DRAFT PROPOSAL

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

The MUCOOL Collaboration

August 5, 1997

Abstract

This proposal describes a six-year research and development program to develop the hardware needed for ionization cooling, and demonstrate the feasibility of using the ionization cooling technique to produce cooled beams of positive and negative muons for a muon collider. We propose 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.

Contents

1 Executive Summary

A significant effort is currently being devoted to exploring the feasibility of designing and constructing a high-luminosity muon collider. 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 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 coherent reacceleration, 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 also be reduced using ionization cooling by introducing a transverse variation in the absorber density or thickness (e.g. a wedge) at a location where there is dispersion (the transverse position is energy dependent). Theoretical studies have shown that, assuming realistic parameters for the cooling hardware, ionization cooling can be expected to reduce the phase-space volume occupied by the initial muon beam by a factor of $10^5 - 10^6$.

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.

We propose 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. Our goal 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 complete cooling channel might consist of 20 – 30 cooling stages, each stage yielding about a factor of two in phase-space reduction.

The early cooling stages focus the beam using a FOFO lattice, which consists of solenoids with alternating field directions, and lithium hydride absorbers placed in spaces between the solenoids. To minimize the final transverse emittances that can be achieved, the later cooling sections require stronger focussing than can be provided by the solenoids. The last few cooling stages therefore consist of current carrying lithium rods. Both the FOFO and the lithium rod sections will require R&D before a cooling channel can be fully designed. The required FOFO R&D consists of:

- Developing an appropriate rf reacceleration structure. Both travelling wave and standing wave structures are being considered. To reduce the power requirements (by a factor of 2) the rf cells would be operated at liquid nitrogen temperatures, and 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. The rf structure must therefore be prototyped and tested at liquid nitrogen temperatures before a complete cooling stage can be developed.

- Prototyping complete transverse and longitudinal (wedge) cooling stages and measuring their performance in a muon beam of the appropriate momentum.

The required lithium lens R&D consists of:

- Developing 1 m long liquid lithium lenses. 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 focussing, to enable the minimum final emittances to be achieved.

- Prototyping a lens–rf–lens system and measuring its performance in a muon beam of the appropriate momentum.

- Developing, prototyping, and testing a longitudinal cooling system.

The measurements that are needed to demonstrate the cooling capability and optimize the design of the FOFO and lithium lens cooling stages will require the construction and operation of an ionization cooling test facility. This facility will need a muon beam with a central momentum that can be chosen in the range 100 – 300 MeV/c, an experimental area that can accommodate a cooling and instrumentation setup of up to 50 m in length, and instrumentation to precisely measure the positions of the incoming and outgoing particles in six-dimensional phase-space and confirm that they are muons. In an initial design, the instrumentation consists of identical measuring systems before and after the cooling apparatus. Each measuring system consists of (a) an upstream time measuring device to determine the arrival time of the particles to one quarter of an rf cycle ($\sim \pm 300$ ps), (b) an upstream momentum spectrometer in which the track trajectories are measured by low pressure TPC's on either side of a bent solenoid, (c) an accelerating 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 the upstream spectrometer forms a precise time measurement system with a precision of a few ps. The measuring systems are 8 m long, and are contained within a 1.5 T solenoidal channel to keep the beam particles within the acceptance of the cooling apparatus.

The R&D program described in this document can be accomplished in a period of about 6 years. At the end of this period we believe that 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. The cost of the proposed R&D program is estimated to be 32 M$ for the FOFO and lithium lens development, and the instrumentation required for the measurements. At this stage, we have not assessed the cost of the beamline or experimental hall.

2 Introduction

A significant effort is currently being devoted to exploring the feasibility of designing and constructing a high-luminosity muon collider [1]. Of the many technical challenges that have been identified, perhaps the most critical is that of understanding how to produce very intense beams of positive and negative muons. This requires maximizing the total number of muons in the colliding beams, while minimizing the phase-space volume they occupy. Unfortunately the muons, which are produced by charged pions decaying within a high-field solenoidal channel, must be collected from a very diffuse phase-space. Indeed, to maximize the total number of muons available for the collider, they must necessarily be collected from as large a phase-space volume as is practical. Hence, before the muons can be accelerated to high energies, the initial phase-space occupied by the muon "beams" must be compressed. To be explicit, to achieve sufficiently intense muon beams for a high luminosity muon collider the phase-space volume must be reduced by about a factor of 10^5 –10^6. In particular, a reduction of the normalized horizontal and vertical emittances by two orders of magnitude (from 1×10^{-2} m-rad) is required, together with a reduction of the longitudinal emittance by one to two orders of magnitude.

The technical challenge is to design a system that can reduce the initial muon phase-space by a factor of 10^5 –10^6 on a timescale that is short or comparable to the muon lifetime ($\tau_\mu = 2\mu$s). This time-scale is much shorter than the cooling times that can be achieved using stochastic cooling or electron cooling. Therefore a new cooling technique is needed. The cooling technique that has been proposed for the muon collider is ionization cooling [2]. The feasibility of constructing a muon ionization cooling channel that can achieve the phase-space compression required for a high luminosity muon collider is considered to be one of the most critical items for determining the overall feasibility of the muon collider concept [3].

This proposal describes a six-year research and development program to demonstrate the feasibility of using the ionization cooling technique to produce cool beams of positive and negative muons for a muon collider. We propose 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. Our goal 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.

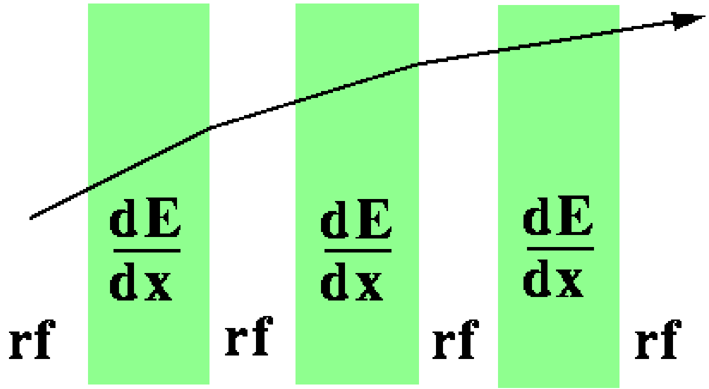

Figure 1: Conceptual schematic of ionization cooling of the transverse phase-space occupied by a muon beam.

3 Ionization Cooling

Ionization cooling is conceptually simple and is described in Section 3.1. An ionization cooling channel is described in Section 3.2.

3.1 Ionization Cooling Concept

Fig. 1 shows a conceptual schematic of ionization cooling. The beam is passed through some material in which the muons lose both transverse- and longitudinal-momentum by ionization loss (dE/dx). The longitudinal muon momentum is then restored by coherent reacceleration, leaving a net loss of transverse momentum (transverse cooling). The process is repeated many times to achieve a large cooling factor.

The equation describing transverse cooling (with energies in GeV) is:

$$\frac{d\epsilon_n}{ds} = -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\epsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp (0.014)^2}{2\ E_\mu m_\mu\ L_R}, \tag{1}$$

where $\beta = \mathrm{v/c}$, ϵ_n is the normalized emittance, $\beta_\perp$ is the betatron function at the absorber, dE_μ/ds is the energy loss, and L_R is the radiation length of the material. The first term in this equation is the cooling term, and the second is the heating term due to multiple scattering. This heating term is minimized if $\beta_\perp$ is small (strong-focusing) and L_R is large (a low-Z absorber).

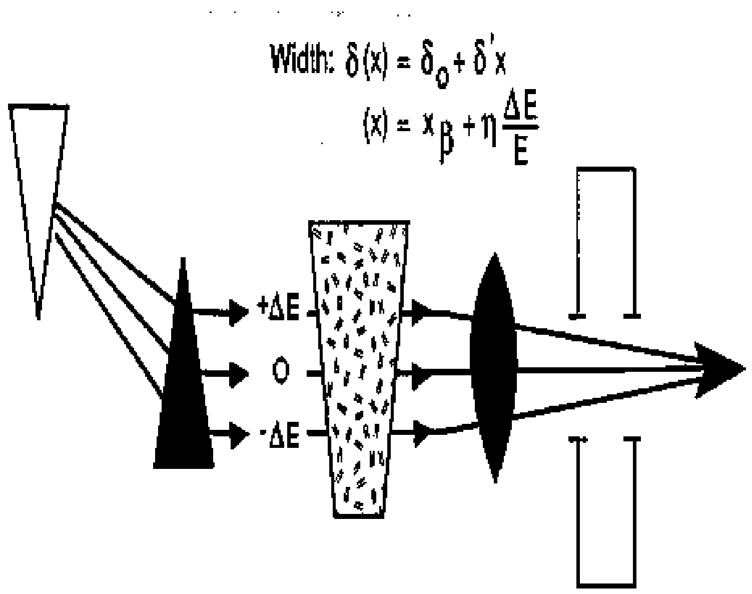

Figure 2: Conceptual schematic of ionization cooling of the longitudinal phase-space using a wedge.

The energy spread is given by:

$$\frac{d(\Delta E)^2}{ds} \;=\; -\;2\;\frac{d\left(\frac{dE_\mu}{ds}\right)}{dE_\mu}\;<(\Delta E_\mu)^2>\;+\;\frac{d(\Delta E_\mu)^2_{\rm straggling}}{ds} \tag{2}$$

where the first term is the cooling (or heating) due to energy loss, and the second term is the heating due to straggling. The heating term (energy straggling) is given by [4]

$$\frac{d(\Delta E_\mu)^2_{\rm straggling}}{ds} \;=\; 4\pi\;(r_e m_e c^2)^2\;N_o\;\frac{Z}{A}\;\rho\gamma^2\left(1-\frac{\beta^2}{2}\right), \tag{3}$$

where N_o is Avogadro's number and ρ is the density.

The energy spread, and hence longitudinal emittance, is reduced by introducing a transverse variation in the absorber density or thickness (e.g. a wedge) at a location where there is dispersion (the transverse position is energy dependent). The concept is illustrated in Fig. 2. The use of such wedges will reduce the energy spread and simultaneously increase the transverse emittance in the direction of the dispersion. Thus, longitudinal cooling is accomplished by the exchange of emittance between the longitudinal and transverse directions.

