
A Muon Collider Facility for Physics Discovery

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Editors:

D. Stratakis¹, N. Mokhov¹, M. Palmer², N. Pastrone³, T. Raubenheimer⁴, C. Rogers⁵, D. Schulte⁶, V. Shiltsev¹, J. Tang^{7,9}, A. Yamamoto^{6,8},

Authors:

C. Aimè^{10,22}, M.A. Mahmoud¹¹, N. Bartosik³, E. Barzi^{1,38}, A. Bersani¹², A. Bertolin¹³, M. Bonesini^{14,39}, B. Caijfi¹², M. Casarsa¹⁵, M.G. Catanese¹⁶, A. Cerri¹⁷, C. Curatolo¹⁴, M. Dam¹⁴, H. Damerau⁶, E. De Matteis¹⁸, H. Denizli¹⁹, B. Di Micco^{20,40}, T. Dorigo¹³, S. Farinon¹², F. Filthaut²¹, D. Fiorina²², D. Giove¹⁸, M. Greco²⁰, C. Grojean^{23,41}, T. Han²⁴, S. Jindariani¹, P. Koppenburg²⁵, K. Krizka²⁶, Q. Li²⁷, Z. Liu²⁸, K.R. Long^{29,5}, D. Lucchesi^{30,13}, S. Mariotto^{31,18}, F. Meloni²³, C. Merlassino³², E. Métral⁶, A. Montella¹⁵, R. Musenich¹², M. Nardecchia^{33,42}, F. Nardi^{30,13}, D. Neuffer¹, S. Pagan Griso²⁶, K. Potamianos³², M. Prioli¹⁸, E. Radicioni¹⁶, L. Reina³⁴, C. Riccardi^{10,22}, L. Ristori¹, L. Rossi^{31,18}, P. Salvini²², J. Santiago^{35,43}, A. Senol¹⁹, L. Sestini¹³, M. Sorbi^{31,18}, G. Stark³⁶, M. Statera¹⁸, X. Sun³⁷, I. Vai²², R. U. Valente¹⁸

Signatories:

K. Agashe⁴⁴, B.C. Allanach⁴⁵, A. Apresyan¹, P. Asadi⁴⁶, D. Athanasakos⁴⁷, A. Azatov^{48,15}, F. Batsch⁶, M.E. Biagini⁴⁹, K.M. Black⁵⁰, . . . Bottaro^{51,52}, A. Braghieri²², A. Bross¹, L. Buonincontri^{13,30}, D. Buttazzo⁵², G. Calderini^{53,114}, S. Calzaferrri²², A. Canepa¹, R. Capdevilla^{54,63}, L. Castelli³⁰,

C. Cesarotti⁵⁵, G. Chachamis⁵⁶, Z. Chacko⁴⁴, A. Chancé⁵⁷, S. Chen⁵⁸, Y.-T. Chien⁵⁹, A. Colaleo^{60,16}, M. Costa^{51,52}, N. Craig⁶¹, Y. Cui⁶², D. Curtin⁶³, R. T. D'Agnolo⁶⁴, G. Da Molin⁶⁵, S. Dasu⁵⁰, J. de Blas⁴³, A. Deandrea⁶⁶, J. Delahaye⁶, A. Delgado⁶⁷, R. Dermisek⁶⁸, K. F. Di Petrillo¹, J. Dickinson¹, M. Dracos⁶⁹, F. Errico^{60,16}, P. Everaerts⁵⁰, L. Everett⁵⁰, G. Ferretti⁷⁰, M. Forslund⁴⁷, R. Franceschini^{20,40}, E. Gabrielli^{71,15}, F. Garosi⁷², L. Giambastiani^{73,13}, C. Giralddin³⁰, A. Glioti⁵⁸, L. Gray¹, A. Greljo⁷⁴, J. Gu⁷⁵, H.E. Haber³⁶, C. Han⁷⁶, J. Hauptman⁷⁷, B. Henning⁵⁸, K. Hermanek⁶⁸, M. Herndon⁵⁰, T.R. Holmes⁷⁸, S. Homiller⁵⁵, S. Jana⁷⁹, H. Jia⁵⁰, Y. Kahn⁸⁰, D. M. Kaplan⁸¹, W. Kilian⁸², K. Kong⁸³, G.K. Krintiras⁸⁴, G. Krnjaic¹, R. LOSITO⁶, L. Lee⁷⁸, W. Li⁸⁵, I. Low^{86,115}, Q. Lu⁵⁵, Y. Ma²⁴, F. Maltoni^{87,116}, L. Mantani⁴⁵, D. Marzocca¹⁵, P. Mastrapasqua⁸⁷, K. Matchev⁸⁸, A. Mazzacane¹, N. McGinnis⁸⁹, P. Meade⁴⁷, B. Mele⁴², P. Merkel¹, F. Mescia^{90,117}, R. K. Mishra⁵⁵, A. Mohammadi⁵⁰, R. Mohapatra⁹¹, P. Montagna^{10,22}, N. Neufeld⁶, H. Newman⁹², Y. Nomura⁹³, I. Ojalvo⁹⁴, P. Panci^{95,52}, D. Pagani⁹⁶, P. Paradisi^{73,13}, A. Pellegrina⁶⁰, A. Perloff⁹⁷, F. Piccinini²², M. Pierini⁶, M. Procura⁹⁸, R. Radogna^{60,16}, T. Raubenheimer⁴, D. Redigolo⁹⁹, J. Reuter²³, F. Riva¹⁰⁰, T. Robens¹⁰¹, F. S. Queiroz^{102,102}, F. Sala¹⁰³, J. Salko⁷⁴, E. Salvioni^{73,13}, I. Sarra⁹¹, J. Schieck^{104,118}, M. Selvaggi⁶, V. Sharma⁵⁰, F. M. Simone^{60,16}, A. Stamerra^{60,16}, D. Stolarski¹⁰⁵, J. Stupak¹⁰⁶, S. Su¹⁰⁷, R. Sundrum¹⁰⁸, M. Swiatlowski⁸⁹, A. Sytov¹⁰⁹, T. Tait¹¹⁰, E. A. Thompson²³, R. Torre¹², L. Tortora^{40,6}, S. Trifinopoulos¹⁵, M. Valente⁸⁹, N. Valle^{10,22}, R. Venditti^{60,16}, P. Verwilligen¹⁶, L. Vittorio^{51,52}, P. Vitulo^{10,22}, E. Vryonidou¹¹¹, C. Vuosalo⁵⁰, H. Weber⁴¹, Y. Wu¹¹², A. Wulzer⁶⁵, K. Xie²⁴, K. Yonehara¹, H.-B. Yu⁶², A. Zaza^{60,16}, Y. J. Zheng⁸³, D. Zuliani^{30,13}, J. Zurita¹¹³

¹Fermi National Accelerator Laboratory, Batavia, IL 60510-0500, United States; ²Department of Physics, Brookhaven National Laboratory, Upton, NY 11973-5000, United States; ³Istituto Nazionale di Fisica Nucleare, Sezione di Torino via P. Giuria, 1, 10125 Torino, Italy; ⁴SLAC National Accelerator Laboratory, United States; ⁵Rutherford Appleton Laboratory, Harwell Oxford, Didcot OX110QX, United Kingdom; ⁶CERN, Switzerland; ⁷Sun Yat-sen University, guangzhou 510275, China; ⁸High Energy Accelerator Research Organization KEK, Tsukuba, Ibaraki 305-0801, Japan; ⁹Institute of High-Energy Physics, Beijing, China; ¹⁰Università di Pavia, Italy; ¹¹Center for High Energy Physics (CHEP-F), Fayoum University, 63514 El-Fayoum, Egypt; ¹²Istituto Nazionale di Fisica Nucleare - Sezione di Genova - via Dodecaneso 33, 16146 Genova - Italy; ¹³INFN Sezione di Padova, Padova, Italy; ¹⁴Istituto Nazionale di Fisica Nucleare, Italy; ¹⁵INFN Sezione di Trieste, Trieste, Italy; ¹⁶INFN, Bari, Italy; ¹⁷MPS School, University of Sussex, Sussex House, BN19QH Brighton, United Kingdom; ¹⁸Laboratori Acceleratori e Superconduttività Applicata (LASA), Istituto Nazionale di Fisica Nucleare (INFN), Via Fratelli Cervi 201, 20054 Segrè Milano, Italy; ¹⁹Department of Physics, Bolu Abant İzzet Baysal University, 14280, Bolu, Turkey; ²⁰Università degli Studi di Roma Tre, Italy; ²¹Radboud University and Nikhef, Nijmegen, The Netherlands; ²²INFN, Sezione di Pavia, Pavia, Italy; ²³Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany; ²⁴University of Pittsburgh, United States; ²⁵Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands; ²⁶Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA, United States; ²⁷Peking University, Beijing, China; ²⁸School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA, United States; ²⁹Imperial College London, Exhibition Road, London, SW7 2AZ, UK, United Kingdom; ³⁰Università di Padova, Italy; ³¹Dipartimento di Fisica Aldo Pontremoli, Università degli Studi di Milano, Via Celoria, 16, 20133 Milano, Italy; ³²Particle Physics Department, University of Oxford, Denys Wilkinson Bldg., Keble Road, Oxford OX1 3RH, United Kingdom; ³³Sapienza University of Rome, Italy; ³⁴Florida State University, United States; ³⁵CAFPE, Spain; ³⁶SCIPP, UC Santa Cruz, United States; ³⁷State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China; ³⁸Ohio State University, Columbus, OH 43210, United States; ³⁹Dipartimento di Fisica Università Milano Bicocca, Italy; ⁴⁰Istituto Nazionale di Fisica Nucleare sezione di Roma Tre, Italy; ⁴¹Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, 12489 Berlin, Germany; ⁴²INFN Rome, Italy; ⁴³Departamento de Física Teórica y del Cosmos, Universidad de Granada, Campus de Fuentenueva, E-18071 Granada, Spain. ; ⁴⁴Maryland Center for Fundamental Physics, University of Maryland, College Park, MD 20742, USA, United States; ⁴⁵DAMTP, Wilberforce Road, University of Cambridge, Cambridge CB3 0WA,

