THE US MUON ACCELERATOR PROGRAM*

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Abstract

An accelerator complex that can produce ultra-intense beams of muons presents many opportunities to explore new physics. A facility of this type is unique in that, in a relatively straightforward way, it can present a physics program that can be staged and thus move forward incrementally, addressing exciting new physics at each step. At the request of the US Department of Energy's Office of High Energy Physics, the Neutrino Factory and Muon Collider Collaboration (NFMCC) and the Fermilab Muon Collider Task Force (MCTF) have recently submitted a proposal to create a Muon Accelerator Program that will have, as a primary goal, to deliver a Design Feasibility Study for an energy-frontier Muon Collider by the end of a 7 year R&D program. This paper presents a description of a Muon Collider facility and gives an overview of the proposal.

INTRODUCTION

Understanding the mechanism behind mass generation and electroweak symmetry breaking, searching for, and perhaps discovering, supersymmetric particles and hunting for signs of extra space-time dimensions and quantum gravity, constitute some of the major physics goals of an energy-frontier lepton collider. In addition, experiments that can make very-high precision measurements of standard model processes open windows on physics at energy scales far beyond any foreseeable direct reach. The Muon Collider provides a possible realization of a multi-TeV lepton collider. A muon accelerator facility also presents the unique opportunity to explore new physics within a number of distinct programs that can be brought online as the facility evolves.

A schematic that shows the possible evolution of a muon accelerator complex which ultimately reaches a multi-TeV Muon Collider is given in Fig. 1[1]. The front-end of the facility provides an intense muon source that can perhaps support both a Neutrino Factory and an energy-frontier Muon Collider. The muon source is designed to deliver $O(10^{21})$ low energy muons per year within the acceptance of the accelerator system, and consists of (i) a multi-MW proton source delivering a multi-GeV proton beam onto a liquid Mercury-jet pion production target, (ii) a high-field target solenoid that radially confines the secondary charged pions, (iii) a long solenoidal channel in which the pions decay to produce positive and negative muons, (iv) a system of RF cavities in a solenoidal channel that capture the muons in bunches and reduce their energy spread (phase rotation), and (v) a muon ionization cooling channel that reduces the transverse phase space occupied by the beam by a factor of a few in each transverse direction. At this point the beam could be used for low-energy muon experiments and also will fit within the acceptance of an accelerator system for a Neutrino Factory. However to obtain sufficient luminosity, a Muon Collider requires a great deal more muon cooling. In particular, the 6D phase-space must be reduced by $O(10^6)$, which requires a longer and more complex cooling channel. Finally after the cooling channel, the muons are accelerated to the desired energy and injected into decay rings for the Neutrino Factory or into a storage ring for the Muon Collider. In a Neutrino Factory, the ring has long straight sections in which the neutrino beam is produced by the decaying muons. In a Muon Collider, positive and negative muons are injected in opposite directions and collide for about 1000 turns before the luminosity becomes degraded due to the muon decays.

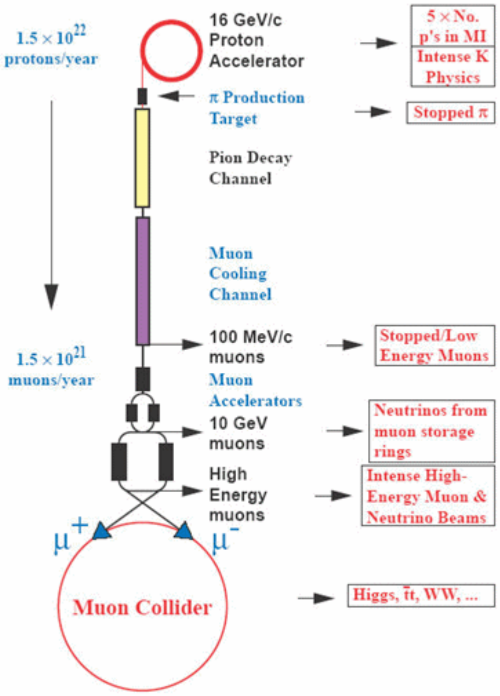

Figure 1: Schematic of Muon Accelerator complex

PRESENT STATUS

The two collaborations (NFMCC and MCTF) that are joining to form the Muon Accelerator Program, have well

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over a decade's worth of R&D to draw upon as a foundation.