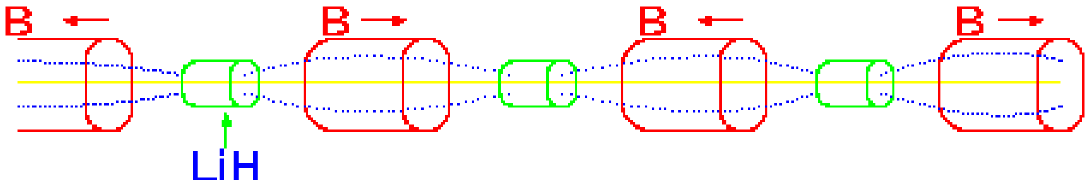

Figure 3: Conceptual schematic of a FOFO ionization cooling lattice.

3.2 Ionization Cooling Channel

A complete muon ionization cooling channel might consist of 20 – 30 cooling stages. Each stage would yield about a factor of 2 in phase-space reduction and would consist of the following three components:

1. A low Z material in which energy is lost, enclosed in a focusing system to maintain a low $\beta_\perp$. There are two realizations of this currently under consideration:
   - A FOFO lattice consisting of axial solenoids with alternating field directions. Lithium hydride absorbers are placed between the solenoids, in spaces where the $\beta_\perp$'s are minimum (see Fig. 3).
   - Current carrying liquid lithium "rods". The magnetic field generated by the current provides the focussing, and the liquid lithium provides the absorber.
2. A lattice that includes bending magnets to generate dispersion, and wedges of lithium hydride to lower the energies of the more energetic particles. This results in an exchange of longitudinal and transverse emittance.
3. A linac to restore the energy lost in the absorbers. In the FOFO scheme the rf cells would be embedded within the solenoid coils (Fig. 4).

It is reasonable to use FOFO lattices in the earlier cooling stages where the emittances are large. To obtain smaller transverse emittances as the muon beam travels down the FOFO cooling sections, the minimum $\beta_\perp$'s must decrease. This is accomplished by increasing the focussing fields and/or decreasing the muon momenta. Current carrying lithium rods would be used in the last few cooling stages to obtain much stronger radial focussing and minimize the final emittances.

Based on these ideas, a conceptual design of a complete cooling system has been defined, and the performance of the system calculated using analytic expressions for the

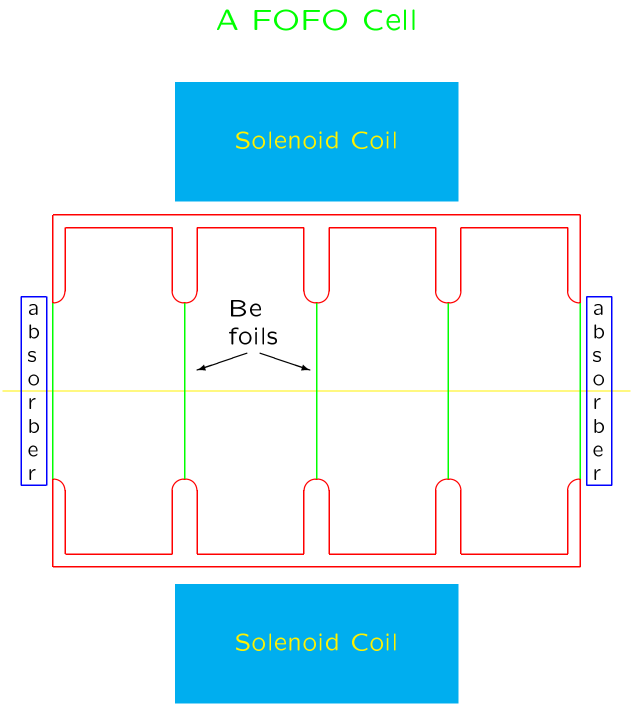

Figure 4: A schematic of a FOFO section in which rf cavities are embedded within the solenoid coils.

beta functions, cooling and heating rates, and emittance acceptances. The length of the system is 750 m, and the total acceleration used is 4.7 GeV. The fraction of muons that have not decayed and are available for acceleration at the end of the system is calculated to be 55 %. The calculated transverse emittance, longitudinal emittance, and beam energy are shown as a function of stage number in Fig. 5. In the first 15 stages the wedge sections are designed so that the longitudinal emittance is rapidly reduced, while the transverse emittance is decreased relatively slowly. The object is to reduce the bunch length, thus allowing the use of higher frequency and higher gradient rf in the reacceleration linacs. In the next 10 stages, the emittances are reduced close to their asymptotic limits. In the last stages, the emittance is further reduced in current carrying lithium rods. In order to obtain the required very low equilibrium transverse emittances, the focussing strength has been increased by allowing the energy to fall to 15 MeV. The use of energies this low results in a blow up of the longitudinal emittance, and at this stage no attempt is made to correct this by the use of dispersion and wedges.

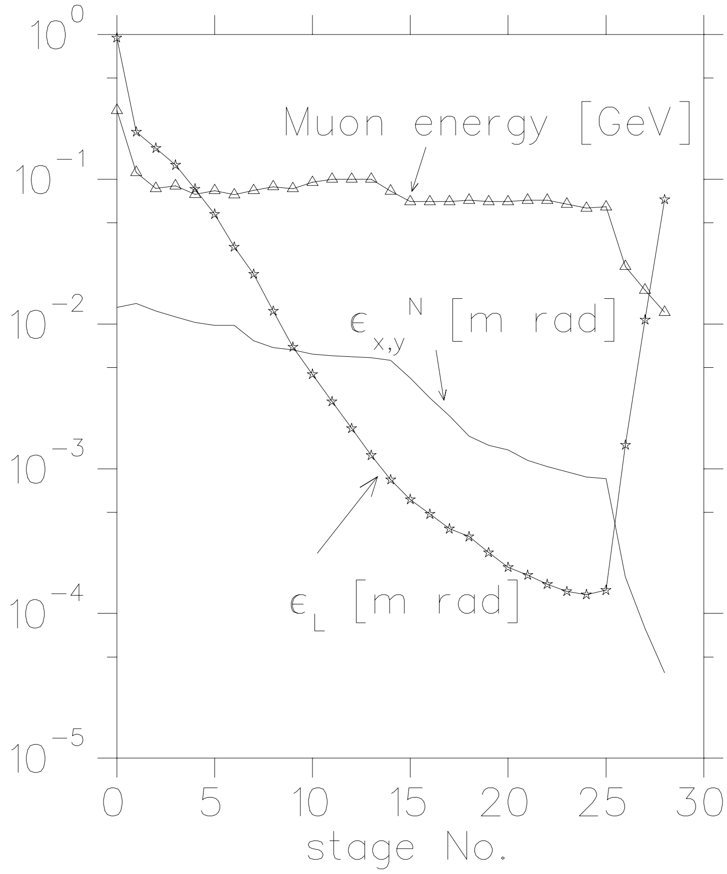

Figure 5: Calculated transverse emittance ($\epsilon_\perp$), longitudinal emittance (ϵ_L), and beam energy shown as a function of stage number in a 750 m long cooling FOFO and lithium lens cooling channel.

The details of the lattices required for most of the cooling stages in the cooling channel are still being developed. Therefore, a complete FOFO plus lithium lens cooling channel has not yet been simulated. However, simulations have been made of many of the individual components used in the cooling system, and cooling has been studied in different materials and with different beta functions. Furthermore, Monte Carlo calculations have been done to study wedge cooling using different beta functions and dispersions, and transverse cooling in lithium lenses has been simulated under a wide range of conditions.

As an interesting example, in Fig. 6 results are shown from a simulation of a cooling channel constructed entirely from lithium lenses plus reacceleration. The cooling channel

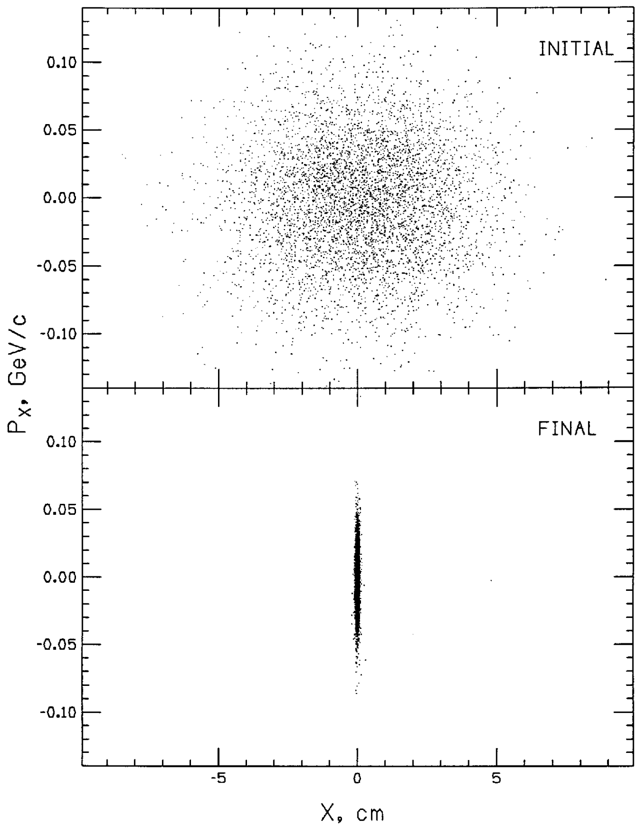

Figure 6: Results from a simulation of a lithium lens cooling channel.

consists of twelve 2 m long lithium lenses with reacceleration at the end of each lens. The gradient is increased from lens to lens, following the reduction in beam size as the beam is cooled. The calculation predicts a reduction in the normalized rms transverse emittance from $\sim 10000\pi$ mm-mrad to 80π mm-mrad. The parameters of the simulated cooling setup have not been optimized. However, the predicted final transverse emittance is already consistent with the requirements for a high-luminosity muon collider.

