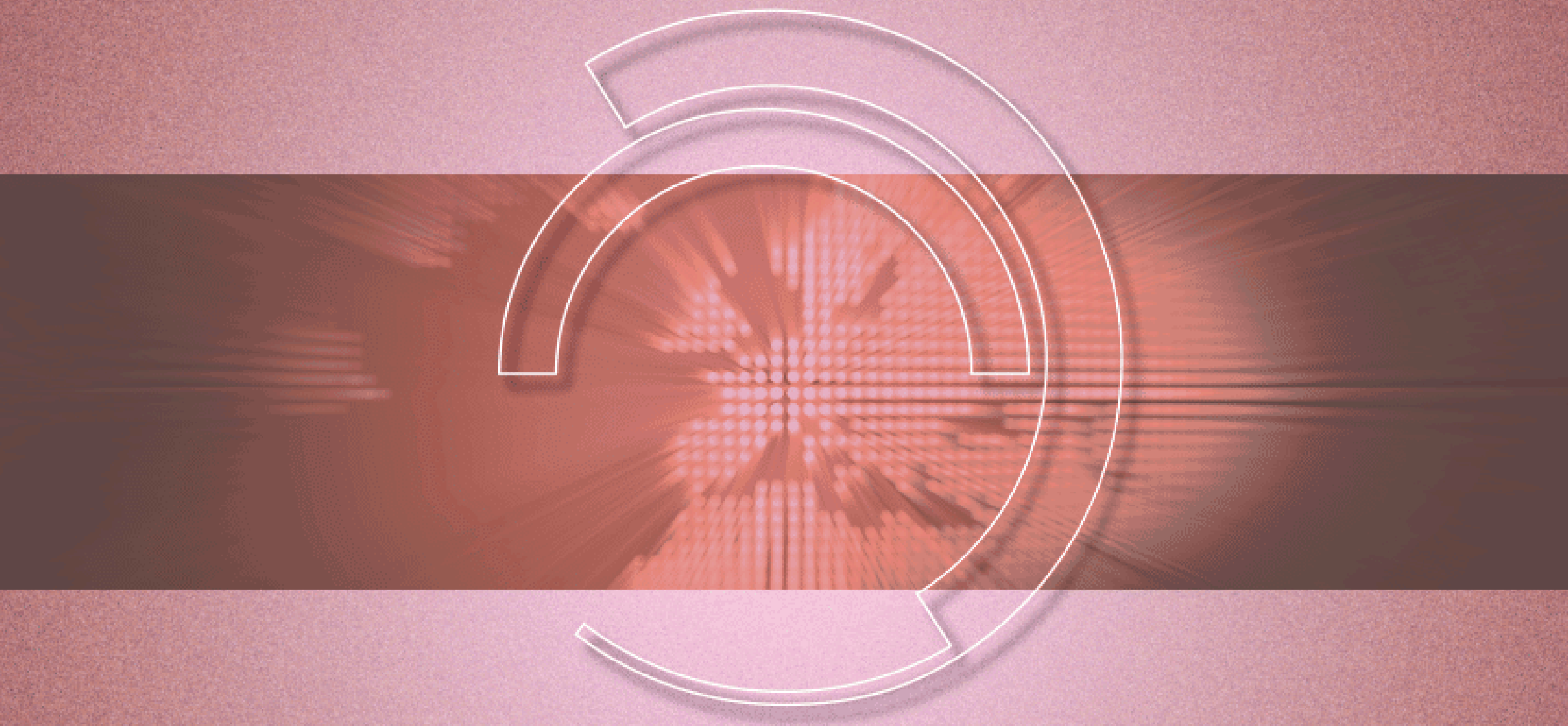
March 2025

The Muon Collider



EUROPEAN STRATEGY FOR PARTICLE PHYSICS

European Strategy Update

International MUON Collider Collaboration

International
MUON Collider
Collaboration

The Muon Collider

Input for the European Strategy for Particle Physics

CERN

ESPPU Muon Collider: Volume 1

Where we are now

immediate

Abstract

The present version is from October 10, 2024.

