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**Ionization Cooling Research and Development Program for a High  
Luminosity Muon Collider**

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## Ionization Cooling Research and Development Program for a High Luminosity Muon Collider

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### Abstract

High luminosity muon colliders will require the development of a muon cooling channel that can compress by a factor of  $10^5 - 10^6$  the diffuse phase space occupied by muons from a pion decay channel. A research and development program to develop the hardware needed for muon ionization cooling is described.

A significant effort is currently being devoted to exploring the feasibility of designing and constructing a high-luminosity muon collider [1, 2, 3]. Of the many technical challenges that have been identified, perhaps the most critical is that of understanding how to produce sufficiently intense beams of positive and negative muons. To accomplish this a new beam cooling technique must be developed. The technique that has been proposed [4] involves passing the beam through an absorber in which the muons lose transverse- and longitudinal-momentum by ionization loss ( $dE/dx$ ). The longitudinal momentum is then restored by re-acceleration, leaving a net loss of transverse momentum (transverse cooling). The process is repeated many times to achieve a large cooling factor. This cooling technique is called ionization cooling. The beam energy spread can be reduced by introducing a transverse variation in the absorber density or thickness (a wedge) at a location where there is dispersion (the transverse position is energy dependent). Theoretical studies have shown that [2], with “realistic” parameters for the cooling hardware, ionization

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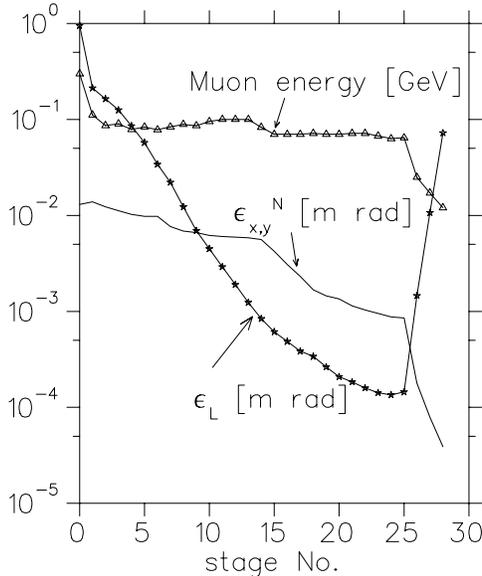


Figure 1: Calculated transverse emittance ( $\epsilon_{x,y}$ ), longitudinal emittance ( $\epsilon_L$ ), and beam energy shown as a function of stage number for the 750 m long cooling channel.

cooling can be expected to reduce the phase-space volume of the initial muon beam by a factor of  $10^5 - 10^6$  (Fig.1). Ionization cooling is a new technique that has not been demonstrated. Specialized hardware must be developed to perform transverse and longitudinal cooling. It is recognized that understanding the feasibility of constructing an ionization cooling channel that can cool the initial muon beams by factors of  $10^5 - 10^6$  is on the critical path to understanding the overall feasibility of the muon collider concept.

An R&D program has been proposed [5] to design and prototype critical sections of the muon ionization cooling channel. These sections would be tested by measuring their performance when exposed to single incoming muons with momenta in the range 100 – 300 MeV/c. The phase-space volume occupied by the population of muons upstream and downstream of the cooling sections would be measured sufficiently well to enable cooling to be demonstrated, the calculations used to design the cooling system to be tested, and optimization of the cooling hardware to be studied. The goal of this R&D is to develop the muon ionization cooling hardware to the point where a complete ionization cooling channel can be confidently designed for the First Muon Collider.

Initial design studies have shown that a cooling channel might consist of 20 – 30 cooling

