteration with beam dynamics, cryogenics, and energy deposition studies. The resulting performance limit plots for **dipoles, quadrupoles, and combined-function magnets** are shown below in Table H.1.

I Appendix: Radiofrequency Cavities

I.1 RF systems for rectilinear cooling

The preliminary RF cavity design for each stage of the rectilinear cooling channel was developed based on the shape presented in [39] following the beam dynamics specification in Table D.7. The other geometrical parameters characterizing the cavity shape are chosen to maximize the shunt impedance ($R/Q \cdot Q_0$) and reduce surface losses (P_{diss}) on the windows and cavity walls. The peak surface electric field (E_{peak}) is also minimized to avoid RF breakdown risk. The RF cavity frequency (f_0), the cavity length (L_{cav}), and the nominal RF gradient along the cavity axis (E_{nom}) for the studied RF cavities are reported in Table D.7. Table I.1 summarizes the relevant RF figures of merit computed for the operating frequencies of the studied cavities. Most of the power is dissipated in the cavity walls.

	Q_0 10^4	t_f μs	DF 10^{-4}	R/Q Ω	P_{diss} MW/cavity	$\frac{P_{\text{diss,Be}}}{P_{\text{diss}}}$ -	$E_{\text{peak,Cu}}$ MV/m	$E_{\text{peak,Be}}$ MV/m
Stage A1	3.06	31.203	1.17	171.73	4.25	0.377	11.72	27.383
Stage A2	3.14	32.087	1.21	149.68	4.34	0.085	23.249	26.511
Stage A3	2.20	11.248	0.43	160.36	2.06	0.201	20.802	31.507
Stage A4	2.22	11.345	0.43	150.21	2.21	0.085	27.873	31.829
Stage B1	3.91	39.954	1.51	183.70	2.678	0.23	12.162	21.25
Stage B2	3.56	36.323	1.37	170.47	2.807	0.164	15.251	21.757
Stage B3	3.15	32.148	1.21	141.27	4.07	0.031	26.175	24.429
Stage B4	3.59	36.71	1.38	154.02	3.92	0.009	27.732	22.823
Stage B5	2.23	11.366	0.43	140.85	1.18	0.026	24.116	22.027
Stage B6	2.22	11.36	0.43	137.40	1.89	0.007	33.288	26.514
Stage B7	2.22	11.354	0.43	136.87	1.97	3.08×10^{-3}	35.25	25.981
Stage B8	2.22	11.347	0.43	137.39	1.79	8.32×10^{-4}	34.67	22.885
Stage B9	2.22	11.344	0.43	138.11	2.14	3.16×10^{-4}	38.528	23.268
Stage B10	2.22	11.342	0.43	139.06	1.51	1.56×10^{-4}	32.522	18.341

Table I.1: RF figures of merit for the RF cavities in the rectilinear cooling channel

The filling time t_f , which is the time required to fill the cavity to the nominal voltage $V_{\text{nom}} = E_{\text{nom}} L_{\text{cav}}$, is given by:

$$t_f \approx \frac{2Q_L}{\omega_0} \ln \left(\frac{2\beta_c}{\beta_c - 1} \right), \quad (\text{I.1})$$

where $Q_L = Q_0/(1 + \beta_c)$, with Q_0 being the intrinsic quality factor, β_c the coupling factor, and ω_0 is

the angular frequency of the cavity's operating mode. The beam duty factor (DF) can be calculated as the ratio between the average power and the peak dissipated power:

$$DF = \frac{P_{ave}}{P_{diss}} = \frac{\int_0^\infty P(t)dt \cdot f_b}{V_{acc}^2/(R/Q \cdot Q_0)}, \quad (I.2)$$

where $P(t)$ is the time-dependent power calculated from the cavity voltage profile and $V_{acc} = TTF \cdot V_{nom}$ the accelerating cavity voltage, with TTF being the Transit-Time factor, given by:

$$TTF = \frac{\int_{z_{min}}^{z_{max}} E_z e^{jkz} dz}{\int_{z_{min}}^{z_{max}} E_z dz}, \quad (I.3)$$

where $k = \omega_0/(\beta c)$ is the wave number with c being the speed of light in a vacuum and β the relativistic velocity factor. The geometric shunt impedance, R/Q , is calculated, considering the TTF as:

$$\left(\frac{R}{Q}\right) = \frac{|V_z(0,0)|^2}{\omega_0 U_0} TTF^2, \quad (I.4)$$

where $U = \omega_0$ is the energy stored in the cavity.

Table I.4 reports the power requirements for each stage of the cooling channel. The peak input RF power is given by:

$$P_g = P_{diss}\beta_c. \quad (I.5)$$

The duty factor of the RF power source (DF_g) is given as the ratio between the average power of the generator and the peak input RF power.

$$DF_g = \frac{P_{ave,g}}{P_g} = \frac{P_g t_f \cdot f_b}{P_g}, \quad (I.6)$$

The total plug power for the RF systems was calculated considering the generator (η_G) and modulator (η_M) efficiencies reported in Table I.2 as:

$$P_{g,ave,tot} = \frac{N_{cav} P_{ave,g}}{\eta_G \eta_M}, \quad (I.7)$$

where N_{cav} is the total number of cavities for each stage.

Parameters	Symbol	Unit	Value
Coupling factor	β_c	-	1.2
Bunch repetition frequency	f_b	Hz	5
Generator efficiency	η_G	-	0.7
Modulator efficiency	η_M	-	0.9

Table I.2: RF parameters for the rectilinear cooling channel

For the RF frequency, cavity length and nominal RF gradient of the rectilinear cooling RF system, please refer to Table D.7. Table I.3 displays in addition the RF cavity window radius, window thickness and the relativistic beta of the muon beam at each stage.