Keywords

Collider, muon, accelerator physics, technology

Contents

NOTES TO CONTRIBUTORS. PLEASE READ BEFORE EDITING

Deadlines:

- 31st October 2024 - Midnight EST:
  - Key messages for each part complete, even in bullet points.
  - Ready for editing team to start to look at what needs to be modified and changed.
  - Establishing R&D plan and cost. Establish deliverables.
- 20th December 2024 - Midnight EST:
  - Content complete to submit to Advisory Board.
- 31st January 2024 - Midnight EST:
  - Final draft complete to begin copy editing.

Each file has a *compile.tex* file. Compiling this file will show only your chapter. This prevents long wait times for compiling the whole document. For the same reason, please only upload figures which are a reasonable filesize (e.g. kB rather than MB). Otherwise large figures will be compressed.

Adding extra packages? Please define it in *packages.tex*, not in *main.tex*.

Sections are to be labelled \label{1:secname:sec}, where the number indicates Part 0, 1 or 2, and *secname* = 'intro', 'front', 'highacc' etc. Subsections are to be labelled as \label{1:secname:sec:subsecname}. Figures as \label{1:secname:fig:figname}. Tables as \label{1:secname:tab:tabname}.

If you are including parameter tables, please also update the parameter spreadsheet.
Please use siunitx package as much as possible when defining units, for consistency. E.g. $10\,\mathrm{TeV}$, $\mathrm{T/m^2}$, 2.99×10^8

The journal has requested for one bibliography for the whole report. Please include in BibTeX style in *bib/bibliography.bib*.

(Style preference) Please write one sentence per LaTeX line, for readability.

Any further comments or questions on style or formatting, please contact *taylor.r@cern.ch*.

Part I

Executive Summaries

Introduction and Overview

D. SCHULTE, STEINAR, N. PASTRONE, S. JINDARIANI, K. BLACK, M. PALMER

The Muon Collider is a unique high energy collider concept which will produce, cool, accelerate and collide two muon beams of opposite charge.
The muon is fundamental - unlike the proton - and it has a high mass and low synchrotron radiation production - unlike the electron. For these two reasons, the muon collider is considered by many to be The Dream Machine of high energy physics, having equal capacity for high-energy discovery like hadron colliders, and for precision measurements like electron accelerators.
The muon collider community is growing momentum, with substantial international interest and enthusiasm, with many calling for the scientific community to "*shoot for the muon*" and aim high. Even despite its namesake, the muon collider does not have to remain a dream machine. This report contains the proposals and steps necessary to make the muon collider a reality, even within our lifetime.

The report is split into two sections:
Part 1: Evaluation Report is the most up to date status of the current design of the muon collider. These studies are the culmination of years of work, between the MAP study and the more recent IMCC and MuCol studies. From these studies, we have established what is available with current technology, and what requires further developments.
Chapter 2: R&D and Implementation describes the Research & Development roadmap that is needed to bring the muon collider into reality. The muon collider relies on a wide range of advanced inter-dependent technologies, therefore the R&D roadmap suggests a series of test facilities and technology demonstrators which benefit progress in all fields of accelerator technology. In addition, two site-specific implementations are considered, at CERN and at Fermilab.

Chapter 1

Motivation

A. NAME, A. NAME

1.1 Muon Collider Performance

1.1.1 Situational Analysis

[A commentary on the current status of future accelerators and their respective prospects]

The Muon Collider has two key performance indicators which determine the success of the intended physics programme.

1.2 Developing the muon collider study

[Explicitly stating the desired outcome of this report.]

1.2.1 Towards the R&D plan

[Current R&D funding is less than minimum expressed in last year's ESPPU. Strongly recommend ramping up to an aggressive R&D plan to at least match the Aspirational roadmap of last ESPPU. What is needed for us to secure performance.]

1.2.2 Towards a CDR

[The feasibility steps that would need to be taken to greenlight a CDR. The proposal for an intermediate decision step in 2027 after MuCol to support the CDR process.]

1.2.3 Towards a demonstrator

[The proposal for a minimal, local CERN demonstrator in the TT7 transfer line, and the timescale to have this ready before the next ESPPU.]