4 Cooling Hardware Research and Development

Although the initial simulations of a muon cooling scheme are encouraging, it should be noted that ionization cooling is a new technique that has not yet been demonstrated. In particular, there are practical challenges in designing lattices that can transport and focus the large initial emittances without exciting betatron oscillations that blow up the emittance and attenuate the beam. There are also potential problems with space charge and wake field effects. The theoretical design of an ionization cooling channel

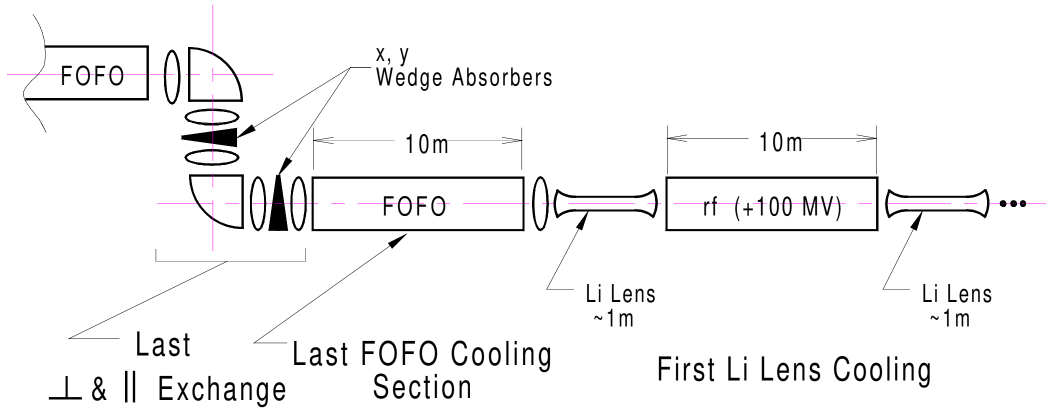

Figure 7: Schematic of the region of the ionization cooling channel in the neighborhood of the transition between the FOFO and lithium lens cooling sections.

that overcomes these challenges is progressing. These studies have advanced to the stage where the hardware components needed for cooling can be identified and their operational parameters specified. To enable us to confidently design a complete muon cooling channel for the First Muon Collider within a few years will require a vigorous R&D program to (i) develop, test, and optimize the various cooling hardware components, and (ii) to construct critical sections of the cooling channel and demonstrate their cooling capabilities.

In particular we propose to design, prototype, test, and optimize the sections of the cooling channel in the neighborhood of the transition between the FOFO cooling and lithium lens cooling stages (Fig. 7). To carry out this R&D program will require support for the design and construction of FOFO, lithium lens, and wedge cooling hardware, and construction of a cooling test facility to make the necessary performance measurements. In the following sub-sections we describe the components of the proposed ionization cooling hardware R&D program. In Section 5 we describe the test facility required to measure the performance of the cooling hardware prototypes, and the measurements to be made.

Solenoid Characteristics	
Period	45 cm
Peak Field	7.5 T
Warm Bore Radius	16 cm
RF Characteristics	
Frequency	800 MHz
Average Gradient	29 MV/m
Absorber Characteristics	
Material	LiH
Minimum dE/dx	1.66 MeV/cm
Radiation Length	97.1 cm
Beam Characteristics	
Kinetic Energy	89.5 $\pm$ 4 MeV
Momentum	164 $\pm$ 5 MeV/c
Input $\epsilon_{x,rms}$	1200 π mm-mrad
Output $\epsilon_{x,rms}$	600 π mm-mrad
β_{min}	10 cm
Input $\sigma_{x,rms}$	10 mm
Input $\sigma_{z,rms}$	8 mm

Table 1: Parameters for a FOFO muon ionization cooling stage in the neighborhood of the transition between the FOFO and lithium lens cooling systems.

4.1 FOFO Transverse Cooling Hardware

The parameters describing a FOFO cooling section in the neighborhood of the transition between the FOFO and lithium lens cooling systems are summarized in Table 1. We are proceeding with design studies of explicit realizations of a FOFO cooling section with these parameters. Both traveling wave and standing wave rf structures are being considered. The characteristics of the rf systems currently being studied are summarized in Table 2. The solution currently favored consists of a π-mode standing wave cavity built in 5 m sections. Each cell is 15.75 cm in length and the 5 m section consists of 32 cells. To reduce the rf cost (by a factor of 2) the cells would be operated at liquid nitrogen temperatures. This also facilitates maximizing the shunt impedance. The rf cell

	Standing Wave	Traveling Wave
RF frequency [MHz]	800	800
Mode	π	$2\pi/3$
Cavity Length [cm]	15.75	10.50
Cavity Inner Radius [cm]	14.6	14.35
Cavity Outer Radius [cm]	15.1	14.85
Q/1000	2.5×29	2.5×26
Peak Axial Gradient [MV/m]	45	35
Average Gradient [MV/m]	29	29
Shunt Impedance [MΩ/m]	2.5×76	2.5×64
Fill Time [μsec]	$3\tau = 34$	$1\tau = 13$
RF Peak Power [MW]	126	110

Table 2: Cavity parameters for standing and traveling wave FOFO ionization cooling schemes.

structure is inserted within a FOFO lattice with a period of 45 cm. For the chosen beam momentum of 165 MeV/c the axial magnetic field should be 7.5 T so that the betatron period matches the 45 cm period. A 36 cm long solenoid coil with a 32 cm inner diameter and a 41 cm outer diameter would be capable of delivering this field. The peak field encountered within the coil itself is 9 T, which will allow operation of the solenoid with NbTi cable at 4.2° K.

The cooling expected from a short prototype FOFO cooling section has being studied with the use of various simulation tracking models. As an example, Fig. 8 shows results from a simulation of one of the last stages (number 18) of the FOFO cooling channel. The parameters of this section, together with a summary of the results from the calculation, are listed in Table 3. The figure shows, as a function of length along the channel, (a) the rms of the distribution of beam particle radii, (b) the transverse emittance, (c) the longitudinal emittance, and (d) the total 6 dimensional emittance. It is seen that the transverse emittance is reduced by a factor of two, and the overall six-dimensional phase space volume is decreased by a factor of two, even though the longitudinal emittance increases due to energy loss straggling.

Although the FOFO lattice design studies are still in progress, they are sufficiently advanced to enable the key R&D issues associated with the construction of a FOFO

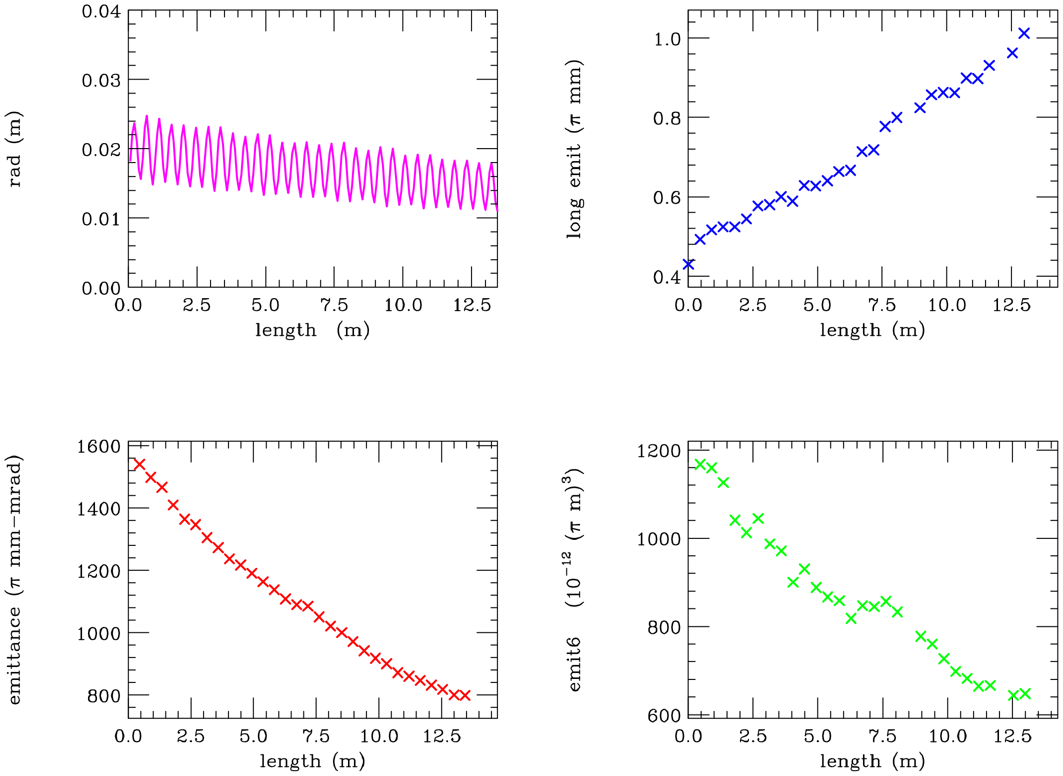

Figure 8: Results from a simulation of a FOFO cooling stage. Beam parameters are shown as a function of length: (top left) the rms beam radii, (bottom left) transverse emittance, (top right) longitudinal emittance, and (bottom right) total 6–dimensional emittance.

Axial Field Maxima	T	7.5	
Axial Field period	cm	45	
RF frequency	MHz	800	
RF max acceleration	MV/m	25	
Nominal momentum	MeV	164	
LiH absorber lengths	cm	2.5	
length	m	13	
Simulation Results		Initial	Final
particles tracked		1000	996
transverse emittance$_n$	π mm mrad	1600	800
rms dp/p	%	3.2	4.7
rms bunch length (ct)	cm	1	1.6
long. emittance	π mm rad	.45	1
6 Dim. emittance	10^{12} π^3 m^3	1200	600

Table 3: Parameters of a simulated FOFO cooling section, and a summary of its calculated performance.

cooling channel to be identified. In particular it should be noted that the rf cells need to be operated at liquid nitrogen temperatures. Furthermore, in the FOFO cooling lattice the open apertures that would be expected in normal rf cells are closed by beryllium foils. This facilitates a higher accelerating field on axis, but is a novel design that needs to be developed and demonstrated. After finalizing the initial design of the FOFO cooling stage, the proposed FOFO ionization cooling R&D program would consist of the following:

- Fabricate a cavity with a beryllium foil.
- Fabricate a 3-cell cavity, and then fabricate a 6-cell cavity which includes space for a LiH absorber.
- Construct and test at liquid nitrogen temperatures 1 m models of standing and/or traveling wave cavities, evaluate the coupling characteristics, study cavity tuning, and decide which type of cavity (traveling wave or standing wave) to pursue.
- Construct a 1 m long cavity for high-power rf testing at liquid nitrogen temperatures, and demonstrate operation of this cavity in a high-field solenoid.

- Construct a prototype FOFO ionization cooling section and measure its performance when exposed to muons in the appropriate momentum range. The measurements should demonstrate the cooling capability of the prototype and enable optimization of the design to be studied. Depending on the cavity-type choice, the prototype cooling section would either consist of two 5 m long standing wave sub-sections or one 10 m long traveling wave section.

- Develop and test a prototype energy (wedge) cooling section.

4.2 Lithium Lens Research and Development

Lithium rods with surface fields of 10 T were developed at Novosibirsk (BINP), and have been operated with high reliability as focusing elements at FNAL and CERN [5]. Although these lithium lenses have many similar properties to those required for ionization cooling, there are some key differences which will require lithium lens technology to be extended to its practical limits. In particular:

- Ionization cooling requires much longer lenses than previously developed. Lenses with lengths of the order of a meter are required to maximize the amount of cooling in a single absorber and hence minimize the number of transitions from absorber to absorber.