	Window radius mm	Window thickness μm	Relativistic β -
Stage A1	240	120	0.923
Stage A2	160	70	0.894
Stage A3	100	45	0.894
Stage A4	80	40	0.901
Stage B1	210	100	0.886
Stage B2	190	80	0.885
Stage B3	125	50	0.887
Stage B4	95	45	0.886
Stage B5	60	30	0.889
Stage B6	45	20	0.888
Stage B7	38	20	0.887
Stage B8	28	20	0.884
Stage B9	23	10	0.881
Stage B10	20	10	0.884

Table I.3: Beam dynamics specifications for the RF cavities in the rectilinear cooling channel

	P_g MW/cavity	DF_g 10^{-4}	N_{cav} -	$P_{g,tot}$ MW	$P_{g,av}$ kW	$P_{plug,tot}$ kW
Stage A1	5.094	1.560	348	1772.7	277.09	439.83
Stage A2	5.21	1.610	356	1854.9	297.87	472.82
Stage A3	2.468	0.567	405	999.4	56.70	90.00
Stage A4	2.655	0.573	496	1317.1	75.41	119.70
Stage B1	3.214	2.077	132	424.2	88.1	139.843
Stage B2	3.368	2.097	185	623.1	130.682	207.432
Stage B3	4.882	1.611	240	1171.6	188.801	299.684
Stage B4	4.701	1.843	165	775.673	142.945	226.897
Stage B5	1.419	0.573	275	390.1	22.37	35.51
Stage B6	2.262	0.71	220	497.7	35.35	56.11
Stage B7	2.363	0.613	160	378	23.17	36.783
Stage B8	2.143	0.615	284	608.5	37.449	59.443
Stage B9	2.573	0.571	208	535.1	30.556	48.517
Stage B10	1.806	0.572	188	339.8	19.434	30.848

Table I.4: RF power requirements in the rectilinear cooling channel

I.2 RF systems for low-energy acceleration

In the low-energy acceleration, only the design of RLA2 is being considered for the computation of RF parameters. The baseline cavity geometry is chosen to be the LEP2 cavity. A summary of the assumed parameters can be found in Table I.5. For the calculation of the losses in the power generation, the parameters of the ILC-powering system were used (Table I.7). The resulting powering parameters for the RLA2 cavities can be found in table I.6.

Parameter	Symbol	Unit	Value linearizer	Value accelerator
Fundamental mode RF frequency	f_{RF}	MHz	352	1056
Accelerating gradient	G_{acc}	MV/m	15	25
Geometric shunt impedance	R/Q	Ω	247.25	360.72
Active length	l_{active}	m	1.686	0.845
Total length	l_{total}	m	1.851	1.011
Number of cells	-	-	4	6
$E_{\text{peak}}/E_{\text{acc}}$	-	-	2.4	2.4
$B_{\text{peak}}/E_{\text{acc}}$	-	mT/(MV/m)	3.9	3.9
Iris aperture (inner/end cell)	-	mm	286/241	94/80
Cavity quality factor	Q_0	-	$\geq 1 \times 10^{10}$	$\geq 1 \times 10^{10}$
Cell-to-cell coupling	k_{cc}	%	1.51	1.62

Table I.5: Parameters of the LEP2 cavity from [40]

Parameter	Unit	RLA2 acc	RLA2 lin
Synchronous phase	$^\circ$	95	275
Frequency	MHz	352	1056
Number of bunches/species	-	1	
Combined beam current (μ^+ , μ^-)	mA	134	
Total RF voltage	GV	15.2	1.69
Total number of cavities	-	600	80
Total number of cryomodules	-	200	16
Total RF section length	m	1110.6	80.8
External Q-factor	10^6	0.38	0.21
Cavity detuning for beam loading comp.	kHz	0.04	0.21
Beam acceleration time	μs	35.5	
Cavity filling time	μs	344	65
RF pulse length	ms	0.38	0.1
RF duty factor	%	0.19	0.05
Peak cavity power	kW	3425	2965
Average RF power	MW	5.16	0.16

Table I.6: RF parameters for the low-energy acceleration chain. For the synchronous phase, 90° is defined as being on-crest

Parameter	Unit	Value
Max. klystron power	MW	10
Klystron efficiency	%	65
Additional power requirement	%	~ 32
Klystron repetition rate	Hz	5
Klystron frequency	MHz	1300
RF pulse length	ms	1.65
RF duty factor	%	0.83

Table I.7: ILC RF-power parameters [41] in the Distributed Klystron Scheme (DKS). The additional power requirement includes low-level RF overhead as well as distribution losses.

I.3 RF systems for high-energy acceleration

A first approximation of the power requirements for the RCS chain has been performed using the ILC cavities, cryomodules, and powering infrastructures [41] as a baseline, the results of which can be found in Table I.8.

Parameter	Unit	RCS1	RCS2	RCS3	RCS4	All
Synchronous phase	°	148	153	134	118	-
Number of bunches/species	-	1	1	1	1	-
Combined beam current (μ^+ and μ^-)	mA	43.3	39.0	19.6	5.4	-
Total RF voltage	GV	27.6	17.5	15.7	72.7	133.0
Total number of cavities	-	865	548	492	2275	4180
Total number of cryomodules	-	97	61	55	253	466
Total RF section length	m	1079	684	614	2838	5214
External Q-factor	10^6	1.29	1.76	1.84	4.34	-
Cavity detuning for beam loading comp.	kHz	-1.04	-0.90	-0.54	-0.19	-
Max. detuning due to orbit length change	kHz	0	6.63	1.17	1.3	-
Beam acceleration time	ms	0.34	1.1	2.37	6.37	-
Cavity filling time	ms	0.26	0.43	0.45	1.06	-
RF pulse length	ms	0.60	1.53	2.82	7.43	-
RF duty factor	%	0.30	0.76	1.41	3.72	-
Total number of klystrons	-	109	50	41	91	291
Cavities per klystron	-	8	11	12	25	-
Peak cavity power	kW	855	634	598	294	-
Total peak RF power	MW	739	348	294	668	-
Peak RF power to beam	MW	634	310	222	347	-
Average cavity power	kW	2.57	4.85	8.44	10.9	-
Average RF power to cavity during cycle	MW	2.22	2.66	4.15	24.8	33.8
Average wall plug power for RF system	MW	4.22	5.11	7.79	42.2	59.3
HOM power losses per cavity per bunch	kW	23.0	22.2	12.2	3.79	-
Average HOM power per cavity	W	78	244	280	242	-

Table I.8: RF parameters for the RCS chain. The average RF power uses the RF pulse length as a reference within the cycle, assuming a 5 Hz repetition rate. The wall plug power includes an additional power input requirement of $\sim 32\%$ above the cavity input power as well as a klystron efficiency of 65 %, both according to the ILC DKS scheme [41]. The number of cryomodules is based on the assumption of the integration of 9 cavities into one cryomodule. The total RF section length only takes the total length of the cavities, but not the additional space for the cryomodules or interconnects into account. The synchronous phase is defined as 90° being on-crest.

The parameters of the ILC cavity can be found in Table I.9. To calculate the losses, parameters from the ILC DKS powering scheme are used (Table I.7). While these parameters are used for initial beam dynamics and power requirements studies, other frequencies and cavities are under investigation for muon acceleration. The power requirements do not consider cryogenic losses and the impact of the detuning, which is necessary due to the orbit change during the acceleration. The calculated parameters assume a linear ramp of the magnet system. In the accelerator, a harmonic magnet ramp is foreseen, which will require additional cavities.