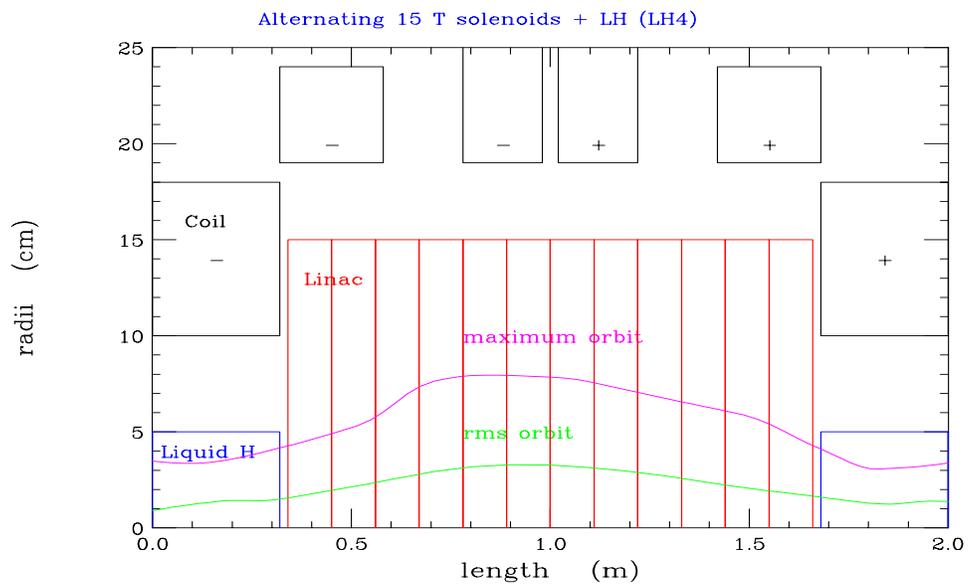


Figure 2: Schematic of a 2 m section (one period) of the alternating solenoid transverse cooling lattice described in the text.

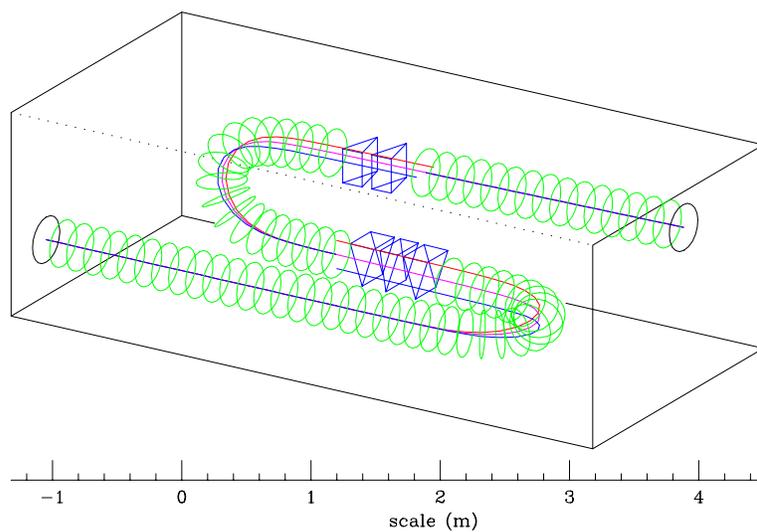


Figure 3: Schematic of the bent solenoid longitudinal emittance exchange section.