Component Development and Proof-of-Principle Experiments

The NFMCC has pursued component development and proof-of-principle experiments that inform the design studies and establish the viability of the proposed accelerator subsystems. Two systems were identified and given the highest priority for R&D:

1. a target that can be operated within a high field solenoid with a 4 MW primary proton beam, and
2. an ionization cooling channel in which rf cavities operate along with energy absorbers within a lattice of multi-Tesla solenoids

The proof-of-principle MERcury Intense Target (MERIT) experiment [2], designed and constructed by the NFMCC with its international partners, ran successfully at CERN at the end of 2007. MERIT has established the viability of using a liquid-mercury jet injected into a high field solenoid with a 4 MW proton beam suitable for a NF and/or MC. The Muon Ionization Cooling Experiment (MICE) [3] is an international multiphase proof-of-principle experiment that is hosted by RAL. The MICE muon beam line is currently being commissioned, and the remaining components have been designed and are under construction, with the NFMCC contributing major pieces of the test channel and instrumentation. MICE is expected to be completed in 2013.

Complementing the MICE cooling channel demonstration, the MuCool program has been developing and testing cooling channel components. In particular, a good understanding of the performance of rf cavities operating within multi-Tesla solenoidal fields is critical if we are to have confidence in the design of muon ionization cooling channels. MuCool measurements [4] have shown that normal conducting rf (NCRF) copper vacuum cavities break down at lower gradients in multi-Tesla magnetic fields. The measurements also indicate that surface preparation is important, and that, although not yet tested with beam, the breakdown effect may be mitigated by using high-pressure gas within the cavity [5]. In addition, new ideas for "magnetically insulated" cavities and for using advanced surface treatments (i.e., atomic layer deposition, ALD) [4] are promising.

The International Design Study for a Neutrino Factory (IDS-NF)

One of the primary deliverables for MAP is US participation in the International Design Study for the Neutrino Factory [6] with the goal of producing a Reference Design Report for the facility in the time frame of 2013. The Neutrino Factory design studies that have prepared the way for this RDR include (i) Feasibility Study 1 [7,8], which was hosted by FNAL in 1999 and resulted in an end-to end design and simulation for a NF together with a first cost estimate, (ii) Feasibility Study 2 [9], which was hosted by BNL in 2001 and resulted in an improved design that increased the performance of the NF to meet the requirements established by the earlier physics study [10], (iii) Feasibility Study 2a [11, 12], which, based on work in the period 2002–2005, updated the Study 2 design to improve its cost effectiveness, reducing the estimated cost by about one-third while maintaining performance, (iv) the International Scoping Study (ISS) [13,14,15], which was an international NF study hosted by RAL in 2006 that established a baseline design (similar to the Study 2a design). Following the internationalization of NF R&D and the successful outcome of the ISS, the International Design Study for the Neutrino Factory is now under way and has a tremendous body of work to draw upon.

Muon Collider Design Feasibility Study (DFS)

Over the past 6 years, MCTF and NFMCC researchers have made great progress in the design and simulation of a multi-TeV MC: (i) detailed modeling and particle tracking have been initiated for the three most promising ionization cooling channel approaches—the Helical Cooling Channel (HCC), the "Guggenheim" channel, and the "FOFO Snake" channel composed of tilted superconducting solenoids, (ii) a novel Interaction Region (IR) optics scheme has been proposed that allows significantly larger energy spread in the colliding beams than previously considered and (iii) muon beam dynamics in ILC-type 1.3 GHz superconducting rf cavities have been numerically studied.