United Kingdom; ⁴⁶Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA., United States; ⁴⁷YITP, Stony Brook, United States; ⁴⁸SISSA International School for Advanced Studies, Via Bonomea 265, 34136, Trieste, Italy; ⁴⁹INFN, Frascati National Laboratory, Italy; ⁵⁰University of Wisconsin-Madison, United States; ⁵¹Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56126, Pisa, Italy; ⁵²INFN Sezione di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy; ⁵³CNRS/IN2P3, Paris, France; ⁵⁴Perimeter Institute, Canada; ⁵⁵Department of Physics, Harvard University, Cambridge, MA, 02138, United States; ⁵⁶Laboratório de Instrumentação e Física Experimental de Partículas (LIP), Av. Prof. Gama Pinto, 2, P-1649-003 Lisboa, Portugal; ⁵⁷IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France; ⁵⁸Theoretical Particle Physics Laboratory (LPTP), Institute of Physics, EPFL, Lausanne, Switzerland; ⁵⁹Physics and Astronomy Department, Georgia State University, Atlanta, GA 30303, U.S.A., United States; ⁶⁰Department of Physics, Università degli Studi di Bari, Italy; ⁶¹University of California, Santa Barbara, United States; ⁶²University of California-Riverside, United States; ⁶³Department of Physics, University of Toronto, Canada; ⁶⁴Université Paris Saclay, CNRS, CEA, Institut de Physique Théorique, 91191, Gif-sur-Yvette, France; ⁶⁵Dipartimento di Fisica e Astronomia, Università di Padova, Italy; ⁶⁶IP2I, Université Lyon 1, CNRS/IN2P3, UMR5822, F-69622, Villeurbanne, France; ⁶⁷University of Notre Dame, United States; ⁶⁸Physics Department, Indiana University, Bloomington, IN, 47405, USA, United States; ⁶⁹IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France; ⁷⁰Chalmers University of Technology 40220 Gothenburg , Sweden; ⁷¹Physics Department, University of Trieste, Strada Costiera 11, 34151 Trieste, Italy; ⁷²SISSA, Italy; ⁷³Dipartimento di Fisica e Astronomia, Università degli Studi di Padova, Italy; ⁷⁴Albert Einstein Center for Fundamental Physics, Institute for Theoretical Physics, University of Bern, CH-3012 Bern, Switzerland; ⁷⁵Department of Physics, Fudan University, Shanghai 200438, China; ⁷⁶School of Physics, Sun Yat-Sen University, Guangzhou 510275, China; ⁷⁷Iowa State University, Ames, Iowa, 50011 USA, United States; ⁷⁸University of Tennessee, Knoxville, TN, USA, United States; ⁷⁹Max-Planck-Institut für Kernphysik, Germany; ⁸⁰Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA, United States; ⁸¹Illinois Institute of Technology, United States; ⁸²Department of Physics, University of Siegen, 57068 Siegen, Germany; ⁸³Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA, United States; ⁸⁴Department of Physics and Astronomy 1082 Malott, 1251 Wescoe Hall Dr. Lawrence, KS 66045, United States; ⁸⁵Rice University, Houston, TX 77005, USA, United States; ⁸⁶High Energy Physics Division, Argonne National Laboratory, Lemont, IL 60439, USA, United States; ⁸⁷Center for Cosmology, Particle Physics and Phenomenology, Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium; ⁸⁸Physics Department, University of Florida, Gainesville FL 32611 USA, United States; ⁸⁹TRIUMF, 4004 Westbrook Mall, Vancouver, BC, Canada V6T 2A3; ⁹⁰Universitat de Barcelona, Spain; ⁹¹University of Maryland, college Park, USA, United States; ⁹²California Institute of Technology, United States; ⁹³Department of Physics, University of California, Berkeley, CA 94720, USA, United States; ⁹⁴Princeton University, United States; ⁹⁵Pisa University, Italy; ⁹⁶INFN, Sezione di Bologna, Via Irnerio 46, 40126 Bologna, Italy; ⁹⁷Department of Physics, University of Colorado, 390 UCB, Boulder, CO 80309, United States; ⁹⁸University of Vienna, Faculty of Physics, Boltzmannngasse 5, 1090 Vienna, Austria; ⁹⁹INFN Florence, Italy; ¹⁰⁰Département de Physique Théorique, Université de Genève, 24 quai Ernest-Ansermet, 1211 Genève 4, Switzerland; ¹⁰¹Rudjer Boskovic Institute, Zagreb, Croatia; ¹⁰²International Institute of Physics, Universidade Federal do Rio Grande do Norte, Campus Universitario, Lagoa Nova, Natal-RN 59078-970, Brazil; ¹⁰³Laboratoire de Physique Théorique et Hautes Énergies, Sorbonne Université, CNRS, Paris, France; ¹⁰⁴Institut für Hochenergiephysik der Österreichischen Akademie der Wissenschaften, Nikolsdorfer Gasse 18, A-1050 Wien, Austria; ¹⁰⁵Ottawa-Carleton Institute for Physics, Carleton University, 1125 Colonel By Drive, Ottawa, ON, K1S 5B6, Canada; ¹⁰⁶University of Oklahoma, United States; ¹⁰⁷University of Arizona, United States; ¹⁰⁸Maryland Center for Fundamental Physics, University of Maryland, College Park, MD 20742, USA, United States; ¹⁰⁹INFN Division of Ferrara, Italy; ¹¹⁰Department of Physics and Astronomy, University of California, Irvine, CA 92697 US, United States; ¹¹¹University of Manchester, Manchester M13 9PL, UK, United Kingdom; ¹¹²Department of Physics, Oklahoma State University, Stillwater, OK, 74078, USA, United States; ¹¹³Instituto de Física Corpuscular, CSIC-Universitat de València, Valencia, Spain; ¹¹⁴LPNHE, Sorbonne Université, France; ¹¹⁵Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208, USA, United States; ¹¹⁶Dipartimento di Fisica e Astronomia, Università di Bologna, via Irnerio 46, I-40126 Bologna , Italy; ¹¹⁷Institut de Ciències del Cosmos

(ICC), Spain; ¹¹⁸Atominstitut, Technische Universität Wien, Stadionallee 2, A-1020 Wien, Austria

Abstract

Muon colliders provide a unique route to deliver high energy collisions that enable discovery searches and precision measurements to extend our understanding of the fundamental laws of physics. The muon collider design aims to deliver physics reach at the highest energies with costs, power consumption and on a time scale that may prove favorable relative to other proposed facilities. In this context, a new international collaboration has formed to further extend the design concepts and performance studies of such a machine. This effort is focused on delivering the elements of a ~ 10 TeV center of mass (CM) energy design to explore the physics energy frontier. The path to such a machine may pass through lower energy options. Currently a 3 TeV CM stage is considered. Other energy stages could also be explored, e.g. an s-channel Higgs Factory operating at 125 GeV CM. We describe the status of the R&D and design effort towards such a machine and lay out a plan to bring these concepts to maturity as a tool for the high energy physics community.

1 Executive Summary

High-energy lepton colliders can serve as facilities for precision and discovery physics. The decrease of s-channel cross sections as $1/s$ requires that luminosity increases with energy, ideally proportional to s , the square of the centre-of-mass energy. The only mature technology to reach high-energy, high-luminosity lepton collisions is linear electron-positron colliders; the highest energy for which a conceptual design exists is the Compact Linear Collider (CLIC) at 3 TeV.