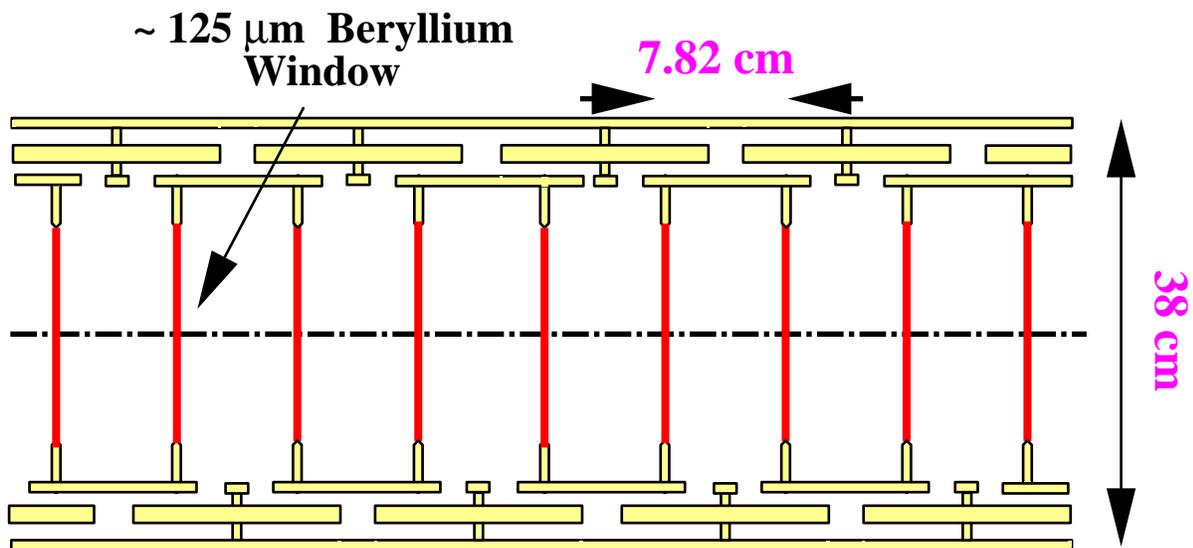


Figure 4: Interleaved  $\pi/2$  accelerating structure.

stages, each stage yielding about a factor of two in phase-space reduction (Fig. 1). The early cooling stages focus the beam using a lattice consisting of solenoids with alternating field directions. Liquid hydrogen absorbers are placed within the solenoids, and RF cavities are placed in matching sections in which the field direction is flipped between the high-field solenoids (Fig. 2). To minimize the final transverse emittances that can be achieved, the later cooling sections require the strongest radial focusing that can be achieved. The last few cooling stages therefore use either very high-field (30 T) alternating solenoids, and/or current carrying lithium lenses. The dispersion required for the wedge cooling stages can be obtained using bent solenoids (Fig. 3), which produce a momentum dependent “curvature drift” orthogonal to the bend plane. The alternating solenoid, wedge, and the lithium lens components will require R&D before a cooling channel can be fully designed. The required alternating solenoid, wedge, and lithium lens R&D consists of:

- Developing an appropriate RF structure (Fig. 4). To reduce the peak power requirements the RF cells would be operated at liquid nitrogen temperatures. To maximize the accelerating field on axis the aperture that would be open in a conventional RF cell will be closed by a thin beryllium window.
- Prototyping a 10 m section of an alternating solenoid transverse cooling stage and measuring its performance in a muon beam. A 2 m sub-section is shown in Fig. 2.

- Prototyping a wedge cooling section and measuring its performance in a muon beam.
- Developing  $\sim 1$  m long liquid lithium lenses [6]. Note that the muon collider repetition rate of 15 Hz would result in a thermal load that would melt a solid lithium rod. Long lenses are required to minimize the number of transitions between lenses.
- Developing lenses with the highest achievable surface fields, and hence the maximum radial focusing, to enable the minimum final emittances to be achieved.
- Prototyping a lens–RF–lens system and measuring its performance in a muon beam.
- Developing, prototyping, and testing a hybrid lithium lens/wedge cooling system.

The measurements that are needed to demonstrate the cooling capability and optimize the design of the alternating solenoid, wedge, and lithium lens cooling stages will require the construction and operation of an ionization cooling test facility, which will need (i) a muon beam with a central momentum that can be chosen in the range 100 – 300 MeV/c, (ii) an experimental area that can accommodate a cooling and instrumentation setup of initially  $\sim 30$  m in length, and (iii) instrumentation to precisely measure the positions of the incoming and outgoing particles in six-dimensional phase-space and confirm they are muons. In an initial design, the instrumentation consists of measuring systems before and after the cooling apparatus, each having (a) an upstream time measuring device to determine the muon arrival times to 1/4 of an RF cycle ( $\sim \pm 300$  ps), (b) an upstream momentum spectrometer in which track trajectories are measured by TPC's on either side of a bent solenoid, (c) an RF cavity to change the particles momentum by an amount that depends on its arrival time, (d) a downstream momentum spectrometer, which is identical to the upstream spectrometer, and together with the RF cavity and upstream spectrometer forms a precise time measurement system with a precision of 8 ps. The measuring systems are 8 m long, and are contained within a high-field solenoidal channel.

The proposed R&D can be accomplished in about 6 years. At the end of this period we believe it will be possible to assess the feasibility and cost of constructing an ionization cooling channel for the First Muon Collider, and begin a detailed design of the complete cooling channel.

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