- The muon collider repetition rate will require the lithium lenses to operate at 15 Hz. The resulting thermal load on a solid lithium lens would increase its temperature to the melting point ($T_{melt} = 186°$C). It is therefore desirable to operate with lithium in the liquid phase, flowing through the lens for cooling.

- To minimize the final emittances, the maximum radial focussing, and hence the maximum surface fields are required. It is hoped that liquid lithium columns can be used to raise the surface field to 20 T.

The parameters of the lithium lenses needed for a muon ionization cooling channel are listed in Table 4. Prototype liquid lithium lenses have been developed at Novosibirsk [6]. Currently a contract between BINP and Fermilab exists for the development of high-field liquid lithium lenses for antiproton collection. As the liquid lithium lens technology is

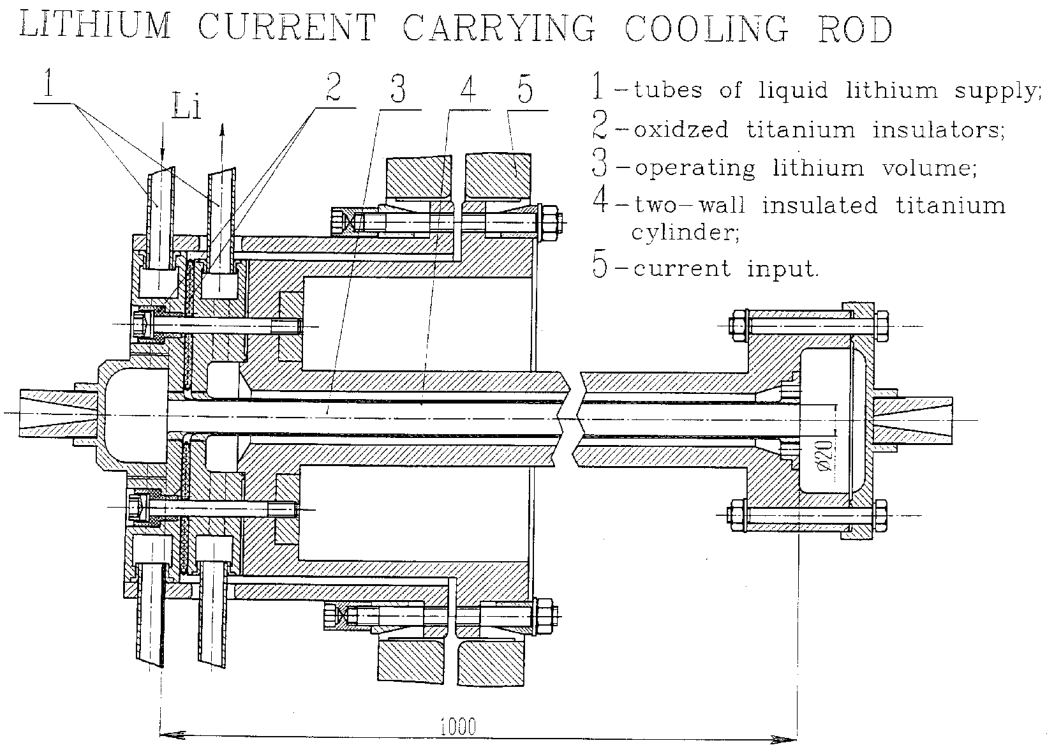

Figure 9: Schematic of a 1 m long liquid lithium lens with a surface field of 10 T designed by Silvestrov to be used for ionization cooling.

established it will be transferred to Fermilab, where further development can be pursued. The lithium lens R&D effort can be extended to develop the longer lenses needed for ionization cooling. Figure 9 shows a schematic of a 1 m long lithium lens designed at BINP by Silvestrov to be used for ionization cooling. The lens uses liquid lithium, and has a radius of 1 cm and a surface field of 10 T. A collaboration with Lawrence Livermore National Laboratory is being explored to develop a similar 1 m long lens for ionization cooling. This lens would then be tested in a muon beam of the appropriate energy ($\sim$ 260 MeV/c). A second lens would be constructed to enable a complete cooling step to be tested, including reacceleration after the first lens and matching into the second lens. Simulations indicate that a single 1 m long lens would cool the normalized rms transverse emittance from 1000π mm-mrad to 670π mm-mrad, and cool the six-dimensional emittance to 60% of its initial value. Addition of a second lens is predicted to cool the normalized rms transverse emittance to $\sim 500\pi$ mm-mrad, reducing the six-dimensional emittance to 40% of its initial value.

In addition to the development and testing of the first Silvestrov-type long liquid lithium lenses, we would propose to extend the lens R&D to try to maximize the surface fields, and study the inclusion of other materials and geometries. Note that material choices are limited since a cooling lens must be both a good conductor and be constructed from low-Z material to minimize multiple scattering. A possible alternative to lithium is beryllium (Z = 4) which has a higher density but may be too brittle. Boron and carbon might also be integrated into the design, and designs with alloyed materials might be developed. Higher density solid materials would be needed for the longitudinal (wedge) cooling. Designs which integrate the active lens with wedge absorbers have been initiated.

The proposed lithium lens R&D program consists of the following:

- Construction of a 1 m long liquid lithium lens of design similar to the one developed by Silvestrov.
- Measurement of the performance of this prototype lens when exposed to muons in the appropriate momentum range.
- Construction of a second liquid lithium lens and measurement of the performance of the lens-rf-lens system.
- Development and testing of lenses suitable for wedge cooling.
- Development of lenses that achieve the highest practical surface fields.

5 Ionization Cooling Test Facility

The experiments required to demonstrate ionization cooling and to develop and optimize the cooling hardware described in the previous sections will not be trivial. They will require an ionization cooling test facility with the following capabilities:

B (T)	B′ (T/m)	Radius (cm)	Length (m)	I (MA)	$\tau(\delta = 0.7r)$ μs	ΔT/pulse (^{0}C)
10	1000	1.0	1	0.5	1000	78
15	3000	0.5	1	0.375	250	177
20	8000	0.25	1	0.25	63	316
20	16000	0.125	1	0.125	15	303
20	40000	0.050	1	0.050	2.2	278

Table 4: Lithium lens parameters for a muon ionization cooling channel.

- Injection of single muons with momenta in the range 100 - 300 MeV/c into a test cooling setup of length up to $\sim$ 50 m.
- Measurement of the six-dimensional phase-space volume occupied by the populations of the incoming and outgoing muons with a precision of a few %.
- Measurement of the non-decay loss of muons traversing the cooling setup with a precision corresponding to O(10%) for a full cooling stage. Since the non-decay losses are expected to be $\sim$1%, each measurement will require O(10^4) muons within the phase-space acceptance of the cooling apparatus.

To provide these capabilities the facility will need to have a low energy muon beamline, the infrastructure to operate the cooling prototypes to be tested (services, shielding, overhead crane coverage, refrigerants for superconducting magnets, rf power for accelerating cavities including modulators, klystrons, etc), and instrumentation to identify incoming and outgoing muons and determine their positions, directions, momenta, and their entrance and exit times with respect to the rf acceleration cycle.

Work on an initial design of the required facility is proceeding. In the following subsection we describe our current understanding of the beam requirements and candidate beamlines for satisfying our requirements. The remaining subsections then describe the measurements to be made and the instrumentation that will be required.

5.1 Low Energy Muon Beamline

The prototype cooling hardware tests described in the previous sections require a high purity ($> 99\%$) tagged muon beam with a central momentum of 165 MeV/c for the FOFO cooling channel measurements and 260 MeV/c for the lithium lens measurements. Anticipating that as the cooling hardware R&D program advances we will require some flexibility in choosing the momenta of the muons used for the measurements, the cooling test facility beamline will need to provide muons with central momenta that can be chosen in the range $\sim 100 - 300$ MeV/c. A small spread in beam momentum is also required. Existing low energy muon beamline parameters suggest that $\Delta p/\mathrm{p} = 5\%$ is a reasonable goal. Finally, we require a normalized rms transverse beam emittance of $\sim 2000\pi$ mm-mr to provide an appropriate test of the cooling hardware.

An understanding of the beam intensity requirements is not straight-forward since this depends on details of the beamline, the cooling hardware, the measurements to be made, and the instrumentation to make the measurements. To maximize the fraction of muons in the beam that are useful for the measurements it is necessary to match the beam emittance with the emittance acceptance of the cooling apparatus. Unfortunately useful cooling only occurs for beam particles arriving at the right phase in the reacceleration rf cycle (within about 5% of the rf period). At the present time we believe the instrumentation needed to measure the incoming and outgoing muons can record up to $\sim$10 tracks per beam "bunch" with times between the tracks as short as 5 ns, and handle 15 "bunches" per second. With these considerations in mind, initial studies indicate that several beamline possibilities look promising. In particular we are studying three possible beamline scenarios, namely (i) an upgraded and relocated D2 beamline at BNL, (ii) a new beamline in the FNAL Meson Area made from existing magnets, and (iii) a new beamline from the FNAL Booster, also made from existing magnets.

Further details of the beamline scenarios under study are described in the following sub-sections.

5.1.1 An Upgraded and Relocated D2 Beamline at BNL

A low energy muon channel (D2) presently exists at BNL and is shown in Fig. 10. It was designed using the backward-decay configuration, consisting of a pion collection part, a pion decay part, and a muon matching part, each separated by bending magnets. Since

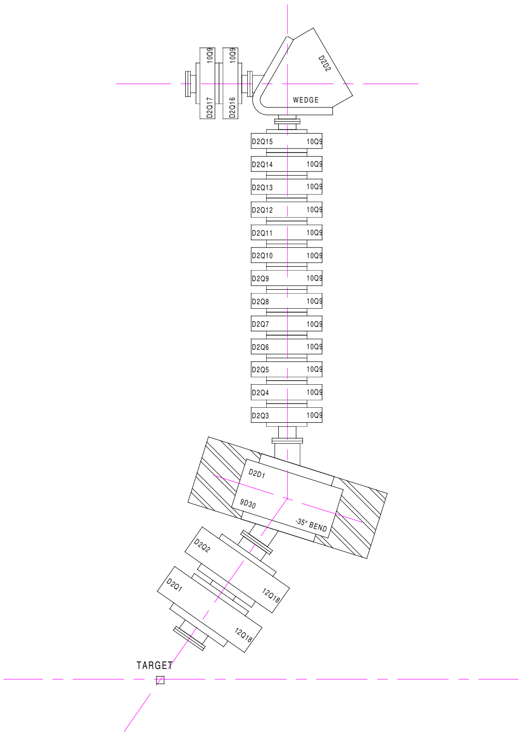

Figure 10: Schematic of the existing D2 muon beamline at BNL.

the backwards muons have about half the momentum of the undecayed pions, this configuration produces a muon beam with very small pion contamination. The major background particles should be electrons. The D2 line uses slow extracted beam from the AGS. In its present configuration it is limited to muons with less than 150 MeV/c momentum. The available muon flux has been measured to be 2×10^6 per 10^{13} protons on target. By replacing the last dipole and using higher current cables from the power supplies, it should be possible to use this beam for an $\sim$10 m FOFO demonstration, but it is unlikely to be useful for a higher momentum lithium lens experiment, and due to space limitations it would not be possible to use the D2 beamline to test longer cooling setups. It would therefore be necessary to build an upgraded D2 beamline at a new location, for example at the end of the A2 or B2 test beams where there are large pion fluxes. These higher energy lines are located in large experimental halls, with convenient access to overhead cranes, utilities, etc.