The Muon Collider (MuC) promises to be able to extend the lepton collider energy reach to much higher energies. The strong suppression of synchrotron radiation compared to electrons allows muon beam acceleration in rings making efficient use of the RF systems for acceleration. The overall power consumption of a 10 TeV MuC is expected to be lower than that of CLIC at 3 TeV. Additionally the beam can repeatedly produce luminosity in two detectors in the collider ring. The ratio of luminosity to beam power is expected to improve with collision energy, a unique feature of the MuC. The compactness of the collider makes it plausible that a cost effective design might be achieved; however this must be verified with more detailed estimates. If the technical challenges can be overcome, the MuC offers a potential route to long-term sustainability of collider physics.

To foster the Muon Collider concept an International Muon Collider Collaboration (IMCC) has been initiated after the recommendation of the update of the European Strategy for Particle Physics, initially hosted at CERN. The collaboration will address the muon collider challenges and develop the concept and technologies in the coming years in order to be able to gauge if the investment into a full conceptual design and demonstration programme is scientifically justified. This will allow the Strategy Processes in the different regions to make informed decisions.

Currently, the limit of the energy reach has not been identified. The study focuses on a 10 TeV design with an integrated luminosity goal of 10 ab^{-1} . This goal is expected to provide a good balance between an excellent physics case and affordable cost, power consumption and risk. Once a robust design has been established at 10 TeV - including an estimate of the cost, power consumption and technical risk - other, higher energies will be explored.

A potential initial energy stage at 3 TeV with an integrated luminosity of 1 ab^{-1} is also considered. This option might cost around half as much as the 10 TeV option, and can be upgraded to 10 TeV or beyond by adding an accelerator ring and building a new collider ring. Only the 4.5 km-long 3 TeV collider ring would not be reused in this case. This stage could potentially start colliding beams in the mid 2040s - depending on the strategic decisions. This also requires that sufficient funding is available already during the design phase and that all challenges can be successfully addressed with no delays.

The muon collider thus promises a sustainable path toward the very high energy. Its large energy and luminosity reach makes the direction and the development of the technologies attractive. Potential intermediate stages provide important physics results on the way on timescales more adapted to the human life span and provide the motivation for the scientists and engineers that is the most important driver of the technological progress.

Muon Collider technology must overcome several significant challenges to reach a level of maturity similar to linear colliders. An increased level of R&D effort is justified at the current time, because the muon collider promises an alternative path toward high-energy, high-luminosity lepton collisions that extends beyond the expected reach of linear colliders. Supporting technologies such as high-power proton drivers, high-field solenoids and high-gradient RF cavities have, in the last decade, approached the level required to deliver the requisite luminosity.

Past work has demonstrated several key MuC technologies and concepts, and gives confidence that the concept is viable. Component designs have been developed that can cool the initially diffuse beam and accelerate it to multi-TeV energy on a time scale compatible with the muon lifetime. However, a fully integrated design has yet to be developed and further development and demonstration of technology are required. In order to enable the next European Strategy for Particle Physics Update (ESPPU), the next

Particle Physics Project Prioritisation Process (P5) and other strategy processes to judge the scientific justification of a full Conceptual Design Report (CDR) and demonstration programme, the design and potential performance of the facility must be developed in the next few years.

An R&D programme has been developed in the frame of the European Roadmap for Accelerator R&D. The programme addresses the key challenges and is based on consultations of the community at large, combined with the expertise of a dedicated Muon Beams Panel. It benefited from significant input from the MAP design and studies and US experts.

The proposed programme of work, if fully resourced, will allow the assessment of realistic luminosity targets, detector backgrounds, power consumption and cost scale, as well as whether one can consider implementing a MuC at CERN or elsewhere. Mitigation strategies for the key technical risks and a demonstration programme for the CDR phase will also be addressed. The use of existing infrastructure, such as existing proton facilities and the LHC tunnel, will also be considered. Based on the conclusions of the next strategy processes in the different regions, a CDR phase could then develop the technologies and the baseline design to demonstrate that the community can execute a successful MuC project.

No cost estimate for the CDR and demonstrator phase exists but experience indicates that typically 5-10% of the final project cost would need to be invested before the project construction can start. A muon cooling demonstrator facility would be expected to be the largest single component of the CDR programme, with the potential to provide direct scientific output in its own right.

The resources available to the MuC programme over the next five years will depend on decisions made in the different regions and in particular in the US.

The muon collider programme is synergistic with other R&D efforts, and will directly benefit from progress in the domains of high-field magnets, RF systems and recirculating linacs. The muon collider requires high-field dipoles, similar to proton facilities, and in particular robust high-field solenoids. These have a strong synergy with the development for other fields of science and society, e.g. the development of fusion power, high-field science, NMR spectroscopy and MRI machines of the next generation.

Bright muon beams are also important for potential future neutrino physics facilities such as NuS-TORM or ENUBET. A muon cooling demonstrator facility could potentially share a large part of the infrastructure with these facilities, from the proton source to the target.

2 Design Overview

2.1 Status of Design

MAP has developed many concepts and technologies for the muon collider. The rate of progress in this field gives confidence that the muon collider is a viable option. However no integrated design design of the muon collider has been made and further development of the technologies is required. The goal in the coming years is to develop the concept and technologies to a level that one can justify the investment into a technology and concept demonstration programme, including the full concept development and optimisation. The goal of this programme is to be able to commit to the project and to prepare the technical design phase.

2.2 Performance Matrix

2.2.1 Attainable Energy

At this moment, no fundamental limit for the energy reach of the muon collider has been identified. The limitations are expected to come from the cost of the collider complex and from the technological and power consumption challenges to obtain high luminosity at high energy. In this respect the energy reach cannot be separated from the luminosity reach.

The goals for the muon collider design study are thus driven by a balance between an excellent

physics case and affordable cost, power consumption and technical risk. The 10 TeV goal is chosen for these very reasons and supported by a very strong physics case.

Once a firm design has been established for an energy of 10 TeV, including an estimate of the scale of cost, power consumption and technical risk, other higher energies will also be explored.

A 3 TeV design will also be studied as it may be an attractive entry stage for the muon collider with a cost well below the 10 TeV and an already strong physics case. For this concept the challenges in the high-energy complex are reduced; e.g. the requirements for the final focus system magnets are in the same ballpark as for the the HL-LHC. Because of its smaller budget need and size such a stage could be most likely be implemented earlier than the 10 TeV stage. It could be then upgraded to 10 TeV by reusing the full complex, except for the 4.5 km-long 3 TeV collider ring, and by adding an additional accelerator ring and a new collider ring.

2.2.2 *Attainable Luminosity and Luminosity Integral*

The integrated luminosity targets for the muon collider are based on requirements from physics. They follow a scaling to keep the number of s -channel events constant at all energies.

The tentative parameters and luminosity targets have been chosen based on previous MAP studies. They would achieve the integrated luminosity target within five years in a single detector. Paths have been identified to achieve the parameters. The focus of the study is to address the technological challenges on these paths to achieve a robust performance prediction.

Alternative approaches that could lead to higher luminosity will also be explored, e.g. Parametric Ionization Cooling. However, in the near term the focus is to ensure a solid design and advancing technologies.

2.2.3 *Facility Scale*

The dimensions of the muon collider are not known and depend on future technology and design choices. Still, some indication of the dimensions can be estimated.

Considering the largest RCS and collider ring at 10 TeV, one can assume 16 T field in the superconducting static dipoles of both rings and a field range of ± 2 T for the fast-ramping normal magnets in the RCS. In both cases the effective dipole filling factor could be 80%, similar to the LHC. This accounts for flanges, instrumentation, focusing quadrupoles, etc. In case of combined function magnets the filling factor can be higher but the dipole field might have to be reduced in proportion. Further some space for the RF and injection, extraction and interaction region is required. Based on this, the initial estimate of the length is 10 km for the 10 TeV collider and 32 km for the pulsed synchrotron that accelerates the beam from 1.5 to 5 TeV. The total tunnel is comparable to a 3 TeV CLIC, which has an estimated tunnel length of about 50 km to house the linacs and the final focus systems. The pulsed synchrotron could be made more compact using fast ramping HTS magnets with a larger field reach or by performing the acceleration in two stages in the same tunnel, which would require less than 20 km but more superconducting magnets.

The final pulsed synchrotron for the 3 TeV stage would be approximately 12 km long and the collider 4.5 km, using superconducting dipoles with a field of only 11 T.

It is also possible to consider using the LHC tunnel for the final pulsed synchrotron of the 3 TeV stage and for the acceleration to 10 TeV. However more detailed studies are required.

