SUMMARY OF THE LOW-EMITTANCE MUON COLLIDER WORKSHOP (FEBRUARY 6-10, 2006)*

K. Paul, R. P. Johnson#, Muons Inc., Batavia, IL 60510, U.S.A.
V. Yarba, Fermilab, Batavia, IL 60510, U.S.A.

Abstract

The Low Emittance Muon Collider workshop, held at Fermilab February 6-10, 2006, focused on the development of high-luminosity muon colliders using extreme muon beam cooling, where many constraints on muon collider designs are alleviated with beams of smaller emittance and lower intensity. The workshop covered topics related to proton drivers, targetry, muon capture, bunching, cooling, cooling demonstration experiments, bunch recombination, muon acceleration, collider lattices, interaction-point design, site boundary radiation, and detector concepts for energy frontier and Higgs particle studies. Lower emittance allows for a reduction in the required muon current for a given luminosity and also allows high energy to be attained by recirculating the beam through high frequency ILC RF cavities. The highlights of the workshop and the prospects for such colliders are discussed.

INTRODUCTION

During February 6-10, 2006, the first annual Low Emittance Muon Collider workshop [1] was held at Fermilab to advance the development of high-luminosity muon colliders using extreme muon beam cooling. Extreme muon beam cooling reduces many of the difficulties previously associated with larger emittance muon colliders, while presenting unique challenges of its own. Topics relating to protons drivers, muon beam cooling, muon cooling demonstration experiments, bunch recombination, muon acceleration, collider lattices, interaction point design, site boundary radiation, and detector concepts were discussed.

The workshop was sponsored by the Fermilab Technical Division and Muons, Inc. and was attended by 65 scientists, representing 16 different institutions. Of the 65 participants, 31 were not members of the Neutrino Factory and Muon Collider Collaboration (NFMCC).

This paper highlights some of the results of this workshop and discusses the advantages of muon colliders using low emittance muon beams, as well as some of the challenges that low emittance beams present. The paper also presents a possible scenario for a low emittance muon collider, based on recent research and innovations that were presented and discussed at the workshop.

LOW EMITTANCE MUON BEAMS

Low emittance muon beams diminish many of the constraints on muon collider designs. Low emittance beams allow for smaller, higher frequency RF cavities with higher gradient, make beam transport easier, and allow for stronger focusing at the interaction point since that is limited by beam extension in the quadrupole magnets of the low-beta insertion.

Additionally, a low emittance muon beam requires a lower muon current in order to reach the same design luminosity, as seen in Equation 1.

$$L = f\,n\,\frac{N^2}{2\pi\,\beta^*\,\varepsilon_T} \qquad (1)$$

In this relationship, L is the collider luminosity, f is the revolution frequency, n is the number of bunches in the collider, N is the number of muons per bunch, β^* is the average amplitude function at the interaction point, and ε_T is the average transverse emittance of the beam at the interaction point, assuming an approximately round beam and no disruption. This common formula shows how a factor of 10^2 reduction in transverse emittance leads to a factor of 10 reduction in the number of muons per bunch required for the same luminosity. This reduction in the required muon current reduces the significance of many known problems with previous muon collider designs, some of which are listed below.

- Reduced muon beam current leads to fewer high-energy neutrinos produced from muon decay in the collider ring, reducing the site boundary radiation created by high-energy neutrino interactions within the earth or shielding material.
- Fewer muon decays also means fewer decay-produced electrons that act as a background in the detectors.
- Requiring fewer muons in the collider ring reduces the required proton beam power incident on the target, simplifying the design of the proton driver and target region.
- Smaller muon beam current reduces the heat deposited into the muon ionization cooling material.
- Smaller beam current also reduces beam-loading and space-charge effects.