Table I.9: Parameters of the TESLA cavity from [41] and [42].

Parameter	Symbol	Unit	Value
Fundamental mode RF frequency	f_{RF}	MHz	1300
Accelerating gradient	G_{acc}	MV/m	30
Geometric shunt impedance	R/Q	Ω	518
Geometry factor	G	Ω	271
Active length	l_{active}	m	1.065
Total length	l_{total}	m	1.247
Number of cells	-	-	9
$E_{\text{peak}}/E_{\text{acc}}$	-	-	2.0
$B_{\text{peak}}/E_{\text{acc}}$	-	mT/(MV/m)	4.26
Iris aperture (inner/end cell)	-	mm	70/78
Cavity quality factor	Q_0	-	$\geq 1 \times 10^{10}$
Longitudinal loss factor ($\sigma_z = 1\text{mm}$)	$k_{ }$	V/pC	11.05
Cell-to-cell coupling	k_{cc}	%	1.87

In comparison to last year's parameter report, the synchronous phases were adjusted to minimise the bucket area differences at the transition between the accelerators. To calculate the power and coupling parameters, a detuning of $\Delta\omega_m = \Delta\omega_{\text{opt}}/\sin\Phi_s$ was assumed [43].

1.3.1 RF system for the RCS layout at CERN

The design of the RF system for the RCS at CERN is in Table I.10 and is based on the same assumptions as the RF system for the greenfield study. The assumptions are presented in I.3.

Parameter	Unit	RCS1 SPS	RC2 LHC	RCS3 LHC	All
Synchronous phase	°	140	117	135	-
Number of bunches/species	-	1	1	1	-
Combined beam current (μ^+ and μ^-)	mA	37.5	8.56	7.36	-
Total RF voltage	GV	23.1	48.4	62.7	134.0
Total number of cavities	-	724	1514	1964	4202
Total number of cryomodules	-	81	169	219	469
Total RF section length	m	903	1888	2449	5241
External Q-factor	10^6	1.14	2.58	5.06	-
Cavity detuning for beam loading comp.	kHz	-0.97	-0.31	-0.20	-
Max. detuning due to orbit length change	kHz	0	0	1.95	-
Beam acceleration time	ms	0.45	2.58	4.41	-
Cavity filling time	ms	0.22	0.32	1.24	-
RF pulse length	ms	0.66	2.9	5.65	-
RF duty factor	%	0.33	1.45	2.82	-
Total number of klystrons	-	104	109	58	271
Cavities per klystron	-	7	14	34	-
Peak cavity power	kW	961	511	217	-
Total peak RF power	MW	695	773	427	-
Peak RF power to beam	MW	557	368	326	-
Average cavity power	kW	3.19	7.4	6.15	-
Average RF power to beam during cycle	MW	2.31	11.2	12.1	25.6
Average wall plug power for RF system	MW	4.34	18.0	22.7	45.0
HOM power losses per cavity per bunch	kW	21.7	5.78	5.28	-
Average HOM power per cavity	W	98	150	233	-

Table I.10: RF Parameters for the CERN-based RCS acceleration chain. For the synchronous phase, 90° is defined as being on-crest. All other assumptions are discussed in I.3.

J Appendix: Power Converters

J.1 Resistive magnets equivalent circuitual model

At the present state, we are considering that all the resistive magnet length is occupied by dipole magnets. This approach is conservative for the power converters because dipole magnets have the largest energy density. The remainder of this chapter focuses exclusively on the resistive pulsed dipole magnets. Based on the preliminary magnet designs, two representative configurations are used for sizing the power converters across all accelerator scenarios:

- **Dipole 1:** $L_{\text{mag}} = 95 \mu\text{H/m}$, $R_{\text{mag}} = 0.93 \text{ m}\Omega/\text{m}$
- **Dipole 2:** $L_{\text{mag}} = 95 \mu\text{H/m}$, $R_{\text{mag}} = 0.41 \text{ m}\Omega/\text{m}$

Using these parameters, the corresponding peak voltages and powers required from the power converters are computed. The results are reported in Table J.1 for the CERN scenario and Table J.2 for the Green Field scenario.

Table J.1: Important dimensioning values for the power converters of the RCS, CERN scenario

	RCS SPS	RCS LHC1	RCS LHC2
Length NC magnets [m]	4103	18650	12940
Max B [T]	1.8	1.8	1.8
Gap dimensions [mm]	100 x 30	100 x 30	100 x 30
Acceleration time [ms]	0.45	2.60	4.42
Capacitor Energy [MJ]	43	164	71
Magnetic Energy [MJ]	26	96	56
PC Inductive pk Voltage [MV]	10.0	7.9	6.4
PC Resistive pk Voltage [MV]	0.029	0.133	0.092
Resistive / Inductive ratio [%]	0.29	1.7	1.4
PC pk current[kA]	12	12	12
PC pk Power [GW]	110	87	70
duty cycle [%]	≈ 0.45	≈ 2.8	≈ 4.42
Pulse 2 Pulse repeatability @+/- 2 sigma [ppm]	>=100	>=100	>=100
Control accuracy [ppm]	>=100	>=100	>=100

Table J.2: Important dimensioning values for the power converters of the RCS, Green Field scenario

	RCS1	RCS2	RCS3	RCS4
Length NC magnets [m]	3654	2539	4366	20376
Max B [T]	1.8	1.8	1.8	1.8
Gap dimensions [mm]	100 x 30	100 x 30	100 x 30	100 x 30
Acceleration time [ms]	0.34	1.10	2.37	6.37
Capacitor Energy [MJ]	51	17	25	112
Magnetic Energy [MJ]	31	13	20	88
PC Inductive pk Voltage [MV]	11.8	5.0	4.0	7.0
PC Resistive pk Voltage [MV]	0.026	0.018	0.031	0.146
Resistive / Inductive ratio [%]	0.22	0.36	0.77	2.08
PC pk current[kA]	12	12	12	12
pk Power [GW]	130	55	44	77
duty cycle [%]	≈ 0.34	≈ 1.1	≈ 2.37	≈ 6.37
Pulse to pulse repeatability @+/- 2 sigma [ppm]	>=100	>=100	>=100	>=100
Control accuracy [ppm]	>=100	>=100	>=100	>=100

J.2 Partition of the total power into different sectors

Given the extremely high voltage and power levels required across the full accelerator, it becomes necessary to divide the system into many sub-converters, referred to as Power Electronics cells (PE cells). In addition to the scale of the electrical power, an important challenge lies in achieving accurate current control across all PE cells—particularly in systems where the cells operate independently, as in the LHC sector model. For example, in the full-wave resonant topology, implementing current control would require each PE cell to be equipped with a fast, high-power active filter. This adds substantial complexity and cost, especially when regulation must occur within less than 1 ms.