5.1.2 A New Beamline at FNAL Using Existing Magnets

A new low energy forward pion decay channel could be constructed at FNAL using available magnets from the decommissioned muon beamline previuosly used by the MEGA experiment at LAMPF. The available magnets include nine 12QE20 12 inch aperture 65 cm long quadrupoles, eleven 12Q15 12 inch aperture 50 cm long quadrupoles, and three C32XI30 6.1 Kg field 105 cm long bending magnets. The general characteristics of these magnets are being used for our beamline design studies. The new beamline would consist of four parts: a quadrupole collection stage to define the desired beam acceptance, a dogleg dipole bend for momentum selection, a FODO channel between the dipoles to define the pion decay space, and a final quadrupole stage to match into the experiment. Bend angles of 35 degrees were chosen to control muon and hadron backgrounds. The large angle also provides the momentum acceptance required by the experiment without a FODO channel. An interesting variation that is being studied is to exploit the velocity difference between muons from forward pion decays and their parent pions in order to reduce the effective momentum bite incident on the cooling setup within the time-acceptance of the rf cycle. For example, forward muons at 170 MeV/c will have a velocity of 0.85c compared to the parent pion's velocity of 0.75c. The parent pion energy is 211 MeV, and its momentum is 159 MeV/c. In a thirty meter drift region the muon will lead the pion by about 15 ns. The 53 MHz time structure at Fermilab consists of a 3 ns bunch per rf bucket. For a pion beam with well defined momentum, the forward muons will precede the pion beam by about 15 ± 3 ns. The final bend in the beam removes the low energy and backward decaying muons from the beam. The experiment would trigger on the rf structure, and accept tracks consistent with flight times for particles having a velocity of 0.85c.

The new pion decay channel described above would need to be located downstream of a source of pions. We are studying the possibility of using the slow extracted proton beam from the Fermilab Main Injector. The beam would be directed along an existing beamline onto a pion production target in the Meson Area. The pions would enter the new forward pion decay channel, which would be located so that it runs over to the MP tunnel (a second existing beamline in the Meson Area). The experimental facilities for cooling would be located along the second line in the MP tunnel. An advantage of an ionization cooling test facility in the Meson Area at Fermilab is that much of the shielding, dumps, and magnets already exist. This area is near a service building that can house power supplies and control electronics. Excellent crane coverage exists in the beamline and beam dump areas. A portion in the MP tunnel does not have crane coverage, but was designed to accommodate fairly large objects. Fermilab is in the process of coordinating the reconfiguration of the fixed target areas for 120 GeV operation. A final configuration of beamlines and operating conditions is not complete at this time. We note that in the scenario above, the Meast cryo bend would need to be replaced. We have assumed that there will be excess dipoles available from the main ring, and that these would be used to replace the Meast cryo bend. Finally, the beam dump currently in MEast would serve very well for our application.

A second possibility at FNAL would use the fast extracted beam from the booster in the MI-10 line. A new experimental area would have to be built adjacent to the extraction line. The proton beam would be deflected onto a pion production target at the beginning of the new muon beamline. This possibility needs further study.

5.2 Measurement Requirements

To study the performance of the prototype FOFO and lithium lens cooling sections described previously we propose to measure the trajectories of individual muons before and after the cooling apparatus with the cooling setup installed in a muon beam with the appropriate central momentum. This will enable us to select a subset of incoming muons corresponding to an ideal input bunch. The measurements of the incoming and outgoing muons that need to be made are their directions (x', y'), transverse positions (x,y), momenta (P), and arrival time with respect to the rf reacceleration cycle (t). These measurements will enable the phase-space volume occupied by the selected population of muons to be determined upstream and downstream of the cooling apparatus, and correlations between the individual initial and final phase-space coordinates to be studied.

In the following we will define the phase-space volume V occupied by the population of selected muons:

$$V = \prod_{i=1}^{6} \sigma_i, \tag{4}$$

where σ_i is the rms width of the population of muons along the phase-space coordinate i, and the index i runs over the 6 phase-space variables. The uncertainty on V:

$$\frac{\delta_V}{V} = \sqrt{\sum_{i=1}^{6} \left(\frac{\delta_{\sigma_i}}{\sigma_i}\right)^2}. \tag{5}$$

If the relative uncertainty is the same in all six variables i, then:

$$\frac{\delta_V}{V} = \sqrt{6}\frac{\delta_{\sigma_i}}{\sigma_i}. \tag{6}$$

We would initially like to demonstrate the cooling performance of a relatively short (10 m long) FOFO section. This short section is expected to reduce V by almost a factor of 2. To provide an adequate measurement of the cooling, and begin to explore the correlations between the incoming and outgoing muon parameters, we must measure V with a precision of a few %. Therefore, we need to measure the individual σ_i with precisions of $1 - 2\%$. If the selected sample consists of N muons, then it can be shown that [7]:

$$\left(\frac{\delta_{\sigma_i}}{\sigma_i}\right)^2 = \frac{1}{2N}\left(1 + \frac{\sigma_{D_i}^2}{\sigma_i^2}\right)^2 + \left(\frac{\sigma_{D_i}}{\sigma_i}\right)^4 \left(\frac{\delta_{\sigma_{D_i}}}{\sigma_{D_i}}\right)^2, \tag{7}$$

where $\delta_{\sigma_{D_i}}$ is the systematic uncertainty on the detector resolution σ_{D_i}. In practice we will require $\delta_{\sigma_{D_i}} < \sigma_{D_i}$, for example $\delta_{\sigma_{D_i}}/\sigma_{D_i} < 0.2$ would be a reasonable goal. To explore correlations between the positions in phase-space of the incoming and outgoing muons, we also want the detector resolution to be smaller than the width of the corresponding muon distribution, e.g. $\sigma_{D_i} < 0.2\sigma_i$. If N is large, the first term in the preceding equation can be neglected, and the conditions on $\delta_{\sigma_{D_i}}$ and σ_{D_i} that we have just discussed will yield the desired precision $\delta_{\sigma_i}/\sigma_i \sim$1%. If N is small, then the first term in the preceding equation dominates, and $\delta_{\sigma_i}/\sigma_i \sim 1/\sqrt{2N}$. A sample of 10,000 muons would be sufficient to ensure that N is large enough to achieve an overall $\sim 1 - 2\%$ measurement of σ_i.

The precision needed for the timing measurement is $\sigma_{D_t} = 8$ ps. This is very demanding. In practice the time measurement is made at a position displaced from the cooling apparatus. Hence, to extract the arrival time of the muon at the cooling apparatus we must calculate the time-of-flight between the time measuring system and the cooling setup. The uncertainty on the time of flight, $t = L/\beta_z c = L/\beta c\cos\theta$, due to the uncertainty on the momentum is:

$$\delta t = \frac{L}{\beta^2 c\cos\theta}\delta\beta = \frac{L}{\gamma^2\beta_z c}\frac{\delta P}{P} \approx 1000\ [\mathrm{ps}]\left[\frac{L}{1\ \mathrm{m}}\right]\frac{\delta P}{P}, \tag{8}$$

Variable i	Expected input σ_i	Required σ_{D_i}	Required $\delta_{\sigma_{D_i}}$
x	24 mm	200 μm	± 40 μm
y	24 mm	200 μm	± 40 μm
x′	33 mr	5 mr	± 1 mr
y′	33 mr	5 mr	± 1 mr
P	5 MeV/c	0.23 MeV/c	± 0.05 MeV/c
t	40 ps	8 ps	± 2 ps

Table 5: Measurement precisions required to obtain a few % measurement of the phase space volume occupied by the populations of incoming and outgoing muons for the FOFO cooling test.

where θ is the angle of the trajectory with respect to the z-axis. The extrapolation length in the detector arrangement we are currently considering is 4 m. Hence the desired precision on the time measurement $\delta t < 8$ ps sets a requirement on momentum resolution $\sigma_{D_P}/P < 0.002$. To allow for other contributions to the uncertainty on the time measurement we will want to achieve a momentum resolution a factor of $\sqrt{2}$ better than this, and we arrive at the final momentum resolution requirement $\sigma_{D_P}/P < 0.0014$. A careful consideration of the precisions required for all six phase-space variables leads to the results summarized in Table 5.

5.3 Detector Design

We are currently designing a detector scheme that can measure the 6 phase-space variables for the incoming and outgoing muons with the desired precisions. The scheme we are investigating is shown in Fig. 11, and consists of an upstream measuring system, the cooling apparatus to be tested, and a downstream measuring system that is a mirror image of the upstream system. The upstream measuring system is shown in more detail in Fig. 12. To contain the large transverse emittances of the incoming muon populations, the upstream detectors are inside a 1.5 T solenoidal field coaxial with the beam direction. The instrumentation within the solenoidal channel consists of (i) an initial (auxiliary) time measurement device to locate the particles within ~1/4 rf cycle, (ii) the first time

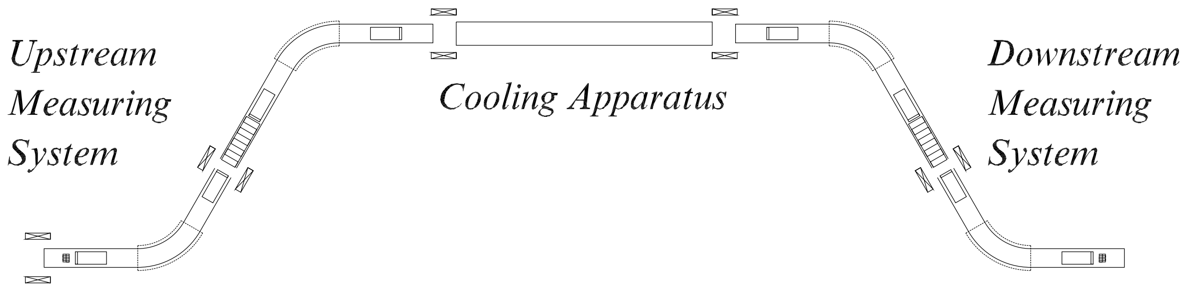

Figure 11: Schematic of a detector arrangement to measure the 6 phase-space variables for the incoming and outgoing muons with the precision discussed in the text.