Low emittance muon beams also present a number of challenges, even with lower beam current. First, the cooling necessary to produce such low emittance beams that can still achieve desirable collider luminosities is very challenging. This issue is being addressed by recent muon cooling innovations and technologies currently in development, which will be discussed in the next section. Second, space-charge and beam-loading effects can still be an issue at lower energies, after the beam has been cooled to its lowest emittance. This issue is being addressed by considering new schemes and layouts for the front end of the collider, also to be discussed in the next

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#rol@muonsinc.com

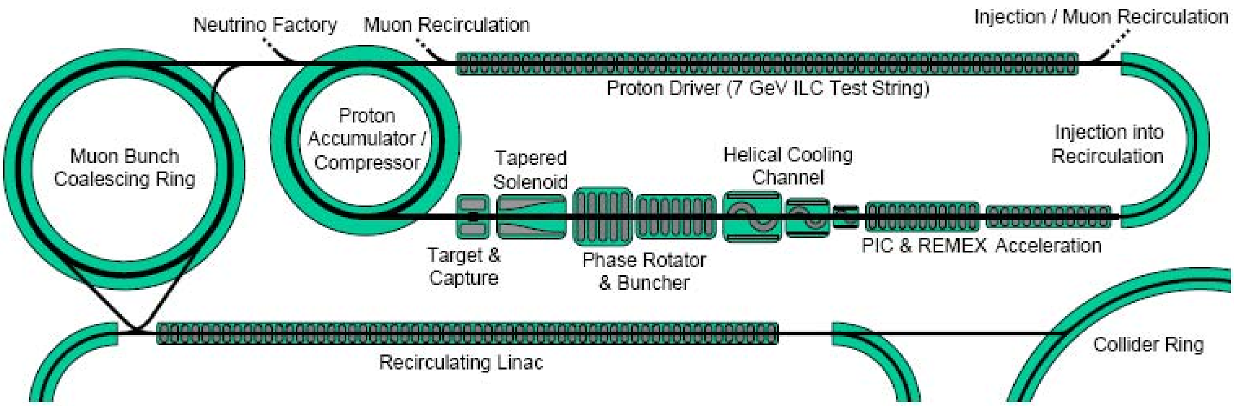

Figure 1: This figure depicts a possible scenario for a muon collider involving a multi-purpose proton driver, extreme muon beam cooling, muon recirculation in the proton driver, bunch coalescing, and synergy with ILC technology.

section. Third, lower emittance beams result in larger beam-beam tune shifts produced during crossing at the interaction points. This issue was discussed at the workshop, and it is believed that the expected beam-beam tune shift in the proposed muon collider* will be acceptable.

MUON COLLIDER

There are a few scenarios for a muon collider that have been discussed both at the workshop and beyond. In this section, one of these scenarios will be described. This scenario incorporates many of the innovations that were presented and discussed at the workshop. However, for a complete list of the workshop presentations and discussion topics, the reader is referred to the LEMC06 Workshop website [1].

General Parameters

One of the most prominent successes of the workshop was an updated list of general muon collider parameter goals. Many of the parameters have not changed for over a decade, but new innovations and developments have given rise to a number of new design goals. A partial list of the parameters pertaining to the muon collider scenario discussed at the workshop is shown in Table 1.

Scenario Layout

Figure 1 shows the layout of a muon collider scenario discussed at the workshop. It was chosen to meet the general parameter goals set at the workshop, described in the previous subsection. One of the features is a possible synergy with ILC-based technology. In this scenario, a 7 GeV, 1.3 GHz ILC RF cavity test string is considered for use in the proton driver and serves a dual purpose for muon recirculation to 21 GeV. We also consider ILC cavities for later recirculation to 2.5 TeV prior to injection into the collider ring.

Table 1: LEMC06 Collider Parameters

Luminosity (L)	10^{35} cm^{-2} s^{-1}
Beam Energy (E_μ)	2.5 TeV
Proton Pulse Repetition Rate (f_{rep})	20 Hz
Proton Beam Power on Target (P)#	< 1 MW
Proton Beam Energy (E_p)	8 GeV
Normalized Transverse Emittance (ε_{NT})	~1 mm mrad
Amplitude Function at IP (β*)	5 mm
Depth of Collider Ring (d)	~250 m
Number of Bunches per Proton Cycle (n)	1
Fraction of Muons Decaying in Ring (δ)	62%
Number of Muons per Bunch (N)	~10^{11}
Muon Beam Current (I_μ)	~3 mA
Beam-Beam Tune Shift ($\Delta\nu$)	< 0.1

Depending on the power of the proton driver, only a fraction of protons per cycle need be incident on the target. After acceleration from the driver, these protons are injected into an accumulator or bunch compressor to narrow the length of the proton pulse before ejection, making the proton pulse as narrow in energy spread as possible before the target. After ejection, the protons are sent to the target.