An alternative approach, inspired by the CERN SPS configuration, is to connect all PE cells in series within a single circuit. This guarantees the same current through each cell, simplifying control to only ensuring repeatability from one pulse to the next.

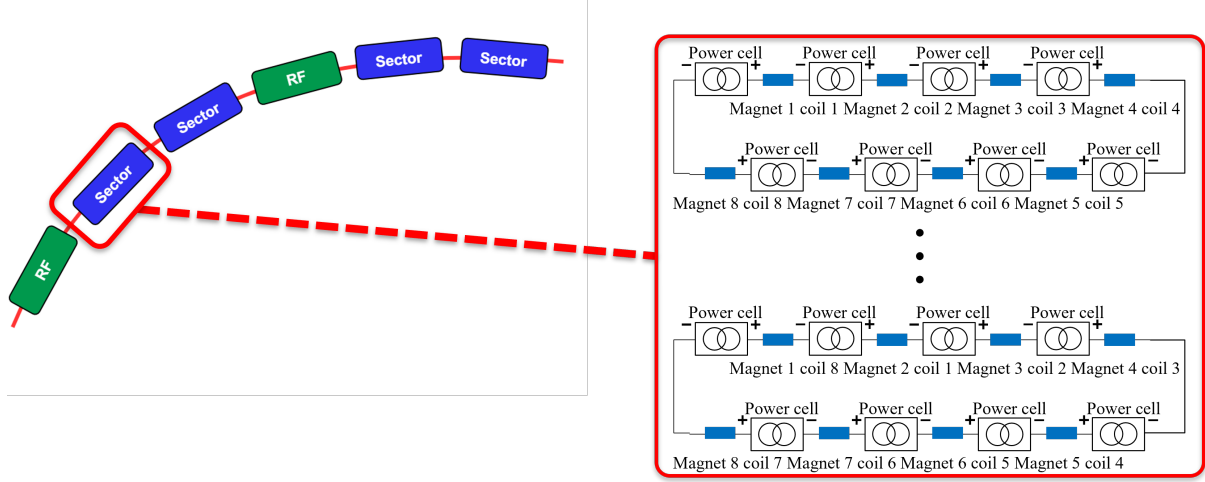


Fig. J.1: subdivision of the total power in sectors (LHC style)

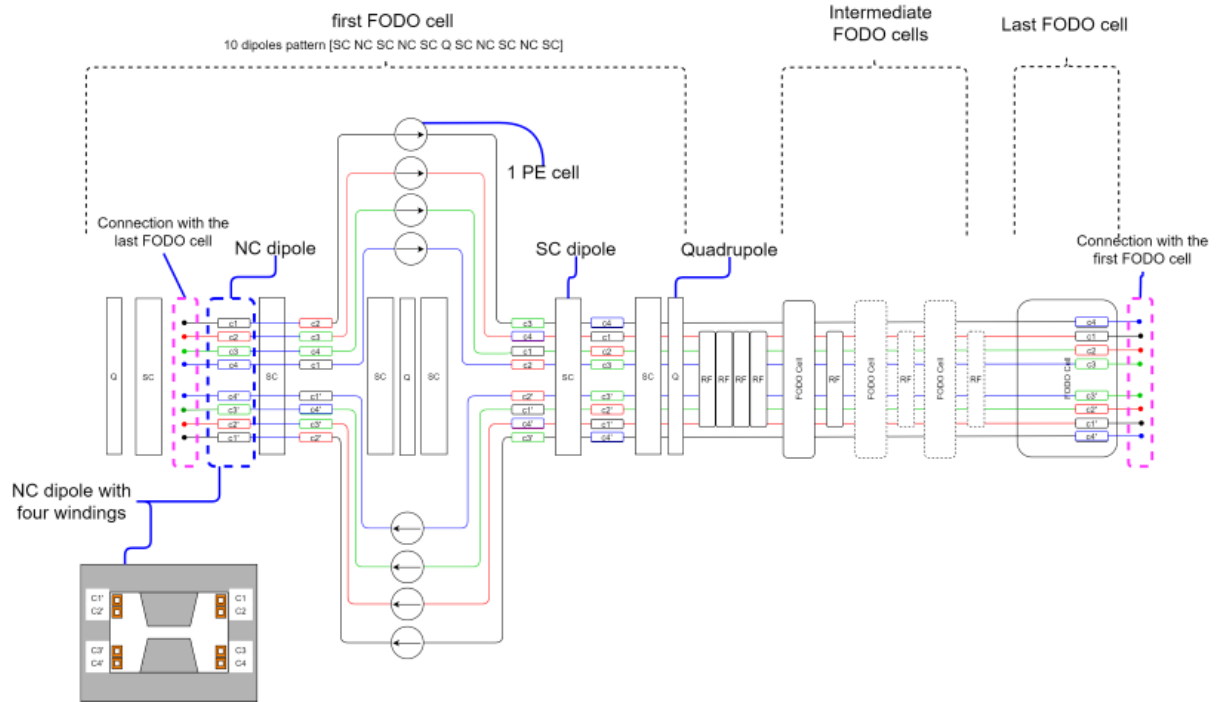
J.3 Power cell topologies

To meet the high power and voltage demands of the RCS, the power converters operate using pulsed resonant circuits. Two main types are considered: the full-wave resonance circuit and the switched resonance circuit. These configurations are illustrated in Figure J.3. In this method, a natural resonance is triggered by connecting one or more pre-charged capacitor bank to the magnets, thus initiating an RLC resonance. This process can be repeated at a frequency of five Hz, aligning with the desired repetition rate. The circuits represented in the figure are identified as "Full wave resonance" (left) and "Switched resonance" (right). Both topologies rely on pre-charging one or more capacitors to an initial voltage, followed by activating a switch to discharge the energy into the load. As the load is almost purely inductive, the capacitors are nearly fully recharged at the end of the pulse. The switch is then opened and remains off until the next pulse cycle begins. The pulse typically lasts a few percent of the total repetition period, which is approximately 200 ms.

The full wave resonance can be composed by either one, two or more parallel branches resonating with the magnets. One switch per branch ignites the resonance starting from pre-loaded capacitors and returning to the initial value (minus the losses of the system) at the end of the oscillation.