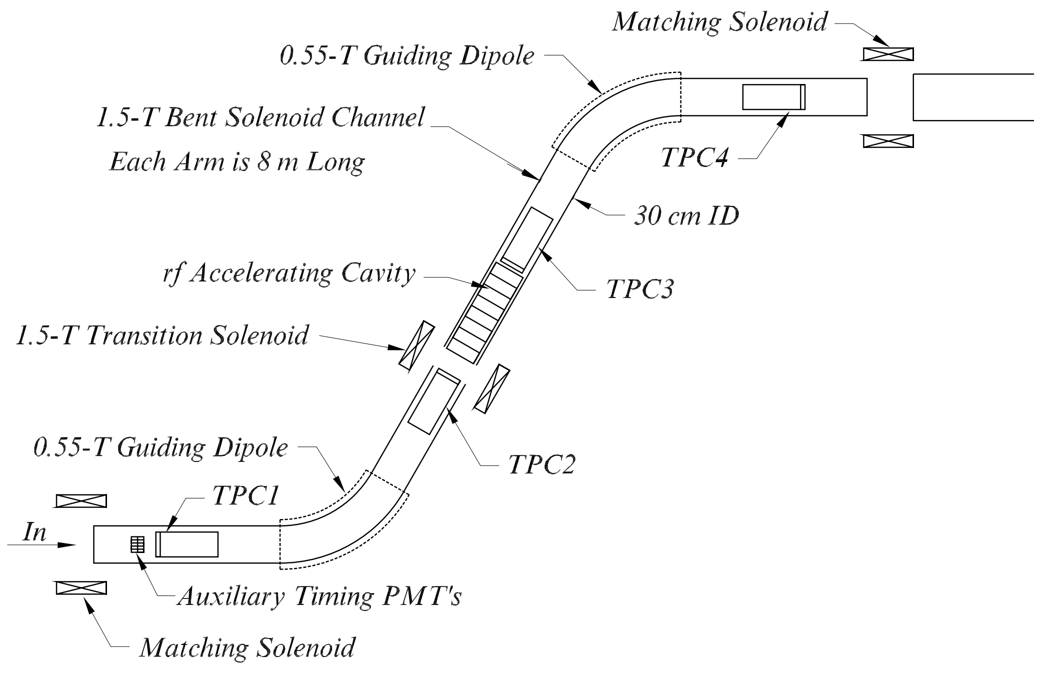

Figure 12: Schematic of upstream measuring system.

projection chamber (TPC 1) to measure the particles trajectory preceding the first bend in the solenoid channel, (iii) TPC 2 following the first bent solenoid and hence determining the initial particle momentum, (iv) an rf acceleration cavity phase locked to the ionization cooling rf reacceleration cavities, (v) TPC 3 following the rf cavity and preceding the second bent solenoid, (vi) TPC 4 following the second bent solenoid and hence determining the momentum after the accelerating cavity and the trajectory of the particle incident on the cooling apparatus. The detector components are discussed in more detail in the following subsections.

5.3.1 Time Measurement

The demanding timing requirement has a strong influence on the overall choice of measuring techniques. The precision needed for the time measurement cannot be achieved by a conventional particle detector. We have investigated using an rf cavity to provide a time-dependent transverse- or a time-dependent longitudinal-kick to the traversing muons, and then extracting the arrival time by measuring the size of the kick. At present we believe the best option is the use of an rf accelerating cavity phased to impart zero energy to a particle in time with the reacceleration rf cycle. This will result in a correlation between the energy (and hence momentum) given to the muon in traversing the cavity and its arrival time. If we use an 8 cell acceleration cavity of the same design used in the FOFO cooling section, and operated in the $TM_{0,1,0}$ mode with a peak field of 40 MV/m, then the cavity will change the particles energy by:

$$\Delta U = 0.16\ [\mathrm{MeV}] \left[\frac{\Delta t}{1\ \mathrm{ps}}\right], \tag{9}$$

which will result in a momentum change:

$$\frac{\Delta P}{P} = 0.001\ \left[\frac{\Delta t}{1\ \mathrm{ps}}\right]. \tag{10}$$

Measurement of the muon's momentum before and after the rf cavity permits inference of the desired time. This technique requires a fourfold momentum measurement of each muon: twice before the cooling apparatus and twice after. We require a momentum resolution $\sigma_{D_p}/\mathrm{P} = 0.008/\sqrt{2}$ to achieve a time resolution $\sigma_{D_t} = 8$ ps. This is less stringent than the requirement on the momentum measurement arising from the precision with which the time must be extrapolated to the cooling setup (discussed previously).

In addition to the main time measurement, an auxiliary measurement with a precision of about 300 ps is required to determine the correct quarter-period of the rf cycle. This auxiliary measurement would also provide the T_0 for the experiment, and combined with the main timing measurement, would provide time-of-flight information over a $\sim$ 3 m flight path that could be used to reject incoming pions and electrons. The time-of-flight difference per meter between particles of masses m_1 and m_2 at momentum P is given by:

$$\Delta t = \frac{1}{\beta_1 c} - \frac{1}{\beta_2 c} = \frac{\sqrt{1 + (m_1 c/P)^2} - \sqrt{1 + (m_2 c/P)^2}}{c}. \tag{11}$$

At 165-MeV/c electrons arrive earlier than muons by 0.625 ns/m and pions arrive later by 0.407 ns/m. The time-of-flight measurement would benefit from a more precise auxiliary timing measurement than 300 ps. A 100-ps timing measurement could be accomplished in the 1.5-T solenoid field with scintillation counters and fine-mesh photomultipliers using, for example, Hamamatsu model R5504 [8] photomultipliers coupled to scintillator bars [9]. Figure 13 shows how these PMT's might be arranged inside the solenoid channel to provide coverage over a radius of 10 cm. Six PMT's face upstream and six face downstream. Microchannel-plate photomultipliers (MCP-PMT's) are also candidates for the auxiliary timing readout, and have the advantage that their response is hardly affected by a magnetic field aligned along the tube axis [10]. Either the fine-mesh PMT's or the MCP-PMT's can provide timing accurate enough to resolve the ambiguity in the rf cavity timing measurement.

5.3.2 Solenoidal Channel

An elegant way of providing the dispersion required for the momentum measurement is to exploit the confining solenoidal field by using 'bent solenoids'. In Fig. 11 a total of four bent solenoids are linked by straight solenoids to form the muon channel of the detector. If the bending plane of the bent solenoids is horizontal, the beam experiences a net vertical displacement (called 'curvature drift' in the plasma-physics community) of O(10 cm). In the proposed detector configuration, the curvature drift is cancelled for muons having the central beam momentum. This is accomplished by using 'guiding dipole' magnets to provide an additional vertical field B_G = 0.55 T superimposed on the field provided by

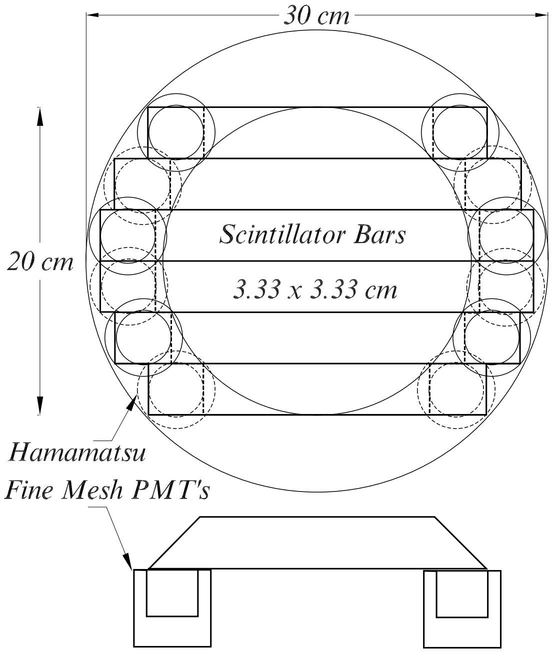

Figure 13: Sketch of a possible arrangement of 12 Hamamatsu R5504 fine-mesh PMT's viewing six 3.33×3.33 cm^2 scintillator bars entirely within the 30-cm-diameter solenoid channel.

the bent solenoid. Off-momentum muons are displaced vertically by an amount:

$$\Delta y \approx \frac{P}{eB_s}\frac{\Delta P}{P}\theta_{\text{bend}}, \tag{12}$$

where $B_s = 1.5$ T is the field of the bent solenoid and θ_{bend} is the bend angle. Note that eq. (12) describes the deflection of the 'guiding ray' (or axis) of the helical muon trajectory and not the trajectory itself. The muon's momentum cannot be determined simply by measuring the height of its trajectory at the entrance and exit of a bent solenoid. Rather, the height of the guiding ray must be reconstructed at both places, which requires precise measurements of the helical trajectories. The momentum resolution of a bent solenoid spectrometer is given by:

$$\frac{\sigma_{D_P}}{P} \approx \frac{1}{\theta_{\text{bend}}}\frac{P}{eB_s}\frac{\sigma_{D_x}}{L^{5/2}}\sqrt{\frac{720}{n}}, \tag{13}$$

where L is the length of the trajectory observed (before and after the bend) with n samples/m, each with transverse spatial resolution σ_{D_x}. As expected, the momentum resolution improves with increasing magnetic field. However, to lower the cost of the solenoid channel we will want to use a relatively low magnetic field. The momentum resolution is improved by increasing θ_{bend} and by increasing L. Since it would be difficult

Table 6: Parameters of the optimized bent-solenoid muon channels.