Pion capture is accomplished in a 20 T solenoid that surrounds the target. The capture solenoid is immediately followed by a tapered solenoid that decreases the field adiabatically from 20 T to ~2 T. The target design and composition can vary depending upon what is needed. Shorter, more efficient cooling channels have fewer muon decays before acceleration to >1 GeV, allowing less efficient, and less demanding, production from the target. These types of pion/muon capture, and their options and

*It is believed that a beam-beam tune shift of $\Delta\nu \leq 0.1$ is acceptable.
#A Proton Beam Power on Target, P < 1 MW, assumes a muon transmission of T > 10% from capture after the target to injection into the collider ring.

variations, have been discussed at great length in the Neutrino Factory Feasibility Studies [2,3].

This scenario follows the tapered solenoid with a high-pressure, gas-filled RF phase rotation and buncher channel. Low-frequencies and high-gradients are believed possible with high-pressure, gas-filled cavities, as the dense gas suppresses RF breakdown. Therefore, gas-filled cavities may be able to quickly rotate the initial, large energy-spread bunch to small energy spread in a quarter phase-energy RF rotation. Following rotation, the bunch is re-bunched at the higher RF frequencies used in the cooling channels. Note that low-frequency phase rotation only applies to a single charge-sign of muons, so the phases must be alternated between pulses to capture both signs, or two simultaneous channels must be constructed with charge separation at the target.

Primary cooling in this scenario is performed with a helical cooling channel (HCC) [4]. The helical cooling channel combines helical dipole and quadrupole magnets with a solenoid to generate continually focusing, dispersive magnetic fields. The beam travels along a helical trajectory through high-pressure gas, exhibiting longitudinal and transverse cooling simultaneously. Most recent simulations of the HCC show reduction of the 6D emittance by a factor of 5×10^4, while theoretical models suggest that cooling factors of 10^6 may be possible.

Following the HCC, the beam requires more transverse cooling, while it has been cooled more than necessary in the longitudinal dimension. Thus, a combined parametric-resonance ionization cooling (PIC) and reverse emittance exchange (REMEX) channel [5] cools the beam transversely while exchanging some transverse emittance for longitudinal emittance. It may be possible that such a channel could be devised in a small ring.

After this front end, the cooled muon beam consists of approximately 10 bunches with a normalized transverse emittance of approximately 2 mm mrad and has been matched into 1.3 GHz RF. The length of this front end is less than 1 km, meaning that less than 50% of the muons have decayed. At this point, the beam is accelerated to 1 GeV and injected into the proton driver linac and circulated three times, for a combined acceleration of the beam up to approximately 22 GeV.

In this scenario, the front end of the collider is sufficient for the preparation of a muon beam for a neutrino factory, as well. After this first recirculating linac, the beam can be sent to a muon storage ring, serving as a neutrino factory. If higher energies are required for the neutrino factory, further recirculation may be done, or additional RF can be installed.

For muon collider operation, the 10 bunch beam must be coalesced into 1 bunch. After ejection from the first recirculating linac, the beam is injected into a fast bunch-coalescing ring. The challenge is to coalesce the 10 bunches, nominally bunched with a few-hundred megahertz spacing, with relatively small decay losses. However, coalescing at higher energy is required if space-charge and beam-loading problems are to be avoided at lower energy.

The last stages of the muon collider consist of an ILC-based recirculating linac, accelerating the beam to 2.5 TeV prior to injection into the collider ring. A Tevatron-like ring is required to store the beams for collision, but the ring must be between 200 m and 300 m deep to allow shielding for the muons. Clever designs for the collider ring are required to maintain luminosity while reducing hazardous radiation associated with the intense, high-energy neutrinos.

CONCLUSIONS

The Low Emittance Muon Collider workshop discussed a number of different collider options, and only one scenario is presented here, which incorporates most of the new techniques and schemes discussed or proposed at the workshop, such as a dual-purpose recirculating linac, fast bunch coalescing, and synergy with ILC-based technology.

Many of the components of the front end are well developed, but still require further development. The pion production and capture section has changed little in the last decade, and the helical cooling channel has shown many successful simulation results in the past years.

Some of the new components, such as the gas-filled phase-energy rotation channel, the bunch coalescing ring, the PIC/REMEX channel or ring, the proton accumulator, matching into and out of the HCC, require a great deal of work. However, no “show stoppers” appear on the horizon, no matter how challenging the requirements appear.

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