2.2.4 *Power requirements*

The goal is to remain at a power consumption for the 10 TeV collider well below the level of CLIC at 3 TeV or FCC-hh. The design has to advance more to assess the power consumption scale in a robust

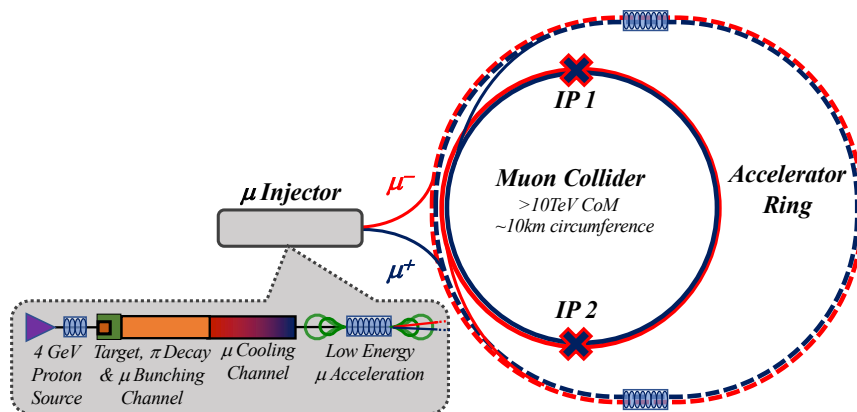


Fig. 1: A conceptual scheme for the Muon Collider

fashion. The scaling of the power consumption with energy is illustrated by some tentative considerations below.

A number of key components drive the power consumption if one extends to high energy:

- The power loss in the fast-ramping magnets of the pulsed synchrotron and their power converter. This is being addressed by a dedicated study.
- The cryogenics system that cools the superconducting magnets in the collider ring. This depends on the efficiency of shielding the magnets from the muon decay-induced heating.
- The cryogenics power to cool the superconducting magnets and RF cavities in the pulsed synchrotron.
- The power to provide the RF for accelerating cavities in the pulsed synchrotron.

The first contribution requires a particular effort as it depends on unprecedented large-scale fast ramping systems and the second and third contributions depends on the shielding choices. The contributions can be estimated reliably once the design choices - such as magnet material and operating temperature, RF system design, shielding thickness etc. - have been made.

2.3 Design Summary

The current muon collider baseline concept was developed by the Muon Accelerator Program (MAP) collaboration [2], which conducted a focused program of technology R&D to evaluate its feasibility. Since the end of the MAP study seminal measurements have been performed by the Muon Ionization Cooling Experiment (MICE) collaboration, which demonstrated the principle of ionisation cooling that is required to reach sufficient luminosity for a muon collider [1]. The MAP scheme is based on the use of a proton beam to generate muons from pions decay and is the baseline for the collider concept being developed by the new international collaboration. An alternative approach Low Emittance Muon Accelerator (LEMMA), which uses positrons to produce muon pairs at threshold, has been explored at INFN [7].

MAP developed the concept shown in Fig. 1. The proton complex produces a short, high intensity proton pulse that hits a target and produces pions. The decay channel guides the pions and collects the muons produced in their decay into a buncher and phase rotator system to form a muon beam. Several cooling stages then reduce the longitudinal and transverse emittance of the beam using a sequence of absorbers and RF cavities in a high magnetic field. A linac and two recirculating linacs accelerate the beams to 60 GeV. One or more rings accelerate the beams to the final energy. As the beam is accelerated, the lifetime in the lab frame increases due to relativistic time dilation so later stage accelerators have

proportionally more time for acceleration, so that fast-pulsed synchrotrons can be used. Fixed-Field Alternating-gradient (FFA) accelerators are an interesting alternative. Finally the two single bunch beams are injected at full energy into the collider ring to produce collisions at two interaction points. The MAP study demonstrated feasibility of key components, but several important elements were not studied. The highest collision energy studied by MAP was 6 TeV. Technical limitations such as beam-induced backgrounds have not been studied in detail at higher energies. Individual elements of the muon source were studied, but integrated system design and optimisation was not performed. Cooling studies assumed limits in practical solenoid and RF fields that now appear to be too conservative; an updated performance estimate would likely yield a better assessment of the ultimate luminosity of the facility. MAP studies considered gallium, graphite and mercury target options, which should be progressed and studied in more detail to assess fully the performance and technical limitations of the system.

2.4 Design Challenges

2.4.1 Muon beam

Although muons offer many potential physics benefits, their use brings substantial complications as well. Indeed, if intense muon beams were easy to produce, they would already be available. Firstly, muons are created as a tertiary beam. The proposed production scheme uses a proton beam to bombard a high-Z target. This produces pions, which are captured in a solenoidal decay channel, where they decay to muons. To produce an acceptably large sample of muons, a multi-MW proton beam is required. A target system capable of tolerating such an intense beam is a substantial challenge. The capture and decay process just described gives rise to a muon beam having a large energy spread and a large transverse phase space. The large transverse phase space has several implications: (1) it favors the use of solenoidal focusing in the lower energy portions of the facility, as opposed to the more conventional quadrupole focusing. A solenoid focuses in both planes simultaneously, avoiding the excessively large beam size in one plane when using an alternating polarity quadrupole channel. (2) it requires a rapid mechanism for reducing the emittance to more tractable values. The second major challenge of muon beams is due to the short lifetime of the muon, only $2.2 \mu\text{s}$ at rest. Clearly, the short lifetime puts a premium on very rapid beam manipulations. A fast emittance cooling technique, “ionization cooling,” is needed to reduce the transverse emittance of the muon beam, along with a very rapid acceleration system. The ionization cooling technique requires high-gradient normal conducting RF cavities due to the need to immerse the cavities in a strong solenoidal magnetic field. Finally, the decays of the muons lead to potentially severe backgrounds in the detector of a Muon Collider. There are also a number of challenges related to the magnet requirements. In the target area, the initial capture magnet is a 20 T solenoid design. In the cooling channel, large aperture magnets having relatively low field, up to 2-3 T and 1.5-m diameter, are utilized. As the beam emittance is reduced through cooling, higher field solenoids with lower diameter bores are needed. In the final cooling stages of a Muon Collider, very high strength solenoids, up to ~ 50 T, are required. In the acceleration system, solenoids with very low fringe fields are needed to permit operation of nearby superconducting RF cavities. In the acceleration system and collider ring, special split-midplane or shielded dipoles are needed to accommodate the high heat load from muon decay electrons.

2.4.2 Machine Detector Interface (MDI)

A multi-TeV Muon Collider needs to deliver high instantaneous luminosity ($\sim 10^{34}$ - $10^{35} \text{ cm}^{-2}\text{s}^{-1}$) to be able to exploit the diverse physics potential opportunities. To reach this goal high intense muon beams, 2×10^{12} muons per bunch, are necessary. At the Interaction Point (IP), where the two $\mu^+\mu^-$ bunches collide, the Beam-Induced Background (BIB) strongly affects the detectors’ performance; therefore an efficient mitigation strategy is required. The background arriving on the detector volume is a huge flux of secondary and tertiary low energy particles, mainly originated from muon decays occurring several decades of meters from the IP, with an additional component of incoherent e^+e^- pair production and

Bethe Heitler muons. The current solution to mitigate such a background flux, initially proposed by MAP, consists of two tungsten cone-shaped shielding (nozzles) around the beampipe, with the origin in proximity of the interaction point, to be accurately designed and optimized for each specific beam energy. The design of the detector and the choice of the sub-detector technology need to cope with the nozzle structure and with the remaining fluxes of particles. The interaction region at 1.5 TeV center of mass energy has been designed and optimized by MAP. It was simulated with a framework developed at Fermilab [13] with the MARS15 code, and it is used as a starting point and benchmark.

Within the International Muon Collider Collaboration, a new framework, based on FLUKA, has been developed to study the beam-induced background at different energies [9]. Studies performed so far demonstrate that, given reasonable assumptions of detector performance, it will be possible to perform the most challenging physics measurements [12]. Preliminary studies performed with a very preliminary configuration of the IR at 10 TeV center of mass energy with the nozzle designed for the 1.5 TeV, indicate that the beam induce background levels around the IP do not increase significantly. Combined interaction region, detector shielding and detector design should be performed to confirm physics performance at 3 TeV and 10 TeV.

2.4.3 *Required key technologies*

The following technologies are required in order to deliver the muon collider.