Parameter	Value
P_{muon}	165 MeV/c
B_{Guide}	0.55 T
B_s	1.5 T
θ_{bend}	1 rad
R_{bend}	1 m
λ_{cycl}	2.31 m
R_s	15 cm
L_s	4 m
Cost per 4-m section	290k$
$\beta^\star$	73 cm
$\sigma_x = \sigma_y$	24 mm
$\sigma_{x'} = \sigma_{y'}$	33 mrad
L_{tracking}	57 cm
n	33 clusters/m

to assemble a planar transport system with $\theta_{\text{bend}} > \pi$, we will choose $\theta_{\text{bend}} \sim 1$ radian. We require that the solenoid channel transmit 99.9% of the beam, and therefore its inner radius must be 3.3 times the largest rms transverse width of the beam in the channel. Because of the vertical dispersion in the bent solenoid, the beam is fattest vertically between the two bends, with rms width

$$\sigma_{y,\text{max}} \approx \sqrt{\left(\frac{P}{eB_s}\frac{\sigma_P}{P}\theta_{\text{bend}}\right)^2 + \frac{2P\epsilon_x}{eB_s}}, \tag{14}$$

where $\epsilon_x = 800\pi$ mm-mrad is the normalized rms transverse emittance of the beam. We chose $3.3\sigma_{y,\text{max}}$ to be 10 cm to match the aperture of the rf timing cavity (whose radius is 14.6 cm). Then eq. (14), together with the requirement that $\sigma_{D_P}/P = 0.0014$, leads to the solenoid field $B_s = 1.5$ T.

The parameters of the bent-solenoid channel are summarized in Table 6. We have performed a numerical simulation of the muon trajectories within the solenoidal channel

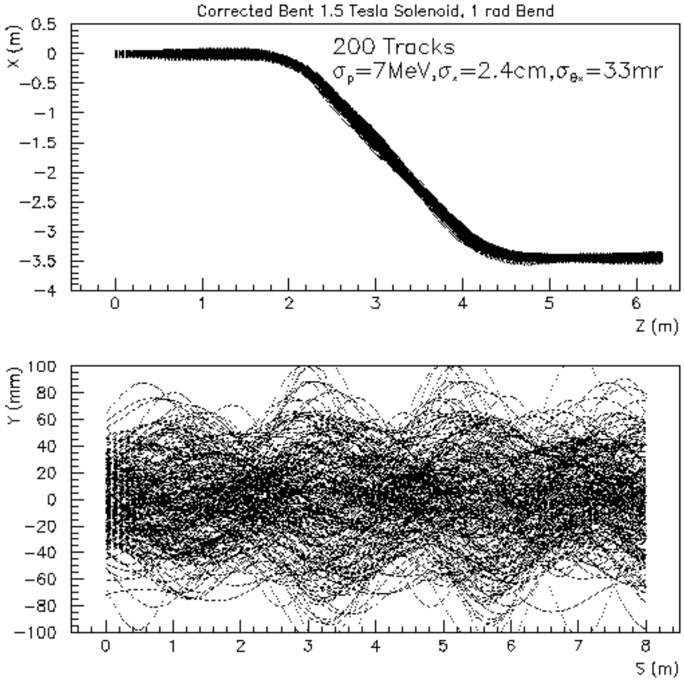

Figure 14: Orbits of 200 muons chosen at random from within the Gaussian phase volume specified in Table 6, projected onto the horizontal and vertical planes.

by integrating the equations of motion. At present we assume that the horizontal fields within the straight solenoid sections are those of an ideal solenoid, and those in the bent solenoids are those of an ideal toroidal sector. Likewise, ideal vertical guiding fields are superimposed on the bent solenoids. Thus Maxwell's equations are piecewise satisfied, but suffer discontinuities at the boundaries between straight and bent solenoids. Figure 14 shows the orbits of 200 muons selected at random from within the Gaussian phase volume specified in Table 6. The periodicity of the orbits with $\lambda_{\rm cycl}$ is readily evident in the upstream part of the channel, but is washed out due to chromatic effects by the end of the channel. Figure 15 shows the x and y profiles of the beam at the beginning, middle and end of the channel. The profiles broaden after the first bend due to the momentum dispersion, Figure 16(a) shows the trajectories of muons that lie along the central ray upstream of the first bend, but differ from the central momentum in increments of 1 MeV/c. The vertical dispersion caused by the bent solenoid is evident. Figure 16(b) shows the vertical displacement of the guiding ray or 200 random muons as a function of

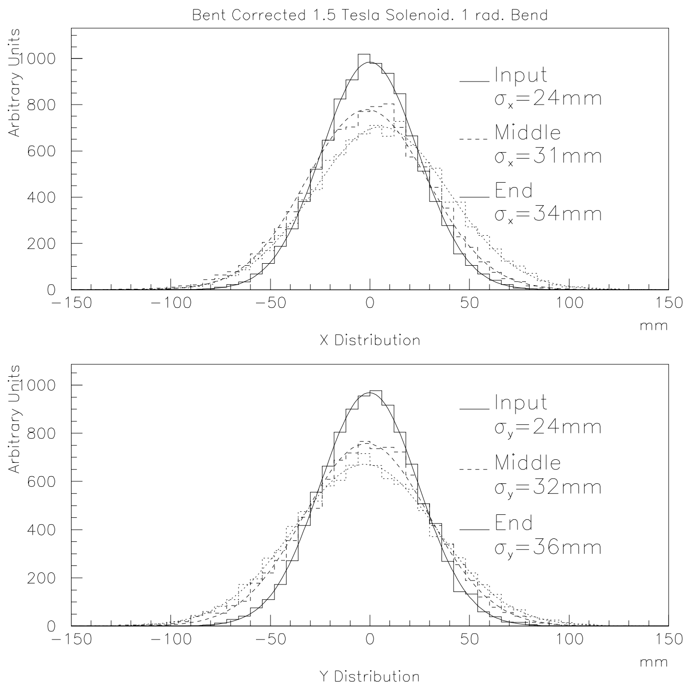

Figure 15: The distribution of muons along horizontal and vertical axes at the beginning, middle (= rf timing cavity) and end of the upstream bent solenoid channel.

their momentum, in agreement with eq. (12).

5.3.3 Low-Pressure Time-Projection Chambers

The momentum measurements require precise measurements of the helical muon trajectories in the solenoidal fields before and after the bends. Since the muons have relatively low momentum, multiple scattering in detector material, and even in atmospheric-pressure gas, will significantly degrade the momentum resolution. Hence, we propose that each arm of the momentum measuring system be a low-pressure device with minimal internal structure.

As an example, we are considering using 8.4-Torr methane at 20°C as the ionization medium in an ionization chamber, yielding one ion pair per 3 cm of track length. Equation (13), with $n = 33$ clusters/m, leads to the choice $L = 60$ cm for the length of the tracking devices. In the strong magnetic field of the detector the ionization electrons drift easily only along the field lines. Hence the drift electric field should be aligned with the magnetic field, leading to a time-projection chamber (TPC) geometry. The drift velocity of ionization electrons is a function of E/P, where E is the electric field and P is the gas

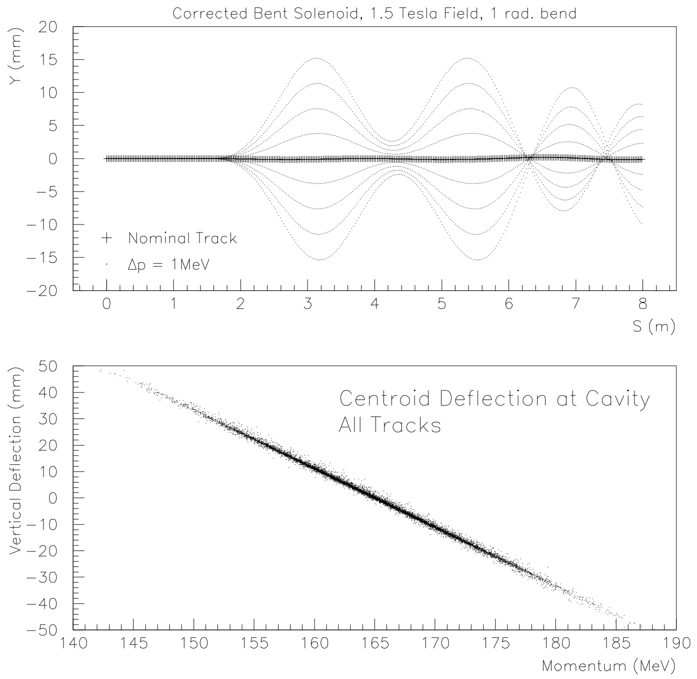

Figure 16: (a) Vertical projection of trajectories of muons that initially lie along the central ray, but depart from the central momentum by 1-MeV/c increments. The vertical momentum dispersion between the bent solenoids is evident. (b) Summary of vertical deflection of the guiding ray of muons as a function of their momentum. Compare to eq. (12).

pressure. The saturation drift velocity of 100 μm/ns (methane) is achieved at a field of only 10 V/cm at 8.4-Torr pressure. The proposed TPC is not a high-voltage device. Gas gain is obtained near a wire mesh anode plane in a gap separated from the ionization/drift region by a wire-mesh grid, as shown in Fig. 17. The induced pulse on a cathode plane subdivided into 1250 5×5 mm^2 pads yields x and y coordinates to 200 μm via charge interpolation. Each pad is sampled at 50 MHz, and the samples are stored in a 512-deep switched-capacitor array and multiplexed into a 12-bit ADC between beam pulses. Interpolation of the samples in time will locate the z coordinate to 200 μm. Over a total drift distance of 60 cm, the TPC will observe 20 points on a track segment, and measure its angle with a precision of about 1 mrad. The momentum resolution of each TPC–bent solenoid–TPC spectrometer will be $\sigma_P/P = 0.0014$ at 165 MeV/c.