1.3 Timeline and staging

1.4 Site considerations

1.5 Synergies and outreach

1.6 Sustainability & environmental considerations

Part II

Evaluation Report

Chapter 2

Physics

A. WULZER, F. MALTONI, P. MEADE, N. CRAIG, A. DE GOUVEA

Chapter 3

Interface

Not specific to the detector type

3.1 Physics and detector needs

P. MEADE, S. PAGAN-GRISO, F. MELONI, N. PASTRONE

3.2 MDI

A. LECHNER

Chapter 4

Detector concepts

4.1 Overview

D. LUCCHESI, F. MELONI, S. PAGAN-GRISO, S. JINDARIANI

4.2 MUSIC

D. LUCCHESI, L. SESTINI, M. CASARSA, D. ZULIANI

4.3 MAIA

K. DIPETRILLO, T. HOLMES

4.4 Performance

D. LUCCHESI, L. SESTINI, M. CASARSA, D. ZULIANI, K. DIPETRILLO, T. HOLMES

4.5 Technologies

T. HEIM, A. APRESYAN, L. LONGO, N. BARTOSIK

4.6 Software & Computing

K. PEDRO, W. HOPKINS, K. KRIZKA, T. MADLENER

Chapter 5

Accelerator complex concepts

5.1 Proton driver

N. MILAS, S. JOHANNESSON

5.2 Muon production & cooling

CHRIS ROGERS

5.3 Acceleration

A. CHANCE, H. DAMERAU, S. BERG

5.4 Collider

C. CARLI

5.4.1 Collective Effects and Integration

ELIAS METRAL

Chapter 6

Accelerator Technologies

6.1 Magnets

L. BOTTURA, B. AUCHMANN, B. BORDINI, M. STATERA, L. COOLEY, S. GOURLAY, S. PRESTEMON

6.2 Power converters

F. BOATTINI

6.3 Radiofrequency

D. GIOVE, A. GRUDIEV, L. THIELE, C. BARBAGALLO

6.3.1 RF system for muon cooling

The RF system for the muon cooling complex consists of approximately 8000 RF cavities operating in the frequency range starting from a few hundred of MHz. The majority of the cavities operate at 352 and 704 MHz in the initial and 6D-cooling channels. The main peculiarity of the RF system is that the RF cavities are interleaved with strong solenoidal magnetic fields, which enhance the cavity breakdown rate. It has been proven to affect the high gradient operation of the RF cavities necessary to re-accelerate muons as fast as possible due to their short life time. This also limits the choice of the RF cavities to normal conducting ones since SRF cavities cannot operate in magnetic field. In order to reach high gradient on the order of a few tens of MV/m in normal conducting cavities, high peak RF power on the order of few MWs per one single cell cavity is needed. This results in very high peak power requirements of a few tens of GW. On the other hand, the single (or few) bunch operation mode results in relatively short pulse lengths of ≈ 10 µs and relatively low duty factor of $\approx 10^{-4}$.

On the design side, based on the input from the muon cooling beam dynamics design, a consistent set of parameters for all of the RF cavities and their associated RF systems will be elaborated creating the backbone of the conceptual design of the RF system for the muon cooling complex. The impact of the beam loading on the muon energy spread will have to be investigated and appropriate mitigation measures to be proposed.

The conceptual design of all of the cavities for the whole moun cooling complex including front end, rectilinear initial and 6D-cooling, bunch merge and final cooling will not be covered due to the large number of different cavities. Design and construction of prototype cavities at nominal RF frequency as well as testing at high gradients in strong magnetic fields is required as next step.

6.3.2 RF system for acceleration

After the cooling channel, a linear accelerator and two Recirculating Linear Accelerators (RLAs) provide an initial acceleration up to 63 GeV. The linacs operate at the RF frequency of 352 MHz and an accelerating gradient of 15 MV/m. Additionally to the accelerating cavities, linearizing cavities at a frequency of 1056 MHz and a gradient of 25 MV/m will be used. Downstream from the RLAs, four Rapid Cycling Synchrotrons (RCSs) will gradually increase the energy of the two muon bunches within a few tens of turns each up to the collision energy of 5 TeV. During the transition from the pre-accelerator and the first RLA, the bunches are split and continue as counter-rotating bunches. The design choices for the RF system will be guided by the requirements resulting from the beam dynamics simulations and the short muon lifetime. As a result, a high RF voltage per turn is required, supplied by hundreds of superconducting 1.3 GHz cavities per RCS, which operate at an accelerating gradient of 30 MV/m. A more detailed description of the acceleration chain can be found in Section **??**.