Fig. J.4 shows an example of a full wave resonance with two harmonics, the fundamental and the second. Because of the additional harmonics the total installed capacitive and inductive energy, is much higher than the energy required by the magnet at peak flux density. In addition the discharge of the capacitors is bipolar which poses significant overdimensioning constraints to the capacitors.

In the switched resonance circuit, a distinct approach is employed. This method leverages two distinct simple resonances for different segments of the resonating wave, as depicted in Fig. J.5. To initialize the pulse, the preload capacitor (see Fig. J.3, right panel) is engaged until the current attains the target negative value. Subsequently, the current pathway is altered by toggling the switches S1 and S2, bringing the boost capacitors into operation.



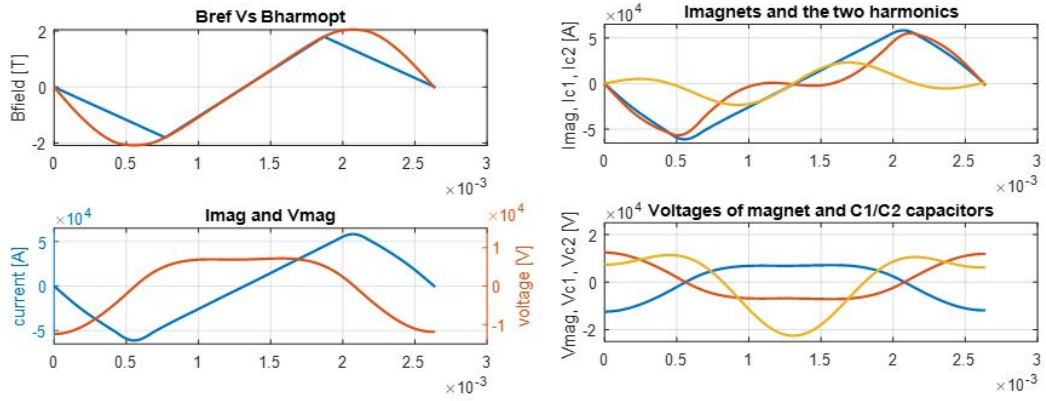


Fig. J.4: full wave resonance example

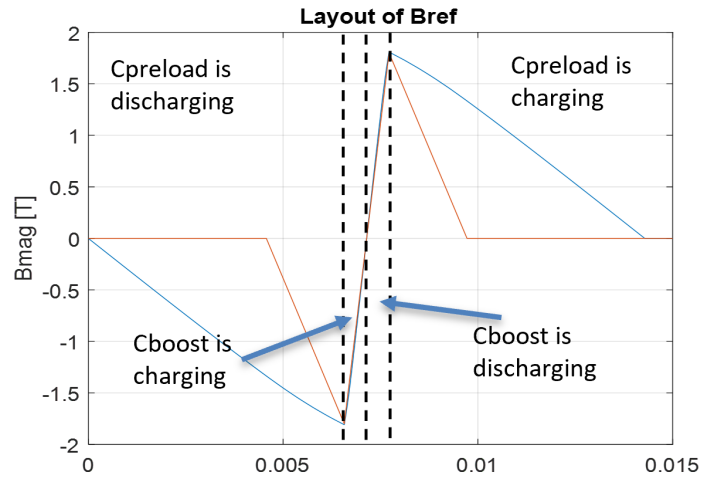


Fig. J.5: Switched resonance principle

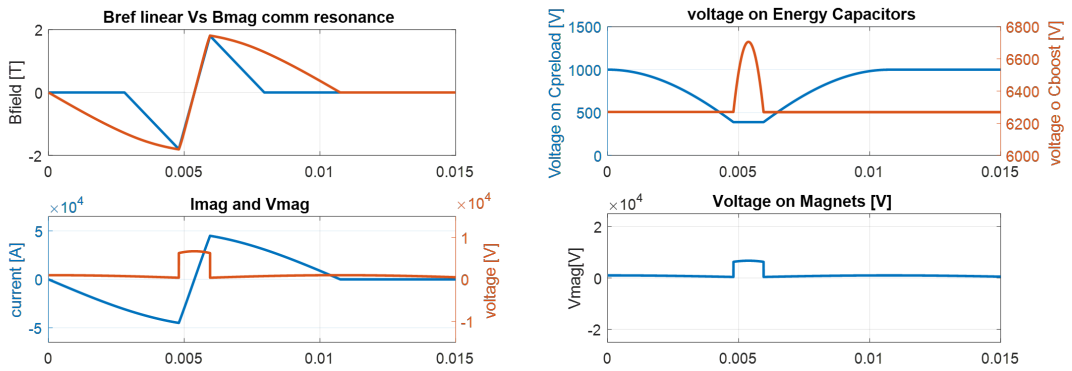


Fig. J.6: Switched resonance example

J.4 The control problem

Tables J.1 and J.2 show some parameters related to the quality of control. In particular they refer to: **Pulse-to-pulse repeatability @ $\pm 2\sigma$:**

This means that on 95% of the pulses, the maximum absolute difference between the current at any time instant of any pulse and the average of them is less than 100 ppm.

Control accuracy:

This means that if we have two separate circuits and we need the currents to be the same in both of them, the control will not be able to make it more accurately than that. In both cases the tables report a target value rather than a limit. We still don't know the statistical parameters of the charger and the jitter of the IGBT+driver; therefore it is difficult to say if we can fit in. Simulations with educated guess values, show, nevertheless, that the reported values would represent a limit with respect to what it is possibly achievable.

K Appendix: Impedance

Transverse HOMs generated by the TESLA cavities would be the main impedance source for the RCS chain. Table K.1 details the shunt impedance, quality factor and resonance frequency of the HOMs considered. Transverse coherent stability simulations were performed to evaluate the impact of the RF cavities and vacuum chambers. To mitigate the instabilities, a transverse damper system can be used to damp the transverse centroid motion of the bunches, and/or chromaticity can be introduced with sextupoles. Parametric scans were performed to find if those are needed and, if necessary, the chromaticity Q' required. The chromaticity was scanned from $Q' = -20$ to $Q' = +20$, and the transverse damper from a 4-turn to a 100-turn damping time, with an additional case without damper.

Tracking simulations were performed using Xsuite [44] and PyHEADTAIL [45]. The bunch motion is simulated through the complete RCS chain. Muon decay is not included in these simulations, therefore the bunch intensity remains constant through the chain, equal to the intensity of 2.7×10^{12} muons per bunch at injection in RCS 1. Results showed that a positive chromaticity of $Q' = +20$ is needed in the accelerators to stabilize the beams and leave enough margin for some initial transverse offset of the bunches, and a 20-turn transverse damper also helps stabilize the beams [46, 47].