- Development of a high power proton driver.
 - Delivery of a high intensity H⁻ ion source.
 - Stripping of the H⁻ ions without excess foil heating.
 - A bunch compressor ring to deliver protons in a single, approximately 2 ns long bunch onto the target.
- A target system capable of managing the large instantaneous beam power.
 - A target that can withstand both high instantaneous current and high average beam power.
 - A suitable shielding system to protect the sensitive capture magnet that surrounds the target.
 - A superconducting capture magnet that can withstand radiation leakage from the target, that can contain the required shielding and that can deliver 15-20 T field to contain the pion beam.
 - A beam dump that can capture the remnant proton beam without detrimental effect on the outgoing pion and muon beam.
- A muon cooling system capable of delivering orders of magnitude of emittance reduction.
 - A system of intermediate field solenoids, tightly integrated with RF cavities and absorbers.
 - A few extremely high-field, small-bore solenoids, with magnetic fields exceeding the current state of the art (~ 30 T).
 - Normal conducting RF systems capable of providing high field gradients in the presence of strong magnetic fields.
- A beam acceleration system that can accelerate the muon beam on a time scale that is compatible with the time-dilated muon lifetime.
 - Fast ramping power supplies to deliver ramp times of several T on a timescale of ms.
 - Superconducting RF systems robust to beam loading and capable of delivering significant RF gradient for rapid muon acceleration.
- A collider ring that can deliver the collisions.
 - Dipole magnets operating at high field, to recirculate the beam as many times as possible before the muons decay.
 - Dipole magnets must be robust to the radiation arising from muon decay.

- The collider ring systems must be movable such that neutrino flux does not produce showering off-site from the collider ring.
- High gradient final focus quadrupoles, comparable to HL-LHC at 3 TeV and more demanding at 10 TeV, that can deliver the small β^* required to deliver requisite luminosity.
- A detector system capable of distinguishing signal from the beam-induced background arising due to muon decays in the collider ring.

2.4.4 Environmental impacts

The muon collider will impact the environment in several ways. Key factors are:

- The land use for the construction of its infrastructure.
- The power that the collider consumes.
- The waste that it generates.
- The production and transport of components.
- Other impact on the environment, e.g. potential radiation.

2.4.5 Land use

As discussed above, the dimensions of the muon collider are not known and depend on future technology and design choices. Still, some indication of the dimensions can be estimated.

The size for the last pulsed synchrotron and the collider ring could be 32 and 10 km, respectively. The collider is therefore expected to be comparable to CLIC at 3 TeV in terms of land use.

If it is possible to reuse the LHC tunnel for the pulsed synchrotron, the total amount of tunnel that needs to be constructed would be significantly reduced. This option will be explored.

2.4.6 Power consumption

The goal is to have a power consumption of the 10 TeV stage significantly below the one of CLIC at 3 TeV or the FCC-hh. No detailed study has been performed up to now. MAP estimated a power consumption of roughly 100 MW, independent of the colliding beam energy, for the muon production [11]. We will develop an improved estimate and focus on the improvement of power consumption drivers.

2.4.7 The generated waste

The muon collider uses leptons in the high-energy part of the collider and is thus a relatively clean machine. The main concern would be the proton target. To minimise the impact of the target, we plan not to use a mercury target but rather a solid graphite target. Other options such as liquid gallium or fluidised tungsten will also be explored and are also more environmentally sensitive than mercury. The total power is in the range of existing and planned targets at other facilities. Therefore no specific problem is expected.

2.4.8 Production and transport of components

This issue has not been studied. However the superconducting systems would be comparatively compact, which indicates that the load to the environment is comparatively limited.

2.4.9 Other impact on the environment

The proposed mechanical system can mitigate the neutrino flux density resulting from muon decay from the arcs sufficiently even at 14 TeV. The insertions, in particular for the experiments, complicate the mitigation and have to be investigated. We expect to be able to find an orientation for the collider complex that mitigates the potential issues.

3 Technology Requirements

3.1 Technology Readiness Assessment

A set of key challenges has been identified for the muon collider. For each of these challenges a path toward addressing it has been identified. Important R&D remains to demonstrate that all obstacles on these paths can be overcome.

It is important to note that in several areas the design targets are indicative and failure to fully achieve them can be mitigated elsewhere in the design. To develop an integrated concept of the collider that allows to fully assess the consequences of such trade-offs is an important part of the studies.

The main risk for the muon collider design arises from insufficient resources to address the challenges.

3.1.1 Proton complex

The challenge of the proton complex arises from the need to combine the protons into short high-charge bunches. The proton source is site-dependent and designs for proton facilities compatible with a muon collider exist. Studies will be performed as resources allow.

3.1.2 High-power target and solenoid

A high-power target is essential to produce a sufficient number of protons to achieve the luminosity goal. Key challenges are the survival of the target itself under the shock waves of the incoming beam pulses and the temperature gradients to remove the deposited heat.

Compared to the MAP study, the power in the target is reduced by a factor three. This allows to consider the use of a solid target in addition to a liquid metal or a fluidized tungsten target. Unwanted particles produced by the proton beam impacting the target leads to heating of the surrounding superconducting solenoid and to radiation damage.

Simulations of a 4 MW mercury-based target demonstrated that a 1.2 m radius of the solenoid provides enough space to shield the magnet and to reach peak powers in the coil of less than 0.1 mW/g, which corresponds to O(1 MGy) per year. FCC-hh assumes that the magnet insulation can withstand an accumulated dose of 30 MGy [4]. This solenoid is very demanding and resembles in cost and stored energy the central solenoid of ITER.

3.1.3 Muon ionization cooling channel design

Muon ionization cooling is required to increase the muon beam brightness to yield a sufficient luminosity. Ionization cooling requires the beam to be repeatedly slowed in absorbers and reaccelerated in RF cavities, while maintaining tight focusing of the muon beam.

The large longitudinal emittance of the beam arising from the target is captured in a sequence of RF cavities as a train of bunches. The emittance is reduced by a rectilinear cooling system comprising weak dipole fields and increasingly strong solenoids. The initial part of the system is optimised for large acceptance, while the final part of the system is optimised for low emittance. When the beam emittance is sufficiently reduced, the bunch train is merged into a single bunch and then cooled further.

In order to reach the lowest emittances, very strong solenoid fields are required with lower beam energy. In this regime longitudinal emittance increases and a phase rotation system is required to minimise energy spread and control chromatic aberrations. Low frequency RF cavities or induction linacs, in regions of relatively low magnetic field, are used for reacceleration.

3.1.4 Operation of RF cavities in a magnetic field

In order to maintain the tight focusing required to yield good cooling performance in the rectilinear cooling system, a compact lattice is required with large real-estate RF gradient. This results in a lattice that has RF operating near to the break down limit while immersed in a strong solenoid field.

The operation of RF cavities in a solenoid field poses specific challenges. The solenoid field guides electrons that are emitted at one location of the cavity surface to another location on the opposing wall and leads to localised heating that can result in breakdown and cavity damage. Operation of copper cavities in 3 T magnetic field showed a maximum useable gradient of only 10 MV/m.

Three approaches to overcome this obstacle are known:

- Use of lower-Z materials such as beryllium to limit the energy loss density.
- The use of high-pressure hydrogen gas inside the cavity. In this case the mean free path of the electrons is limited and does not allow them to gain enough energy to ionise the gas or to produce a breakdown.
- The use of very short RF pulses to limit the duration of the heat load in the cavity.

The first two techniques have been experimentally verified in MUCOOL with a field of about 3 T (limited by the solenoid). They yielded a gradient of 50 MV/m in a beryllium cavity under vacuum and 65 MV/m in a molybdenum cavity with hydrogen [8], demonstrating no degradation in achievable field in the presence of an applied magnetic field.

Systematic studies in a new test stand are required to further develop the technologies. It will also be important to test the cavities in the actual field configuration of the cooling cell, which differs from a homogeneous longitudinal field.

3.1.5 Final cooling and HTS magnet technology

In the final muon cooling system, solenoids with the highest practical field are needed. A design based on 30 T solenoids—a value that has been achieved experimentally—demonstrated that an emittance about a factor two above the target can be achieved [10]; it should be noted that the study aimed at this larger target. Several options to improve the emittance will be studied. With the technology progress, solenoids with field above 40 T are being planned and would benefit the muon collider. Operating the cooling at lower beam energy also allows to reach a smaller emittance; preliminary studies indicate that 30 T may be marginally sufficient to reach the emittance target.

3.1.6 Acceleration stage design

The baseline acceleration stage consists of some linacs followed by a sequence of pulsed synchrotrons that performs the lion share of the acceleration. The synchrotrons combine static superconducting and fast-ramping magnets, which could be either normal- or superconducting. Fast-ramping magnets have been designed and models tested in the MAP study. However, an integrated study of the lattice, the accelerating RF and the fast-ramping magnet system including its powering system is essential to estimate the cost and power consumption of the system. The energy in the field of the magnets is of O(100 MJ). It needs to be recovered from each pulse to the next with high efficiency. The requirements on the quality of the ramp will drive cost and power consumption. Studies in the coming years will address this challenge.

3.1.7 Collider ring design

The collider ring requires a small beta-function at the collision point, resulting in significant chromaticity that needs to be compensated. It also needs to maintain a short bunch. A solution for 3 TeV has been developed and successfully addressed the challenges. A design of 10 TeV is one of the key ongoing efforts.

