

# High field – low energy muon ionization cooling channel

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Muon beams are generated with large transverse and longitudinal emittances. In order to achieve the low emittances required by a muon collider, within the short lifetime of the muons, ionization cooling is required. Cooling schemes have been developed to reduce the muon beam 6D emittances to  $\approx 300 \mu\text{m-rad}$  in transverse and  $\approx 1\text{--}1.5 \text{ mm}$  in longitudinal dimensions. The transverse emittance has to be further reduced to  $\approx 50\text{--}25 \mu\text{m-rad}$  with an upper limit on the longitudinal emittance of  $\approx 76 \text{ mm}$  in order to meet the high-energy muon collider luminosity requirements. Earlier studies of the transverse cooling of low energy muon beams in high field magnets showed a promising performance, but did not include transverse or longitudinal matching between the stages. In this study we present the first complete design of the high field-low energy ionization cooling channel with transverse and longitudinal matching. The channel design was based on strong focusing solenoids with fields of 25–30 T and low momentum muon beam starting at 135 MeV/c and gradually decreasing. The cooling channel design presented here is the first to reach  $\approx 50$  micron scale emittance beams. We present the channel's optimized design parameters including the focusing solenoid fields, absorber parameters and the transverse and longitudinal matching.

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## I. INTRODUCTION

The muon collider offers significant advantages over an electron machine as a lepton collider. Muons, with a mass 200 times heavier than electrons, have an increased cross-section for Higgs production, by  $\approx$  four orders of magnitudes [1]. More importantly, a muon collider does not suffer from some of the difficulties associated with high energy electrons, e.g., synchrotron radiation and beamstrahlung. This allows us to use multistage accelerators with much lower cost and size.

However, producing and accelerating high intensity muon beams is a challenging task. Muon beams are produced from pion beam decay. Pions are generated by the collision of multi-GeV proton beams with a target. The resulting pion beam has large transverse and longitudinal emittances, which require reduction in all six phase-space dimensions to fit within the longitudinal and transverse acceptances of the muon accelerator. In addition to these challenges, muons have a very small lifetime of  $2.2 \mu\text{s}$ , which requires fast and aggressive cooling and acceleration.

Muon colliders were first proposed by Budker in 1969, and later more detailed design concepts were proposed in [2–4]. Muon accelerators must deliver high luminosity

muon beams with transverse emittances less than  $50 \mu\text{m-rad}$  for high-energy muon collider rings. Reduction of the initial large 6D transverse emittance of muon beam is achievable only by ionization cooling, where muon momenta are reduced in all directions as they pass through the absorber material. Absorbers are followed by sets of rf cavities which restore only the longitudinal component of the momentum. This process cools only the transverse emittance directly, but when combined with emittance exchange it also reduces longitudinal emittance, providing 6D phase space cooling of the muon beam.

A complete design concept of a high intensity muon collider from production to collision was given in [5]. The design has five major components; the high power target for pion production [6], the rf bunching, the 6D cooling, the fast acceleration, and finally the injection into the collider ring. The muon collider design starts with the muon front end, consisting of the pion production target and the bunching channel [6–9] that yields bunch trains of both muon signs.

The muon front end is followed by the 6D cooling lattices which reduce the longitudinal emittance until it becomes possible to merge the trains into single bunches, one of each sign. Further cooling in all dimensions is applied to the single bunches in the following 6D cooling lattices.

A complete scheme of muon cooling for a muon collider was presented in [5]. In this scheme muons of both signs are cooled transversely in a linear channel using LiH absorbers in a periodic 2.8 T solenoid lattice with rf cavities for acceleration. This is followed by a 6-D cooling

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## **Table of Contents Low Energy Muon Ionization Cooling Channel Fermilab**

1. Understanding the eBook Low Energy Muon Ionization Cooling Channel Fermilab
  - The Rise of Digital Reading Low Energy Muon Ionization Cooling Channel Fermilab
  - Advantages of eBooks Over Traditional Books
2. Identifying Low Energy Muon Ionization Cooling Channel Fermilab
  - Exploring Different Genres
  - Considering Fiction vs. Non-Fiction
  - Determining Your Reading Goals
3. Choosing the Right eBook Platform
  - Popular eBook Platforms
  - Features to Look for in an Low Energy Muon Ionization Cooling Channel Fermilab
  - User-Friendly Interface
4. Exploring eBook Recommendations from Low Energy Muon Ionization Cooling Channel Fermilab
  - Personalized Recommendations
  - Low Energy Muon Ionization Cooling Channel Fermilab User Reviews and Ratings
  - Low Energy Muon Ionization Cooling Channel Fermilab and Bestseller Lists
5. Accessing Low Energy Muon Ionization Cooling Channel Fermilab Free and Paid eBooks
  - Low Energy Muon Ionization Cooling Channel Fermilab Public Domain eBooks
  - Low Energy Muon Ionization Cooling Channel Fermilab eBook Subscription Services

- Low Energy Muon Ionization Cooling Channel Fermilab Budget-Friendly Options
- 6. Navigating Low Energy Muon Ionization Cooling Channel Fermilab eBook Formats
  - ePub, PDF, MOBI, and More
  - Low Energy Muon Ionization Cooling Channel Fermilab Compatibility with Devices
  - Low Energy Muon Ionization Cooling Channel Fermilab Enhanced eBook Features
- 7. Enhancing Your Reading Experience
  - Adjustable Fonts and Text Sizes of Low Energy Muon Ionization Cooling Channel Fermilab
  - Highlighting and Note-Taking Low Energy Muon Ionization Cooling Channel Fermilab
  - Interactive Elements Low Energy Muon Ionization Cooling Channel Fermilab
- 8. Staying Engaged with Low Energy Muon Ionization Cooling Channel Fermilab
  - Joining Online Reading Communities
  - Participating in Virtual Book Clubs
  - Following Authors and Publishers Low Energy Muon Ionization Cooling Channel Fermilab
- 9. Balancing eBooks and Physical Books Low Energy Muon Ionization Cooling Channel Fermilab
  - Benefits of a Digital Library
  - Creating a Diverse Reading Collection Low Energy Muon Ionization Cooling Channel Fermilab
- 10. Overcoming Reading Challenges
  - Dealing with Digital Eye Strain
  - Minimizing Distractions
  - Managing Screen Time
- 11. Cultivating a Reading Routine Low Energy Muon Ionization Cooling Channel Fermilab
  - Setting Reading Goals Low Energy Muon Ionization Cooling Channel Fermilab
  - Carving Out Dedicated Reading Time
- 12. Sourcing Reliable Information of Low Energy Muon Ionization Cooling Channel Fermilab
  - Fact-Checking eBook Content of Low Energy Muon Ionization Cooling Channel Fermilab
  - Distinguishing Credible Sources
- 13. Promoting Lifelong Learning
  - Utilizing eBooks for Skill Development
  - Exploring Educational eBooks
- 14. Embracing eBook Trends

- Integration of Multimedia Elements
- Interactive and Gamified eBooks

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