K.1 Impedance model for the 10 TeV collider ring

In the 10 TeV collider ring, the main impedance source would be the resistive-wall contribution from the magnets' vacuum chamber. To protect the superconducting magnet coils from muon decay induced heating and radiation damage, a tungsten shield is proposed to be inserted in the magnet cold bore as detailed in Section 12 and described in Ref. [8].

Previous parametric studies performed with Xsuite and PyHEADTAIL showed that a minimum chamber radius of 13 mm, together with a copper coating on the inner diameter are required to ensure coherent transverse beam stability. The current dipole magnet radial build detailed in Table 6.2 foresees a 23.5 mm inner radius, with a 10 μ m copper coating. The vacuum chamber properties used for the impedance model computation are summarized in Table 11.3.

A particularity of the collider ring is its isochronous operation (i.e. with $\eta \approx 0$) [48], obtained with the flexible momentum compaction cells described in Section 6. This is to avoid the large RF voltage that

Frequency f_{res} GHz	$\frac{R_s}{Q}$ [k Ω /m]	Q factor [1×10^4]	Shunt impedance R_s [M Ω /m]
1.659	0.10	31.4	32.61
1.705	1.05	1.35	14.16
1.706	1.21	1.34	16.27
1.728	0.97	0.0413	0.4
1.729	0.45	0.0381	0.17
1.736	1.25	0.0516	0.64
1.737	0.95	0.0574	0.54
1.761	0.35	0.583	2.04
1.762	0.28	0.621	1.72
1.788	0.16	0.867	1.43
1.789	0.18	0.890	1.61
1.798	0.11	1.23	1.29
1.799	0.10	1.21	1.27
1.865	0.79	3.91	30.87
1.865	0.83	4.12	34.07
1.874	1.09	3.88	42.32
1.874	1.07	4.39	47.14
1.88	0.22	4.23	9.38
1.88	0.24	5.15	12.21
2.561	0.13	0.0620	0.08
2.561	0.12	0.0527	0.07
2.577	2.05	0.364	7.46

Table K.1: HOMs from TESLA cavity, complete table, for a single cavity.

	RCS1	RCS2	RCS3	RCS4
Number of cavities	700	380	540	3000

Table K.2: RCS impedance model assumption for number of TESLA cavities

would be needed to bunch beams with very short length and large energy spread. However this freezes the synchrotron motion of the particles within the bunch and can lead to beam breakup instabilities such as those encountered in Linacs [49].

Transverse coherent beam stability simulations were performed with Xsuite and PyHEADTAIL, including the effect of muon beam decay [10]. The beam parameters used for these simulations are summarized in Table K.3. With a chromaticity of $Q' = 0$, the beam becomes unstable over its lifetime in the collider, leading to large transverse emittance growth [10]. A slightly positive chromaticity of $Q' = +2$ is needed to introduce a betatron frequency spread that helps stabilize the beam.

Parameter	Unit	Value
Circumference	m	10 000
Beam energy	TeV	5
Bunch intensity at injection	muons/bunch	1.80×10^{12}
1σ bunch length	mm	1.5
Longitudinal emittance $\epsilon_l = \sigma_z \sigma_E$	MeV m	7.5
Transverse normalized emittance	$\mu\text{m rad}$	25
Momentum compaction factor		0
Total RF voltage	MV	0

Table K.3: 10 TeV collider machine and beam parameters.

L Appendix: Demonstrators

L.1 CTF3 Building background and current use

The TT7 option has been extensively studied in 2024, the results of which are shown in Table L.1. Civil engineering studies reveal this option to be more expensive and complex than initially expected. For this reason we launched a new study to explore the suitability of reusing the CTF3 building to host the demonstrator facility. The reason not to consider it as a first instance was the fact that at the moment there is not an existing extraction system in the CERN PS that could send beam towards CTF3, in contrast to TT7 where the simple installation of a dipole in a transfer line would have provided an option with less impact on operating machines.

The CTF3 building hosted the LIL (Linear Injector of LEP) machine and was later dedicated to the experimental activities around the CLIC study for linear colliders. Although there is no extraction to it, CTF3 has already many characteristics that are needed for the Demonstrator, namely sufficient length that would be sufficient not only for the facility but also for eventual future extensions, a Klystron gallery and all the infrastructure and services necessary to operate such a facility.

Moreover, as former building for the injector of LEP, it has a connection to the PS tunnel and therefore no major civil engineering works will be needed to reconnect it to the PS. Only a well-shielded target area shall have to be created, with therefore the hope that costs and efforts can be mostly concentrated on the components of interest. The beamline parameters of a muon cooling demonstrator at the CTF3 facility are displayed in Table L.2.

Today CTF3 hosts the CLEAR facility, whose continuation is fully compatible with the new facility.

L.2 Proposed demonstrator layout at CTF3:

- Extraction. Protons would be extracted from the PS and transported to CTF3 by reopening and adapting the historic link.
- Floor usage. Depicted in Figure L.1:
 - The lower floor hosts the proton transfer line, target station, pion decay channel, magnetic chicane, beam-preparation system, matching section and the cooling-cell gallery.
 - The upper floor (gallery) hosts klystrons, with waveguide penetrations to the cooling cell gallery—reusing existing infrastructure instead of building a new surface hall. Details of the CTF3 klystrons are in Table L.4.

Area	Parameter Name	Value	Unit
Proton Beam	Beam Energy	14	GeV
	Protons/pulse	1×10^{13}	Protons
	Pulse rep. rate	0.064	Hz (15.6s)
	Avg beam power	1.5	kW
	Avg beam power (target assumption)	5	kW
	RMS pulse length	7.65	ns
Proton transfer line	Number of dipoles	4 (H), 4 (V)	-
	Number of quadrupoles	7	-
	Number of correctors	5	-
Target	Proton Beam Energy	14	GeV
	Proton Beam RMS size	2	mm
	Target Material	Graphite	-
	Target Length	90	cm
	Target Radius	0.6	cm
	Horn Current	220	kA
	Ltot	200	cm
	Target Pion Momentum Range	210 – 330	MeV/c
	Target Pion ϵ_T acceptance	2	mm rad
	Simulated Pion Yield per POT	7.90×10^{-4}	-
	Remote handling	YES	-
Decay channel & magnetic chicane	Decay Channel Lattice	3 quad triplets	-
	Decay Channel Length	9.5	m
	Pion Momentum (Nominal)	270	MeV/c
	Pion Momentum Acceptance	$\pm 50\%$	%
	Target Muon Momentum Range	190 – 210	MeV/c
	Target Muon ϵ_T acceptance	2	mm-rad
	Chicane Type	3-bend	-
	Dispersion at Chicane En	-0.4	m
	β at BPS Injection	3	m
Beam preparation system	Number of RF cavities	16	-
	RF peak gradient	15	MV/m
	RF phase	0	degrees
	RF frequency	704	MHz
	Dipole field	0.67	T
	Dipole length	1.04	m

Table L.1: TT7 Beamline parameters

- Target area. Located around the former combiner-ring centre; the layout permits the construction of a target area with limited works and independent access relative to CLEAR.