All accelerators following the first RCS will be implemented as hybrid RCSs with both normal- and superconducting magnets. Due to the nature of this hybrid magnet design, the orbit length and, thus, the revolution period changes during the acceleration, leading to the necessity of fast frequency tuning capabilities for the cavities.

The large bunch charge of up to 2.7×10^{12} muons per bunch in the RCS chain will lead to significant transient beam loading and HOM-induced power within the cavities. While the instantaneous requirements for cavity powering and HOM power extraction are high, the machine's duty cycle is low. The cavities will, therefore, be operated in a pulsed mode. The requirements for the cavity powering are further increased in the RLAs. The number of passes is ≈ 5, while the beam current is higher than in the first RCS due to the higher bunch charge and lower travel time between cavity passages.

The cavities in the RCS chain will need to be distributed around the ring in several stations to mitigate the influence of the high synchrotron tune. The impact of the beam loading will, therefore, not be consistent in all cavities due to the differing time between the passages of the counter-rotating μ^+ and μ^- bunches. The same challenge applies to the extraction of the HOM power and cavity powering. In the RLAs, the HOM power and cavity powering need to be investigated in detail, as the bunches are planned to pass in buckets directly after each other, which might significantly impact HOM power extraction requirements. The cavity shape design for the RCS chain has to carefully balance the cavity HOMs performance against the fundamental mode performance, which might lead to different designs for each ring due to the different beam currents and bunch lengths. In the cavity design for the low-energy acceleration, one also has to take the particle speed into account, as some of the accelerators operate in an energy regime where the particles are not ultra-relativistic.

A first approximation of the power requirements for the RCS chain has been performed using the ILC cavities, cryomodules, and powering infrastructures [**ch12:ILC-tdr**] as a baseline. The results of which can be found in Table 6.3.1. While the ILC features the same repetition rate (5 Hz) as the muon collider, the beam current and bunch structure differ significantly. The requirements do not consider HOM power contributions, cryogenic loss, impact of orbit change detuning, and counter-rotating beams. To reduce the impact the transient beam loading, a stronger cavity detuning according to [1]. The cavity voltage evolution during the acceleration was simulated with an equivalent circuit approach.

Within the work package, optimised cavity geometries for the specific cases of the muon collider RCSs and the low-energy acceleration complex are planned to be designed. Due to the different beam-

Table 6.3.1: RF parameters for the RCS chain. The average and peak RF power includes losses from the cavity to the klystron, while the wall plug power also includes the klystron efficiency.

	Unit	**RCS1**	**RCS2**	**RCS3**	**RCS4**	**All**
Synchronous phase	°	135	135	135	135	-
Number of bunches/species	-	1	1	1	1	-
Combined beam current (μ^+ and μ^-)	mA	43.3	39	19.8	5.49	-
Total RF voltage	GV	20.9	11.2	16.1	90	138.2
Total number of cavities	-	683	366	524	2933	4506
Total number of cryomodules	-	76	41	59	326	502
Total RF section length	m	962	519	746	4125	6351
Combined peak beam power (μ^+ and μ^-)	MW	640	310	225	350	-
External Q-factor	10^6	0.696	0.775	1.533	5.522	-
Cavity detuning for beam loading comp.	kHz	-1.32	-1.186	-0.6	-0.166	-
Max. detuning due to orbit length change	kHz	0	2	0.33	0.2	-
Beam acceleration time	ms	0.34	1.1	2.37	6.37	-
Cavity filling time	ms	0.171	0.19	0.375	1.352	-
RF pulse length	ms	0.51	1.29	2.73	7.77	-
RF duty factor	%	0.19	0.57	1.22	3.36	-
Peak cavity power	kW	1128	1017	516	144	-
Total peak RF power	MW	1020	496	365	561	-
Total number of klystrons	-	114	53	38	57	262
Cavities per klystron	-	6	7	14	52	-
Average RF power	MW	1.919	2.84	4.43	18.92	28.1
Average wall plug power for RF System	MW	2.95	4.38	6.811	29.1	43.25
HOM power losses per cavity per bunch	kW	25.85	26.16	16.24	5.75	-
Average HOM power per cavity	W	366	384	287	86	-