This work positions the MAP collaboration to effectively enter a directed R&D program whose goal will be to deliver the Muon Collider DFS. The DFS will include a physics and detector study (to be funded separately) and an effort focussed on the accelerator facility design and simulation. The latter work will: (i) Develop an end-to-end design for a multi-TeV MC based on demonstrated technologies and/or technologies that can be demonstrated after a specified R&D program, (ii) By means of end-to-end simulations, demonstrate that the design will meet the required machine performance parameters. The subsystems simulated will be based on sufficient engineering input to ensure that the assumed design includes a reasonable level of realism (i.e., realistic gradients, magnetic fields, alignment tolerances, safety windows, spatial constraints, etc.) and (iii) Document the baseline machine design, including required technologies, description of subsystems, performance estimate, and fabrication and installation approaches (sufficient for initial costing purposes).

US ROADMAP TO THE FUTURE

A proposal [16] that presented a R&D program aimed at completing a Design Feasibility Study (DFS) for a Muon Collider and, with international participation, a Reference Design Report (RDR) for a muon-based Neutrino Factory has been submitted to the US Department of Energy as a joint proposal from the US Neutrino Factory and Muon Collider Collaboration and the Fermilab Muon Collider Task Force. The goal of the R&D program is to provide the HEP community with detailed information on future facilities based on intense beams of muons and give clear answers to the questions of the expected capabilities and performance of these muon-based facilities, while providing defensible estimates for their cost. This information, together with the physics insights gained from the next-generation neutrino and the LHC experiments, will allow the HEP community to make well-informed decisions regarding the optimal choice of new facilities.

Muon Ionization Cooling

With regard to muon ionization cooling (or more generally speaking, the Front-End of the facility), the R&D plan will embark on both design and simulation and hardware efforts. The design and simulation work will study and optimize: 1. Pion capture and decay, bunching and phase rotation, 2. Precooling and 3. 6D cooling and final cooling. A full end-to-end simulation of muon production and cooling (through final cooling) with all interfaces between cooling sections will be a major component of the effort. The hardware effort on cooling has 3 main objectives: 1. Establish the operational viability and engineering foundation for the concepts and components incorporated into the Muon Collider Design Feasibility Study and the Neutrino Factory Reference Design Report, 2. Establish the engineering performance parameters of these components and 3. Provide the basis for a defendable cost estimate. The most critical technical challenge for the Muon Collider is the demonstration of a viable cooling scenario. To this end, the R&D proposal will support the MICE experiment through all its phases and will strive to develop a single scheme for 6D cooling that is backed by rigorous component testing for this chosen scheme. We anticipate critical results from the RF tests in the first two years of the program, at which time, we will proceed with building a short cooling section for one cooling scheme. Fig. 5 presents what we believe will be the Muon Collider Technical Foundation after the 7 Year program is completed.

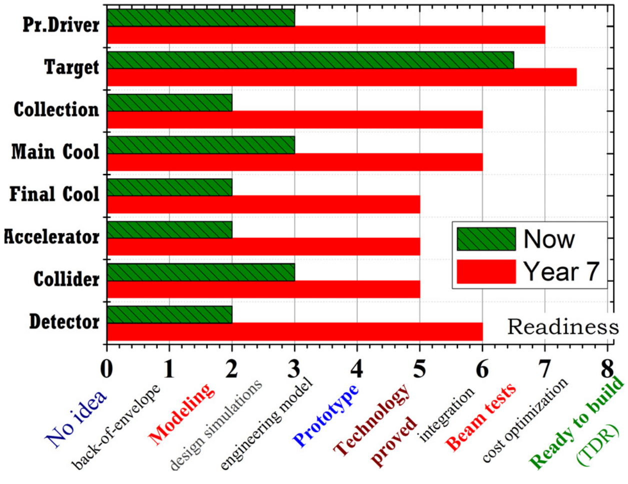

Figure 1: MC Technical Foundation after 7 years.

SUMMARY

A Muon Collider presents a potentially viable approach to a multi-TeV Lepton Collider. We believe that the R&D pursued in the Muon Accelerator Program will address the most critical unanswered questions regarding the feasibility of the underlying technologies needed for this facility and, with the delivery of the DFS for the machine, will greatly impact the HEP community's deliberations regarding new Energy-Frontier machines.

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