High-energy electrons and positrons arising from muon decay and striking the collider ring magnets can cause radiation damage and unwanted heat load. This can be mitigated with sufficient tungsten shielding; a successful design has been developed at 3 TeV. First studies at 10 TeV indicate that the effect is comparable to 3 TeV, since the power per unit length of the particle loss remains similar.

The shielding requires a substantial aperture in the superconducting magnets. The limit for the dipole field is thus given by the maximum stress that the conductor can withstand rather than by the maximum field that it can support. Novel concepts such as stress-managed coils will allow this challenge to be addressed.

3.1.8 Beam induced background

Muon beam decay produces a significant flux of secondary and tertiary particles in the detector in spite of the shielding masks. A detailed study of the impact of this background on the detector performance has been performed at center of mass of 1.5 TeV using two different Monte Carlo programs, Fluka and Mars15. The results agree within a factor less than 2 and demonstrate that the beam-induced background does not limit the physics potential with the current detector technologies and the proposed shielding.

A preliminary investigation of the background effects at center of mass of 3 TeV has been performed by using the Fluka simulation and the MAP Interaction region (IR) designed in 2018 for a 1.5 TeV CM. The shielding structure and the detector are kept exactly the same as used for the 1.5 TeV. This is not optimal for the 3 TeV Interaction Region. Several improvements are already being discussed. Under these conservative assumptions, the results show that the beam-induced background effects on the detector are similar to those found in the 1.5 TeV study and the characteristics are determined by the shielding structure. This gives confidence that the background can also be managed at higher energies.

The collaboration will optimize the configuration of the IR together with the shielding elements to reduce their dimensions, therefore increasing the detector acceptance in the forward region. A proper combined optimization of the system of detector, shielding and IR will enable avoidance of background hot spot points increasing the detector performance in the forward region. These activities require a very close collaboration among detector and accelerator experts, who have to work more closely than in previous facility design activities.

Experts are required in novel shielding materials that can absorb different particle species and momenta. The lessons learned in design of the 3 TeV system will serve as a starting point for the 10 TeV case. Here a change of paradigm is needed. No detector has been designed for such high energy lepton collisions. The beam-induced background and its shielding, together with a possible detector will be studied by using the tools developed for the 3 TeV case, keeping in mind the change of paradigm.

3.1.9 Neutrino flux

The decay of muons in the collider ring produces a dense flux of neutrinos that will exit from the ground at significant distance from the collider. The flux is very dense because the neutrinos have a very small angle with respect to the initial muon trajectory.

Studies are underway to reduce the density of this flux from the collider ring arcs such that it leads to a negligible impact on the environment, similar to the LHC. A solution has been proposed to place beam line components on movers and deforming the ring periodically in small steps such that the muon beam does not point to a specific location for an extended time. This solution allows to reduce the flux to

a negligible level and an order of magnitude below the goal of the MAP study, even for a 14 TeV collider placed 200 m deep underground. The study will address the mechanical aspects of the solution and its impact on the beam operation.

A dedicated effort, supported by civil engineers, beam scientists, FLUKA and radiation experts will also assess the impact of the insertions on the neutrino flux.

The impact of accidental beam loss can be mitigated by placing the tunnel sufficiently deep. In this case a lost muon beam would not be able to penetrate the Earth sufficiently to escape from the surface. The required depth is less than for the neutrino flux mitigation.

3.2 Required R&D

The MAP Collaboration initiated its study with an evaluation of the feasibility of the key sub-systems required to deliver an energy-frontier collider. Several issues were identified as part of the MAP Feasibility Assessment that had the greatest potential to prevent the realisation of a viable muon collider concept. These included:

- operation of RF cavities in high magnetic fields in the front end and cooling channel;
- development of a 6D cooling lattice design consistent with realistic magnet, absorber, and RF cavity specifications;
- a direct demonstration and measurement of the ionisation-cooling process;
- development of very-high-field solenoids to achieve the emittance goals of the Final Cooling system;
- demonstration of fast-ramping magnets to enable RCS capability for acceleration to the TeV scale.

While other machine design and engineering conceptual efforts were pursued to develop the overall definition of a muon collider facility, research in the above feasibility areas received the greatest attention as part of the MAP effort. An important outcome of MAP was that progress in each of the above areas was sufficient to suggest that there exists a viable path forward. The test program at Fermilab's MuCool test area demonstrated operation of gas-filled and vacuum pillbox cavities with up to 50 MV/m gradients in strong magnetic fields [5, 8]; a 6D cooling lattice was designed that incorporated reasonable physical assumptions [14]; a final cooling channel design, which implemented the constraint of a 30 T maximum solenoid field, came within a factor of two of meeting the transverse emittance goal for a high energy collider [10]; and while further R&D is required, fast-ramping magnet concepts [3] do exist that could deliver TeV muon beams. Since the end of the MAP studies a number of technologies have developed, which make the muon collider a promising avenue of study. In particular, new studies are required to leverage the now increased limits of solenoids and RF cavities, which theory suggests should give an improved cooling channel performance

A muon collider with a centre-of-mass energy around 3 TeV could be delivered on a time scale compatible with the end of operation of the HL-LHC. A technically limited time line is shown in Fig. 2 and discussed in greater detail here [6]. The muon collider R&D programme will consist of the initial phase followed by the conceptual and the technical design phases. The initial phase will establish the potential of the muon collider and the required R&D programme for the subsequent phases.

The performance and cost of the facility would be established in detail. A programme of test stands and prototyping of equipment would be performed over a five-year period, including a cooling cell prototype and the possibility of beam tests in a cooling demonstrator. This programme is expected to be consistent with the development of high field solenoid and dipole magnets that could be exploited for both the final stages of cooling and the collider ring development. A technical design phase would follow in the early 2030s with a continuing programme focusing on prototyping and preseries development before production for construction begins in the mid-2030s, to enable delivery of a 3 TeV collider by

Table 1: Tentative target parameters for a muon collider at different energies based on the MAP design with modifications. These values are only to give a first, rough indication. The study will develop coherent parameter sets of its own.

Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	\mathcal{L}	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	N	10^{12}	2.2	1.8	1.8
Repetition rate	f_r	Hz	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	20
Longitudinal emittance	ϵ_L	MeV m	7.5	7.5	7.5
Transverse emittance	ϵ	μm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.07
IP beta-function	β	mm	5	1.5	1.07
IP beam size	σ	μm	3	0.9	0.63

2045. The programme is flexible, in order to match the prioritisation and timescales defined by the next ESPPU, P5 and equivalent processes.

Based on the MAP design, target parameter sets have been defined for the collider as a starting point, shown in table 1 above. The parameter sets have a luminosity-to-beam-power ratio that increases with energy. They are based on using the same muon source for all energies and a limited degradation of transverse and longitudinal emittance with energy. The design of the technical components to achieve this goal are a key element of the study. It is important to emphasize that a 10 TeV lepton collider is uncharted territory and poses a number of key challenges.

- The collider can potentially produce a high neutrino flux that might lead to increased levels of radiation far from the collider. This must be mitigated and is a prime concern for the high-energy option.
- The Machine Detector Interface (MDI) might limit the physics reach due to beam-induced background, and the detector and machine need to be simultaneously optimised.
- The collider ring and the acceleration system that follows the muon cooling can limit the energy reach. These systems have not been studied for 10 TeV or higher energy. The collider ring design impacts the neutrino flux and MDI.
- The production of a high-quality muon beam is required to achieve the desired luminosity. Optimisation and improved integration are required to achieve the performance goal, while maintaining low power consumption and cost. The source performance also impacts the high-energy design.

Integrated accelerator design of the key systems is essential to evaluate the expected performance, to validate and refine the performance specifications for the components and to ensure beam stability and quality. A description of the key technology challenges and their relation to the state-of-the art can be found here [6].