and machine parameters in the low- and high-energy acceleration, the impact of this optimisation will be significant. The target parameters, such as the fundamental mode frequency or HOM stability requirements, will be discussed with the other working groups involved. For the final choice of the frequency, the power requirements of the acceleration and cryomodules might play a significant role.

During the acceleration, muons will constantly decay, resulting in many seed particles for multipacting, which might lead to breakdowns. The magnitude of this effect needs to be studied in detail and be included in the shape optimisation.

For the chosen cavity geometry, the development of an HOM damping scheme as well as HOM coupler and FPCs (Fundamental Power Couplers) design will be conducted according to the requirements of the collective effects and beam dynamic studies. Depending on the powering and beam dynamics requirements, it might be necessary to adjust the number of cells per cavity to stay within the power limits of the couplers. In addition to the design of the cavities, an uncertainty quantification is planned to be conducted in order to investigate the impact of fabrication imperfections on the performance of the cavity. The results of this analysis will serve as a requirement for the fabrication precision in the cavities.

The power consumption of the system will be determined for the different frequencies under consideration.

The work package will focus on the design of the cavities and couplers for both the high- and low-energy acceleration. The integration of the cavities into cryomodules is not part of the work package. Possible improvements to the fabrication procedure could enhance the accelerating gradient for the accelerating cavities and should be examined, as these could significantly reduce the number of required cavities.

6.4 Target

R. FRANQUEIRA XIMENES, A. LECHNER

6.5 Radiation shielding

R. FRANQUEIRA XIMENES, A. LECHNER

6.6 Muon cooling cell

L. ROSSI, R. LOSITO

6.7 Cryogenics

P. BORGES DE SUS, R. VAN WEELDEREN

6.8 Vacuum

J. FERREIRA SOMOZA

6.9 Instrumentation

T. LEFEVRE

6.10 Radiation protection

C. AHDIDA, J. MIKOLAJ MANCZA

6.11 Movers

A. KOHLMAINEN, C. ACCETTURA

6.12 Infrastructure

R. LOSITO

6.13 Safety

S. MARSH

Part III

R&D Proposal and Implementation

Chapter 7

R&D Objectives

7.1 Overview

7.2 Focus 2025-2035

7.3 Timeline

7.4 Plan & Cost

Chapter 8

Physics R&D

A. WULZER, F. MALTONI, P. MEADE, NATHANIEL CRAIG, ANDRE DE GOUVEA

Chapter 9

Detector R&D

N. PASTRONE, F. MELONI, S. PAGAN-GRISO, S. JINDARIANI

9.1 Detector concept and performance

K. DIPETRILLO, T. HOLMES, L. SESTINI, M. CASARSA, D. ZULIANI

9.2 Detector technologies

T. HEIM, A. APRESYAN, I. VAI, I. SARRA, S. RICCIARDI

9.3 Software & computing for detectors

K. PEDRO, W. HOPKINS, K. KRIZKA, T. MADLENER

Chapter 10

Magnets R&D

S. GOURLAY, S. ZIOBIN, S. PRESTEMON, L. BOTTURA, B. AUCHMANN, B. BORDINI, M. STATERA

Chapter 11

Accelerator R&D

R. LOSITO, C. CARLI

11.1 Accelerator design

C. CARLI, S. BERG, P. SNOPOK, D. NEUFFER, N. MILAS, S. JOHANNESSON, C. ROGERS, A. CHANCE, H. DAMERAU, E. METRAL, V. MOROZOV