L.2.1 Work underway - Scope of current studies

- Beamline & optics. End-to-end lattice from PS extraction to the target; decay channel, momentum-selection chicane and BPS matched to the cooling section (baseline “B5-like” cell).
- Integration & access. 3D integration of the tunnel straight and gallery; installation/maintenance scenarios; co-existence planning with CLEAR.

Area	Parameter Name	Value	Unit
Proton Beam	Beam Energy	14	GeV
	Protons/pulse	1×10^{13}	Protons
	Pulse rep. rate	0.064	Hz (15.6s)
	Avg beam power	1.5	kW
	Avg beam power (target assumption)	5	kW
	RMS pulse length	7.65	ns
Extraction	Extraction dipole (New, after PS septa)	1	-
	Bumper magnets	4	-
	Septa	2	-
	KFA71 Kicker	1	-
Proton transfer line	Number of dipoles	1	-
	Number of quadrupoles	5	-
	Number of correctors	TBD	-
Target	Proton Beam Energy	14	GeV
	Proton Beam RMS size	2	mm
	Target Material	Graphite	-
	Target Length	90	cm
	Target Radius	0.6	cm
	Horn Current	220	kA
	Ltot	200	cm
	Target Pion Momentum Range	210 – 330	MeV/c
	Target Pion ϵ_T acceptance	2	mm rad
	Simulated Pion Yield per POT	7.90×10^{-4}	-
	Remote handling	YES	-
Decay channel & magnetic chicane	Decay Channel Lattice	3 quad triplets	-
	Decay Channel Length	9.5	m
	Pion Momentum (Nominal)	270	MeV/c
	Pion Momentum Acceptance	$\pm 50\%$	%
	Target Muon Momentum Range	190 – 210	MeV/c
	Target Muon ϵ_T acceptance	2	mm·rad
	Chicane Type	2-bend	-
	Dispersion at Chicane End	0	m
	β at BPS Injection	<1	m
Beam preparation system	Number of RF cavities	16	
	RF peak gradient	15	MV/m
	RF phase	0	degrees
	RF frequency	704	MHz
	Dipole field	0.67	T
	Dipole length	1.04	m
Matching section	TBD	-	-

Table L.2: CTF3 Beamline parameters

- Assembly/disassembly. Removal of remaining CLIC demonstrator hardware where needed; definition of transport paths and lifting means.
- Civil engineering. Reopening and adapting the PS link; localized works for the target area, access enlargements and main patio improvement; no enlargement of the main gallery and no new surface building are foreseen.

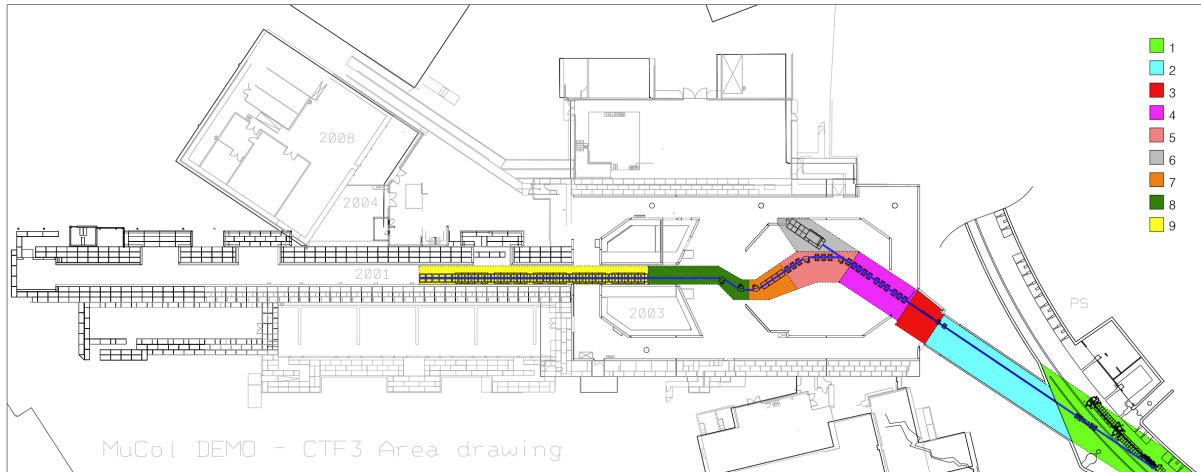


Fig. L.1: CTF3 Area Definition: Proton extraction (light green), Proton Transfer line (cyan), Target area (red), pion decay channel (magenta), magnetic chicane (peach), proton and pion dump (grey), beam preparation system (orange), matching section (dark green), cooling cell channel (yellow).

Area	Parameter Name	Value	Unit
Proton transfer line	Gallery length	22.3	m
	Gallery width	5.3	m
	Gallery height	3	m
Target area	Gallery length	5	m
	Gallery width	11	m
	Gallery height	3	m
Pion Decay channel	Gallery length	9	m
	Gallery width	3	m
	Gallery height	5	m
Magnetic chicane	Gallery length	11	m
	Gallery width	3	m
Beam Preparation system	Gallery length	5	m
	Gallery width	3	m
Matching section	Section length	14	m
Cooling channel	Channel length	36	m
	Channel width	3	m
	Channel height	2.5	m
	Number of cooling cells	30	-
Klystron gallery	Gallery length	41.5	m
	Gallery width	6.5	m
	Gallery height	5	m
	Number of klystrons	15	-

Table L.3: CTF3 Site-specific parameters

- Services. Reuse of surrounding power, cooling-water and ventilation with targeted upgrades; RF plant staged in the gallery.
- Radiation protection. RP modelling of the target/shielding and an operational zoning scheme that does not interfere with CLEAR.