3.3 Required and Desirable Demonstrators

Demonstrations are required both for the muon source and the high energy complex. The compact nature of the muon cooling system, high gradients and relatively high-field solenoids present some unique challenges that require demonstration. The high-power target also has a number of challenges that should be

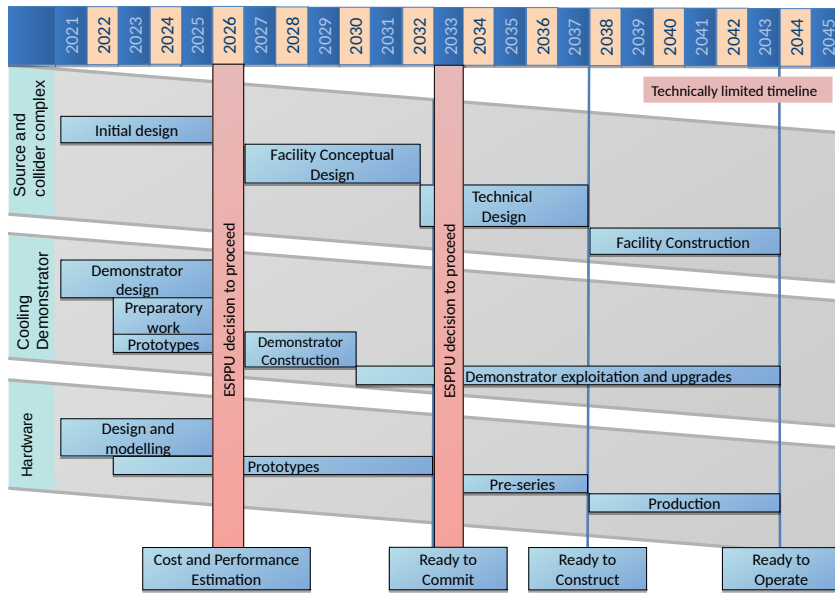


Fig. 2: A technically limited timeline for the Muon Collider R&D programme

evaluated using irradiation facilities or single impact beam tests. The issues in the high energy complex arise from the muon lifetime. Fast acceleration systems and appropriate handling of decay products result in unique challenges for the equipment. The following new facilities are required and will be developed or constructed as part of the program:

3.3.1 Ionization cooling demonstrator

MICE only demonstrated transverse cooling without re-acceleration and operated at relatively high emittance. Further tests must be performed to demonstrate the 6D cooling principle at low emittance and including re-acceleration through several cooling cells. Many of the challenges are associated with integration issues of the magnets, absorbers and RF cavities. For example, operation of normal conducting cavities near to superconducting magnets may compromise the cryogenic performance of the magnet. Installation of absorbers, particularly using liquid hydrogen, may be challenging in such compact assemblies. In order to understand and mitigate the associated risks, an offline prototype cooling system will be required. Such a system will require an assembly and testing area, with access to RF power and support services. This could be integrated with the demonstrator facility, as it will need an area for staging and offline testing of equipment prior to installation on the beamline. The possibility to perform intensity studies with a muon beam are limited. In the first instance such effects should be studied using simulation tools. If such studies reveal potential technical issues, beam studies in the presence of a high intensity source will be necessary, for example using protons.

3.3.2 Ionization Cooling RF development

The cooling systems require normal-conducting RF cavities that can operate with high gradient in strong magnetic fields without breakdown. No satisfactory theory exists to model the breakdown. Considerable effort was made by MAP to develop high-gradient RF cavities. Two test cavities have been developed: The first cavity was filled with gas at very high pressure. The second cavity used beryllium walls. Both tests presented promising results. In the meantime operation of normal-conducting RF cavities at liquid nitrogen temperature has been demonstrated to reduce multipacting. In order to test the concepts above and others further, a dedicated test facility is required. An RF source having high peak power at the

appropriate frequency and a large aperture solenoid that can house the RF cavity will be needed. No such facility exists at present.

3.3.3 Cooling magnet tests

In order to improve cooling performance high field magnets are required with opposing-polarity coils very close together. The possibility to implement high-field magnets (including those based on HTS) will be investigated, with appropriate design studies leading to the construction of high-field solenoid magnets having fields in the range 20 T to 25 T. Very high field magnets are required for the final cooling system. In this system, the ultimate transverse emittance is reached using focusing in the highest-field magnets. As a first step, a 30 T magnet, corresponding to the MAP baseline, would be designed and constructed. Feasibility studies towards a 50 T magnet would also be desirable, which may include material electro-mechanical characterization at very high field as well as technology demonstration at reduced scale. These very demanding magnets are envisaged to be developed separately to the cooling demonstrator. Eventually they could be tested in beam if it was felt to be a valuable addition to the programme. In order to support this magnet R&D, appropriate facilities will be required. Testing of conductors requires a suitable test installation, comprising high field magnets, variable temperature cryogenics and high-current power supplies. Magnet development and test will also require these facilities in addition to access to appropriate coil and magnet manufacturing capabilities.

3.3.4 Acceleration RCS magnets

Acceleration within the muon lifetime is rather demanding. The baseline calls for magnets that can cycle through several T on a time scale of a few ms. The exact specification will be defined during the design work, but it is clear that a resonant circuit is the best suited solution to power the magnets. The design of the magnet and powering system will be highly integrated, and work on scaled prototypes is anticipated. Superconducting RCS magnets may offer higher field reach than normal-conducting magnets, but are challenging to realise owing to heating arising from energy dissipation in the conductor during cycling (AC loss). This heating can lead to demands on the cryogenic systems that outweigh the benefits over normal-conducting magnets. Recent prototypes have been developed using HTS that can operate at higher temperatures, and in configurations leading to lower AC losses, yielding improved performance. In order to continue this research, magnet tests with rapid pulsed power supplies and cryogenic infrastructure will be required.

3.3.5 Effects of radiation in material

The high beam power incident on the target and its surroundings is very demanding. Practical experience from existing facilities coupled with numerical studies indicate that there will be challenges in terms of target temperature and lifetime. Instantaneous shock load on the target will also be challenging. Tests are foreseen to study behaviour of target material under beam in this instance. Tests are desirable both for instantaneous shock load and target lifetime studies. Additionally, the effect of radiation in the target region on the superconducting materials (LTS and HTS) and insulators is an important parameter. As the target solenoid design matures, additional studies may be required taking into account the magnet arrangement, conductor design and estimates of radiation levels. In order to realise such tests, facilities having both instantaneous power and integrated protons on target equivalent to the proton beam parameters assumed for this study are desirable. The database of radiation effects on superconductors (HTS) and insulators also requires an extension to cover the projected conditions in the target area.

3.3.6 Superconducting rf cavities

Development of efficient superconducting RF with large accelerating gradient is essential for the high energy complex. Initially work will focus on cavity design; however eventually a high gradient prototype

at 300-400 MHz frequency will be required. In order to realise such a device, appropriate superconducting cavity production and test facilities will be required including surface preparation techniques and a capability for high power tests.

4 Staging Options and Upgrades

At this moment no limit is known to the energy reach of the muon collider. Practical limits such as cost and power consumption as well as the luminosity reach at each energy are the key considerations for the choice of energies. Other limits might come from the impact on the site resulting from the neutrino flux or the background conditions in the experiments since they could also limit the luminosity.

We therefore consider a programme with energy stages to limit the cost and risk of each stage. Currently, there is no obvious strong benefit of reducing the luminosity at each energy stage and foresee future large upgrades. However, smaller scale improvements of the luminosity at each energy stage can be implemented as will be discussed below.

4.1 Energy Upgrades

The muon collider can be implemented as a staged concept providing a road toward higher energies. The accelerator chain can be expanded by an additional accelerator ring for each energy stage. A new collider ring is required for each energy stage. Currently, we envisage that the new accelerator ring would be a hybrid pulsed synchrotron that uses a combination of fast-ramping magnets interleaved with static superconducting magnets. Hence it may be possible to reuse the magnets and other equipment of the previous collider ring.

Currently, the focus of the study is on 10 TeV. This energy is well beyond the 3 TeV of the third and highest energy stage of CLIC, the highest energy proposal with a CDR. An potential intermediate energy of 3 TeV is envisaged at this moment. Its physics case is similar to the final stage of CLIC and it is expected that this stage would roughly cost half as much as the 10 TeV stage.

A 3 TeV stage is less demanding in several technological areas. It may not be necessary to implement a mechanical neutrino flux mitigation system in the collider ring arcs, moving the beam inside of the magnet apertures may be sufficient. The final focus magnets require an aperture and a gradient comparable to the values for HL-LHC.

In general, it will be possible to implement larger margins in the design at 3 TeV. The operational experience will then allow to accept smaller margins at 10 TeV.

The strength of its dipoles drives the collider ring size and impacts the luminosity. The cost optimum is given by the magnet and tunnel cost; it is possible that cheaper, well established magnet technology - such as NbTi at this moment - would result in a lower cost even if the tunnel has to be longer. For fixed beam current, the luminosity is proportional to the magnet field and is one aspect of the trade-off.

Once the cost scale of the muon collider concept is more precisely known and once the mitigation of the technical challenges are well defined, the energy staging will be reviewed taking into account the physics case and additional considerations from the site and reuse of existing equipment and infrastructure, such as the LHC tunnel. This will provide a sustainable road with important physics cases for its affordable stages.

4.2 Luminosity Upgrades

After the construction of each energy stage the luminosity can be increased by limited modifications using improved technologies. This includes in particular the final cooling and the final focusing systems.

The luminosity of the muon collider is driven by the beam power and brightness and the ability to take advantage of this brightness by focusing to very small sizes beam sizes in the collision point. The

beam power is closely linked to the power consumption of the collider and depends on the efficiency of the muon cooling complex, the accelerating RF systems, the fast-ramping magnet systems and the mitigation of heat load in the superconducting components of the complex induced by muon decay.