11.1.1 Proton complex

11.1.2 Muon cooling systems

11.1.3 High-energy complex

11.1.4 Collider ring

11.1.5 Collective effects

11.2 Machine-detector interface

A. LECHNER

11.3 Neutrino flux mitigation system

11.4 RF systems

D. GIOVE, A. GRUDIEV, E. NANNI, S. BELOMESTNYKH, T. LUO, G. BURT, U. VAN RIENEN, J. PLOUIN

11.4.1 Muon cooling RF

11.4.2 High energy complex RF

11.4.3 RF test stand and test cavities

11.5 Target system

R.F. XIMENES, A. LECHNER, K. YONEHERA

11.6 Instrumentation

T. LEFEVRE

11.7 Radiation shielding

A. LECHNER, R. F. XIMENES, J. FERREIRA SAMOZA, P. BORGES DE SOUSA

11.8 Cryogenics

P. BORGES DE SOUSA, R. VAN WEELDEREN

11.9 Vacuum

J. FERREIRA SAMOZA

11.10 Radiation protection

C. AHDIDA, J. MIKOLAJ MANCZA

11.11 Infrastructure

R. LOSITO

11.12 General safety

S. MARSH

11.13 Other technologies

R. LOSITO

11.14 Software for the accelerator

Chapter 12

Muon cooling technology development and demonstration

C. ROGERS, R. LOSITO, D. STRATAKIS

12.1 Cooling demonstrator programme

A. NAME, A. NAME
Scope, test stands, cooling cells, magnets

12.2 RF Test Stand

L. ROSSI, R. LOSITO, D. GIOVE, E. NANNI, S. GESSNER

12.2.1 RF Testing at SLAC

E. NANNI, S. GESSNER
Measurements of breakdown rates for x-, s-, and l-band cavities in solenoidal fields.

12.3 Muon cooling test module

L. ROSSI, R. LOSITO, E. NANNI

12.4 Demonstrator implementation at CERN

R. LOSITO, C. ROGERS, J. OSBORN, L. ROSSI, P. JURJ

12.4.1 Demonstrator system description

12.4.2 Civil engineering

12.4.3 Infrastructure

12.4.4 Cost and timeline

12.5 Demonstrator implementation at Fermilab

D. STRATAKIS, F. PELLEMOINE, S. BERG, J. ELDRED, K. YONEHARA, E. GIANFELICE, S. NAGAITSEV

12.5.1 Demonstrator system description

12.5.2 Civil engineering

12.5.3 Infrastructure

12.5.4 Cost and timeline

Chapter 13

Other test infrastructure

R. LOSITO

Chapter 14

R&D Programme Synergies

C. ROGERS, L. BOTTURA

Chapter 15

Sustainability Environmental considerations

C. ROSSI, G. APOLLINARI

15.1 Cost drivers and cost scale

15.2 Power drivers and power scale

Chapter 16

Muon Collider implementation

A. NAME, A. NAME

16.1 Overview

A. NAME, A. NAME

16.2 Timeline

SERGO, C. ROGERS, R. LOSITO, L. BOTTURA

16.3 Implementation at CERN

R. LOSITO, J. OSBORN, Y. ROBERTS, C. AHDIDA, C. CARLI, E.MACTAVISH

16.3.1 Timeline

16.3.2 Civil Engineering

16.3.2.1

16.3.2.2 Proton compatible option

16.3.3 Infrastructure

16.3.3.1 Ventilation

16.3.4 Accelerator

16.3.4.1 Muon Cooling

16.3.4.2 RCS

16.4 Implementation at Fermilab

D. STRATAKIS, F. PELLEMOINE, S. BERG, J. ELDRED , K. YONEHARA, E. GIANFELICE, S. NAGAITSEV

16.4.1 Timeline

16.4.2 Civil Engineering

16.4.3 Infrastructure

16.4.3.1 Ventilation

16.4.4 Accelerator

16.4.4.1 Muon Cooling

16.4.4.2 RCS

Bibliography

[1] Ivan Karpov and Philippe Baudrenghien. “Transient beam loading and rf power evaluation for future circular colliders”. In: *Phys. Rev. Accel. Beams* 22 (8 Aug. 2019), p. 081002. DOI: `10.1103/PhysRevAccelBeams.22.081002`. URL: `https://link.aps.org/doi/10.1103/PhysRevAccelBeams.22.081002`.