Area	Parameter Name	Value	Unit
Klystron	RF Frequency	704.4	MHz
	Modulator	Scandinova K200	
	Klystron Voltage	125	kV
	Klystron Current	242	A
	Input power	1320	W
	klystron Efficiency	0.75	
	Modulator output power	30.25	MW
	Klystron Output Power	22.69	MW
	RF system rep. rate	5	Hz
	RF pulse length	15	us
	High voltage pulse length	17	us
	RF power average	1701.56	W
	Modulator efficiency	0.9	
	modulator power consumption	2856.94	W
	klystron solenoid power consumption	5000	W
	Total average power consumption	7856.94	W

Table L.4: CTF3 Klystron parameters**L.2.2 How CTF3 compares to TT7**

- What TT7 would need: To host the same demonstrator, TT7 would require tunnel enlargement ($\approx +3$ m width and $+1$ – 1.4 m height over tens of meters) and a new surface building (klystrons and services), with access road modifications.
- What CTF3 avoids: CTF3 already provides the straight tunnel and the klystron gallery; only local, low impact works (PS link, access improvements, patio/penetrations, target area) are foreseen. Installation can be scheduled outside the accelerator access chain, with no apparent interference with CLEAR. Table L.3 displays the general CTF3 area dimensions.

L.3 Net assessment

CTF3 is simpler and more cost-efficient in every major aspect except one: the new PS extraction/transfer to CTF3, which is the principal project challenge and integration work.

M Appendix: CERN Civil Engineering

The Collider Complex is displayed in Figure M.1, presented below. An injector complex has been designed and implemented, initiating at LINAC 4 and ultimately, injecting into a new 10 km Collider Ring from the LHC. The LINAC 4, SPL and ARCR (Accumulator Ring Compressor Ring) are aiming to be equivalent to the Proton Driver as described in Section 2. The entirety of the complex's surface works would be constructed on CERN land across both the Meyrin and Prévessin sites, minimising territorial and environmental impacts.

Structure	Length (m)	Cross Section
<i>LINAC 4</i>		
SPL		
SPL to SPS Transfer	650	∅4m
SPS sector		
Transfers to Préveessin	930	∅4m & Single Width Tunnel
ARCR	628	∅200m Ring, Double Width Tunnel
Target	50	50m x 30m
Cooling	1000	Double Width Tunnel w/ Surface Structure
Cooling to SC LINAC Transfer	100	Single Width Tunnel
SC LINAC	200	Double Width Tunnel w/ Surface Structure
SC LINAC to RLA 1 Transfer	110	Single Width Tunnel
Racetrack (RLA 1)	700	Single Width Tunnel w/ Surface Structure
RLA 1 to RLA 2 Transfer	600	Single Width Tunnel
Racetrack (RLA 2)	2300	Single Width Tunnel w/ Surface Structure
RLA 2 to SPS Transfer Lines (2: μ^+ , μ^-)	1010	∅4m
<i>SPS</i>		
SPS to LHC Transfer Lines (T112)	536	∅3.5m
SPS to LHC Transfer Lines (T118)	258	∅3.5m
<i>LHC</i>		
LHC to Collider Ring Transfer	4012	∅4m
MUON Collider Ring	10000	∅5.5m

Table M.1: Muon Collider Sequence at CERN. (*Italics* shows existing tunnels). "Single Width" refers to a (5m x 4m) tunnel, whereas "Double width" refers to a (8m x 4m) tunnel.

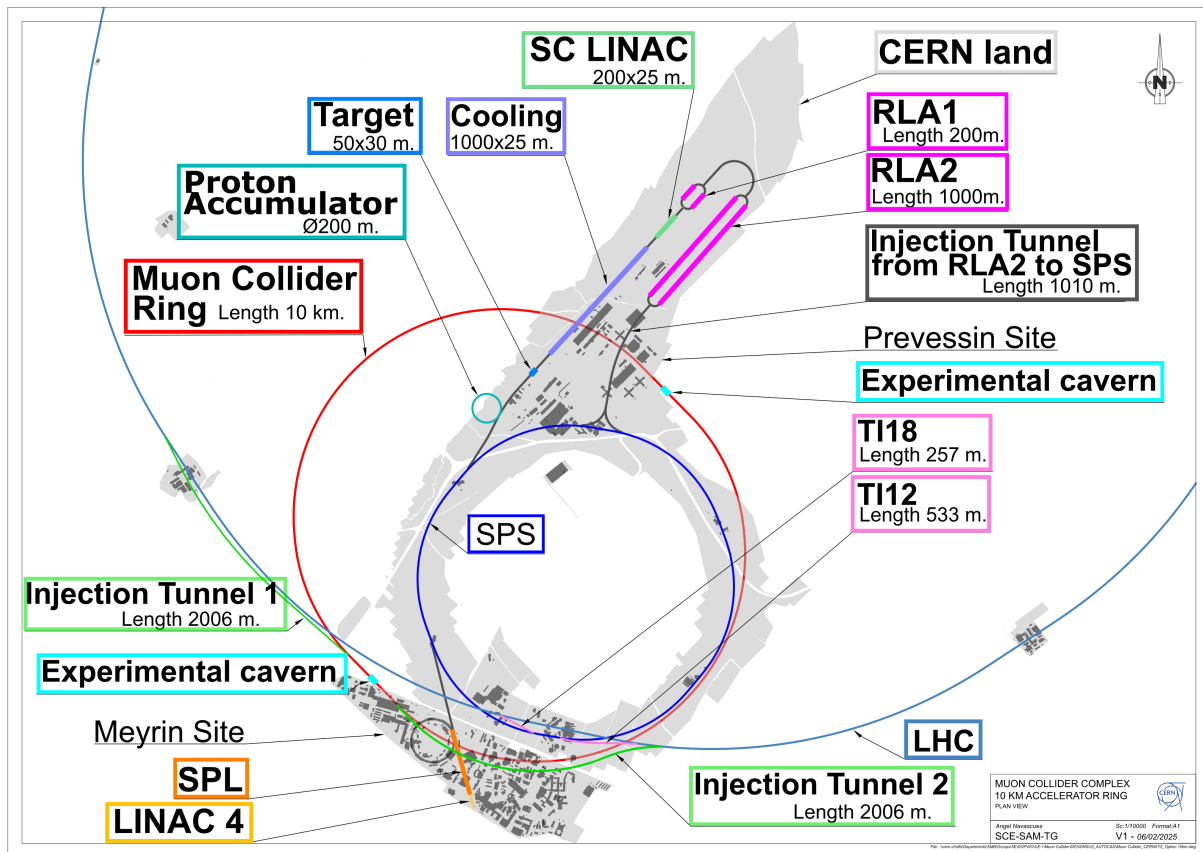


Fig. M.1: Muon Collider Complex.

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