The total drift time of the ionization electrons is about 6 μsec, which is of the same order as, perhaps even longer than, the active time of the rf system of the cooling appa-

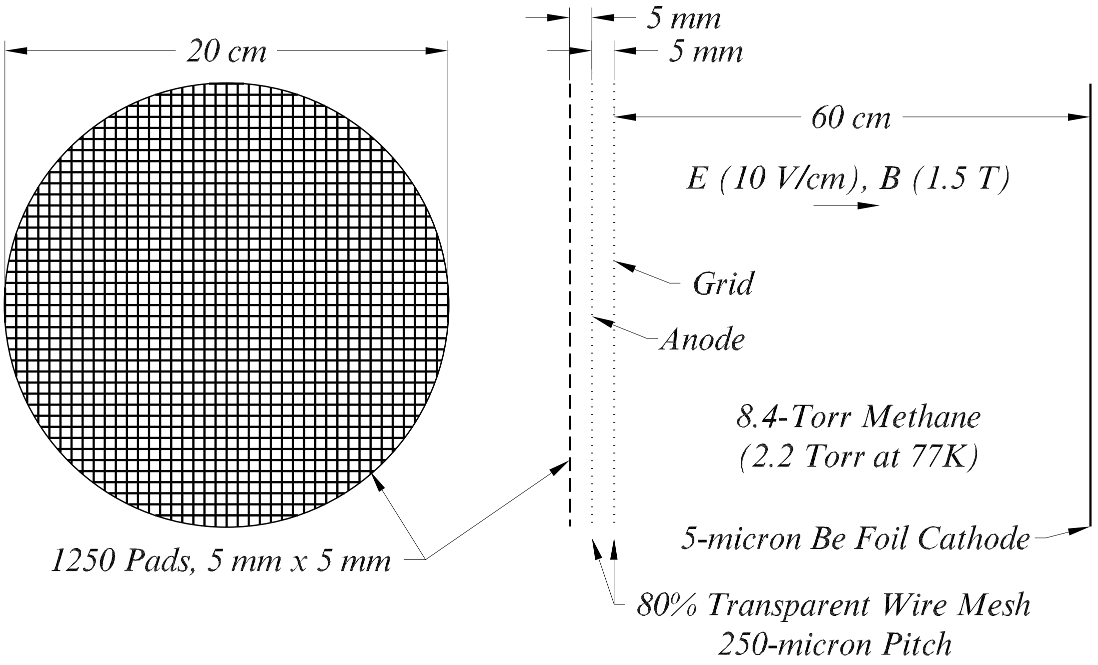

Figure 17: Sketch of the low-pressure time projection chamber.

ratus. So in effect, the detector concurrently samples all muons in a single rf macropulse. To successfully isolate each of these muons there should be no more than about 10 muons per macropulse, independent of the pulse length provided it is in the range 50 ns – 6 μs. A higher rate capability could only be achieved with a detector with shorter drift times, and hence more walls and higher channel count. The additional walls will compromise the angular resolution due to multiple scattering, while the higher channel count raises the detector cost.

6 R & D Plan: Schedule and Funding

In a few years time the US high energy physics community will need to decide which new accelerator facility or facilities should be proposed and built in the US to provide cutting-edge physics beyond the next decade. If on this timescale a high-luminosity muon collider is to be a candidate for the facility of choice, a vigorous R&D program is essential to develop, test, and optimize the hardware needed to build an ionization cooling channel. In this proposal we have described a program of FOFO and lithium lens prototyping and testing that we believe can be accomplished in six years, and that will enable a complete cooling channel to be confidently designed for the First Muon Collider.

6.1 Schedule

The detailed schedule for the R&D program is summarized in Table 8. We assume that the program begins Jan. 1st, 1998, although some low level activities are already proceeding.

The FOFO part of the program can be summarized as follows. In 1998 we would develop the type of rf cavity to be used in the FOFO channel, and design a 1 m test section. In 1999 the test section would be fabricated and tested under power at liquid nitrogen temperature in a high-field solenoid. In parallel with this, a 10 m FOFO prototype channel (alternating solenoids, cavities, and absorbers) would be designed. In 2000, construction of the 10 m prototype would begin, and would take 2 years to complete. During this period, a wedge cooling prototype would be designed and construction begun in 2001. In 2002 the 10 m FOFO prototype would be ready to be moved to the ionization cooling test facility and its performance measured in a muon beam. The wedge cooling prototype would be ready for testing in the following year.

The lithium lens part of the program can be summarized as follows. In 1998 a 1 m long liquid lithium lens would be designed in parallel with the ongoing effort to construct a shorter lens for the Fermilab antiproton program. In 1999, fabrication of the 1 m prototype lens would begin, and a high-gradient prototype lens would be designed. In 2000, fabrication of the 1 m lens plus power supply would be completed and the lens would be bench tested. Fabrication of the high-gradient prototype would begin, and a wedge cooling prototype would be designed. In 2001, construction of the high-gradient prototype lens plus power supply would be completed and fabrication of the wedge cooling prototype would begin. In 2002, the high-gradient prototype would be bench tested, and both the high-gradient and the first 1 m prototype lenses would be moved to the ionization cooling test facility and their performances measured in a muon beam. These measurements would continue into 2003, during which time the wedge cooling prototype would be completed, bench tested, and moved to the test facility.

The FOFO and lithium lens R&D program described above require an ionization cooling test facility to be ready for measurements in 2002. In fact, a test facility could be used as early as the beginning of 2001 to test the 1 m lithium lens prototype. However, we believe preparation of the test facility will take longer than this, and is therefore on the critical path for the R&D program. The schedule for preparation of the test facility can be summarized as follows. In 1998 the beamline, solenoid channel, and instrumentation would be designed, and prototype studies for the instrumentation begun. In 1999 prototype work on the instrumentation would be completed, and construction of both the instrumentation and the bent solenoid channel begun. Fabrication of the solenoids plus instrumentation would take two years, and be completed by the end of 2000. We will assume that during this period a beamline and experimental area could be prepared. Installation, shakedown, and calibration of the instrumentation with beam would take place in 2001, and the facility would be ready for measurements in 2002. We estimate that the FOFO and lithium lens prototypes described in this proposal would require two calendar years of beamtime to adequately measure their performance in varying configurations. If at the end of this R&D program the feasibility of constructing an ionization cooling channel with the desired performance has been established, the test facility would be available for further development and optimization studies and/or for testing production stages of a complete ionization cooling channel.

6.2 Funding

The support that will be required to pursue the ionization cooling R&D program we have described is summarized in Table 9. We have not included the cost of constructing a beamline from existing magnets, or an experimental area. The cost estimates in the table are based on extrapolations from (i) the existing Fermilab-BINP contract for lithium lens development, (ii) a general study of solenoid cost as a function of stored energy made by M. Green, and (iii) estimates of the cost of each component required for the FOFO rf cavities for initial standing-wave and travelling-wave designs. Details are given in Table 7. The estimated cost of the six-year program is 32 M$.

7 Summary

We propose to conduct a six-year R&D program to develop the hardware needed for ionization cooling, and demonstrate the feasibility of using the ionization cooling technique to produce cooled beams of positive and negative muons for a muon collider. Our goal is to develop the cooling hardware to the point where a complete cooling channel can

RF Costs (10 meters)	
	$ K
Vacuum and Controls	300
Low Level Accessories	100
High Level Accessories	600
6 Klystrons	1200
4 Hybrid Couplers	250
4 Loads	150
6 Modulators	1350
Cavities	1000
Total	4950

Table 7: The estimated cost of the rf system for a 10 m FOFO channel. This a substantial component of the cooling system, and will require six 800 MHz klystrons, four hybrid couplers, and six modulators capable of providing 30 μsec pulses. The costs for standing-wave and travelling wave designs are comparable.

be confidently designed for the First Muon Collider. To accomplish this, vigorous R&D efforts are required to develop FOFO and lithium lens cooling hardware, and an ionization cooling test facility must be constructed to measure the performance of prototype devices. We estimate the cost of this R&D program to be 32 M$.

R & D Plan

	CALENDAR YEAR						
	1997	1998	1999	2000	2001	2002	2003
	0	1	2	3	4	5	6
Cavity Studies							
Cu–Be cold cavity test (material props)	----						
Fabricate cavity with Be foils		---					
Fabricate 3–cell cavity		---					
Fabricate 6–cell cavity with space for LiH		--	-				
FOFO Development							
Design 1 m test FOFO		-------					
Construct 1 m test FOFO			----				
High power test of 1 m FOFO in a solenoid			---				
Design 10 m prototype: cavity + alternating solenoid			-------				
Construct 10 m alternating solenoid channel				-------	------		
Construct 10 m cavity				-------	---		
Bench Test 10 m cavity					----		
FOFO prototype measurement in muon beam						xxxxx	
Design wedge cooling prototype				-------			
Construction of wedge cooling prototype					-------	------	
Bench test wdge prototype							---
Wedge prototype measurement in muon beam							xxxxx
Liquid Lithium lens development							
Novosibirsk lens construction & bench tests for antiproton source	---	-------	-------	---			
Design & Construction of 1 m long lens + power supply		-------	-------	---			
Bench Test of 1 m long liquid lithium lens				----			
Design & Construction of high–gradient lens prototype			---	-------	------		
Bench Test of high–gradient lens prototype						----	
Design & Construction of wedge cooling prototype				---	-------	-------	
Bench Test of lithium lens wedge cooling prototype							----
Lithium lens prototype measurement in muon beam						xxx	xx
Cooling Test Facility Preparation							
Design & prototype instrumentation		-------	---				
Construction of solenoids for instrumentation			-------	-------			
Construction of cavities for time measurement			-------	-------			
Construct instrumentation			----	-------			
Installation, shakedown, & calibration running					---xxxx		

Table 8: A summary of the Ionization Cooling R & D Schedule.

COST versus CALENDAR YEAR

	Cost (K$)	1997 0	1998 1	1999 2	2000 3	2001 4	2002 5	2003 6
Cavity Studies								
Cu–Be cold cavity test (material props)	200	100	100					
Fabricate cavity with Be foils	100		100					
Fabricate 3–cell cavity	200		200					
Fabricate 6–cell cavity with space for LiH	300		250	50				
FOFO Development								
Design 1 m test FOFO	100		100					
Construct 1 m test FOFO	500			500				
High power test of 1 m FOFO in a solenoid	200			200				
Design 10 m prototype: cavity + alternating solenoid	200			200				
Construct 10 m alternating solenoid channel	4000				2000	2000		
Construct 10 m cavity	4950				3500	1450		
Bench Test 10 m cavity	500					500		
FOFO prototype measurement in muon beam	1000						1000	
Design wedge cooling prototype	200				200			
Construction of wedge cooling prototype	4000					2000	2000	
Bench test wedge prototype	200							200
Wedge prototype measurement in muon beam	1000							1000
Liquid Lithium lens development								
Novosibirsk lens construction for antiproton source	--	---	----					
Design & Construction 1 m long lens+power supply	700		200	300	200			
Bench Test of 1 m long liquid lithium lens	500				500			
Design & Construction high–gradient lens prototype	1000			200	400	400		
Bench Test of high–gradient lens prototype	500						500	
Design & Construction of wedge cooling prototype	1000				200	400	400	
Bench Test of lithium lens wedge cooling prototype	500							500
Lithium lens prototype measurement in muon beam	1000						500	500
Cooling Test Facility Preparation								
Design & prototype instrumentation	400		300	100				
Construction of solenoids for instrumentation	2000			1000	1000			
Construction of cavities for time measurement	1000			500	500			
Construct instrumentation	5000			2000	3000			
Installation, shakedown, & calibration running	1000					1000		
TOTAL	32250	100	1250	5050	11500	7750	4400	2200

Table 9: A summary of costs for the Ionization Cooling R & D program.

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