An increase in beam power by increasing the repetition rate can be considered. In addition to increased power consumption for the RF, fast-ramping magnet and cooling systems, this would also increase the power in the proton target which is expected to be an important limitation. Whether an operation of two targets by alternating the pulses between them is feasible at acceptable cost remains to be evaluated.

A larger beam brightness resulting from an increase of the bunch charge within the same emittance would also allow to increase the luminosity, even if the repetition rate would have to be reduced to remain at the same power consumption. However, this case might have to mitigate intensity bottlenecks along the collider chain.

The beam brightness depends in particular on the final muon cooling system. Further improvement of the design and the technology of this complex are mainly a technical challenge and could be implemented at relatively limited cost when the muon collider is already operating. Similarly, one can envisage that better final focus quadrupoles would allow an increase of the luminosity at a later stage with limited cost.

4.3 Experimental system Upgrades

Several instrumentation challenges need to be addressed in building detectors able to successfully deliver the physics potential of a multi-TeV muon collider. Detectors and event reconstruction techniques need to be designed to cope with the presence of the beam-induced background (BIB) produced by the muon decays and their interaction with the machine elements at the Machine Detector Interface. The available and incoming detector technologies were proved suited to be exploited in an experiment at a muon collider operating at $\sqrt{s} = 3$ TeV, while the energy regime of the decay products in the environment at $\sqrt{s} = 10$ TeV still demands for in depth dedicated studies. Operating conditions expected at $\sqrt{s} = 1.5$ TeV, simulated with highly comparable results both in MARS15 and FLUKA frameworks, for a 200 days of operation per year, result in $\sim 10^{14-15} \text{ cm}^{-2}\text{y}^{-1}$ 1-MeV-neq fluence in the region of the tracking detector and $\sim 10^{14} \text{ cm}^{-2}\text{y}^{-1}$ in the electromagnetic calorimeter, with a steeply decreasing radial dependence beyond it. The total ionizing dose is $\sim 10^{-3}$ Grad/y on the tracking system and $\sim 10^{-4}$ Grad/y on the electromagnetic calorimeter. With the FLUKA simulation at $\sqrt{s} = 3$ TeV and the preliminary results obtained with the first lattice at $\sqrt{s} = 10$ TeV there is no indication of an effective degradation of the radiation levels in the detector volume. Inner tracking has to cope with a hit density of up to 1,000 hits/cm², with a the density decreasing rapidly as a function of the radial distance from the beam-line. In the expected operating conditions, high performance tracking is necessary to achieve good efficiency and resolution for reconstructing charged leptons, jets, energy sums, displaced vertices originating from the heavy flavor jets, as well as potential new phenomena. Promising tracking technologies rely on the high granularity of silicon pixels, necessary to reduce hit occupancy level of a few %. Moreover excellent timing resolution in the tracking detector and the calorimeter systems would allow a more efficient background rejection on detector and at filtering level. New dedicated muon spectrometers, trigger systems and data acquisition are under study.

It should be mentioned that development of these technologies is beneficial for other future collider options, in particular high energy hadron machines.

5 Synergies with other concepts and/or existing facilities

The ambitious programme of R&D necessary to deliver the muon collider has the potential to enhance the science that can be done at other muon-beam facilities. On the contrary, the progresses in other accelerator facilities will also benefit the design and construction of the muon collider in the future.

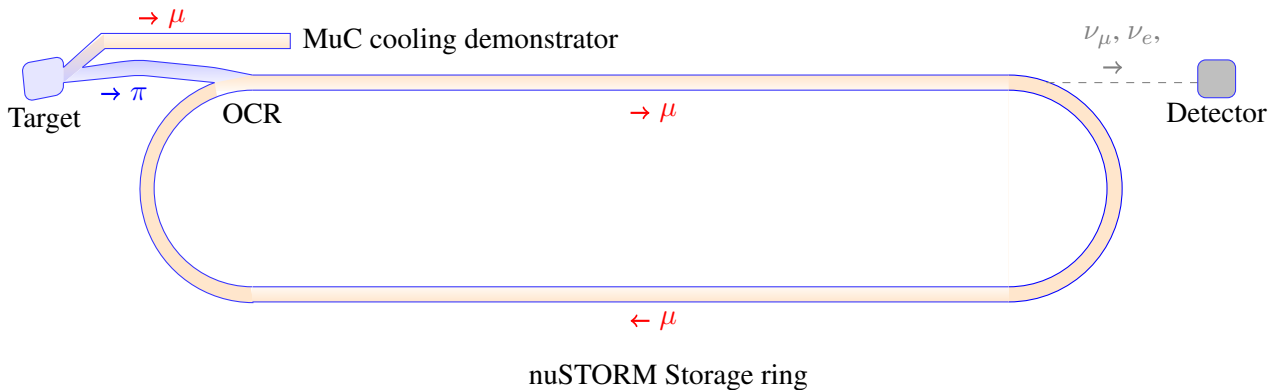


Fig. 3: Schematic showing nuSTORM including the muon cooling demonstrator for the muon collider.

nuSTORM and ENUBET offer world-leading precision in the measurement of neutrino cross sections and exquisite sensitivity to sterile neutrinos and physics beyond the Standard Model. nuSTORM in particular will require capture and storage of a high-power pion and muon beam and management of the resultant radiation near to superconducting magnets. The target and capture system for nuSTORM and ENUBET may also provide a testing ground for the technologies required at the muon collider and as a possible source of beams for the essential 6D cooling-demonstration experiment, for example as in the schematic shown in fig. 3. The ongoing LBNF and T2HK projects and their future upgrades will develop graphite targets to sustain the bombardment of MW-level proton beams, which may also lead to a solution for the muon production target for the muon collider. The next generation searches for charged lepton flavour violation exploit high-power proton beams impinging on a solid target placed within a high-field solenoid, such as Mu2e at FNAL and COMET at J-PARC. The technological issues of target and muon capture for these experiments are similar to those present in the muon collider design. The potential to deliver high quality muon beams could enhance the capabilities of muon sources such as those at PSI, J-PARC and ISIS. The use of frictional cooling to deliver ultra-cold positive and negative muon beams is under study at PSI and may be applicable to the muon collider. FFAs have been proposed as a route to attain high proton beam power for secondary particle sources such as neutron spallation sources, owing to the potential for high repetition rate and lower wall plug power compared to other accelerator schemes. The technology related to FFA will be beneficial to choose the fast acceleration scheme of the lower-energy acceleration stages of the muon collider. High-power proton accelerators are in fast development use throughout the world, including linacs, rapid cycling synchrotrons, and accumulator or compressor rings, for example, proton drivers ranging from hundreds of kW to multiple MW for spallation neutron sources such as SNS, J-PARC, ESS, ISIS and CSNS, those in about 1 MW for neutrino beams such as FNAL and J-PARC proton accelerator complexes, and those in multiple MW and CW mode for accelerator-driven systems such as CiADS and MYRRHA. The progresses made in the facilities will accumulate the required accelerator technologies for the muon collider. The underlying technologies required for the muon collider are also of interest in many scientific fields. The delivery of high field solenoid magnets is of great interest to fields as wide ranging as particle physics, accelerator science and imaging technology. Operation of RF cavities with high gradient is of interest to the accelerator community.

6 Conclusion

The muon collider presents enormous potential for fundamental physics research at the energy frontier. Previous studies, in particular the MAP study, have demonstrated feasibility of many critical components of the facility. A number of proof-of-principle experiments and component tests, such as MICE,

EMMA and the MuCool RF programme, have been carried out to practically demonstrate the underlying technologies.

The muon collider is based on novel concepts and is not as mature as the other high-energy lepton collider options, in particular also compared to the highest energy option CLIC. However, it promises a unique opportunity to deliver physics reach at the energy frontier on a cost, power consumption and time scale that might improve significantly on other energy-frontier colliders. At this stage, building on significant prior work, it was not identified any showstopper in the concept. Therefore a development path can address the major challenges and deliver a 3 TeV muon collider by 2045.

A global effort has identified the R&D effort that it considers essential to address these challenges before the next regional strategy processes to a level that allows estimation of the performance, cost and power consumption with adequate certainty. Execution of this R&D is required in order to maintain the timescale described in this document. Ongoing developments in underlying technologies will be exploited as they arise in order to ensure the best possible performance. This R&D effort will allow future strategy processes to make fully informed recommendations. Based on the subsequent decisions, a significant ramp-up of resources could be made to accomplish construction by 2045 and exploit the enormous potential of the muon collider.

Bright muon beams are also the basis of neutrino physics facilities such as NuSTORM and ENUBET. These could potentially share an important part of the complex with a muon cooling demonstrator.

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