TARGETRY FOR A $\mu^+\mu^-$ COLLIDER *

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Abstract

The requirement for high luminosity in a $\mu^+\mu^-$ collider leads one to conclude that a prodigious source of pions is needed followed by an efficient capture/decay channel. Significant targetry issues are raised by these demands. Among these are i) the best target configuration to tolerate a high-rep rate, high-power proton beam ($\sim 10^{14}$ ppp at 15 Hz), ii) the pion spectra of the produced pions and iii) the best configuration for maximizing the quantity of captured pions. In this paper, the current thinking of the $\mu^+\mu^-$ collider collaboration for solutions to these issues is discussed. In addition, we give a description of the R&D program designed to provide a proof-of- principle for a muon capture system capable of meeting the demands of a future high-luminosity machine.

1 INTRODUCTION

Since leptons are point-like particles, in contrast to hadrons which are a composite of quarks and gluons, leptons fully participate in high-energy interactions. For hadrons, such as protons or mesons, kinetic energy is shared with their constituents thus diluting the energy reach of the collision. This lepton energy advantage is on the order of a factor of 10, i.e. a lepton-lepton collision of 1 TeV has the same physics reach as a $\sim$ 10 TeV proton-proton collision. The muon shares this lepton energy advantage with the electron.

The muon, on the other hand, has a mass of 105.6 MeV and is therefore a factor of 207 times more massive than the electron. This provides one with the important capability of reducing synchrotron radiation by this mass ratio to the 4th power. Consequently, with muons, one can contemplate the possibility of circular high-energy lepton machines. This capability means that high-energies can be achieved with the possibility of recirculating the particle beams thus providing more efficient use of accelerating systems while allowing for a smaller footprint for the entire machine complex. Once the goal energy has been reached, we can now consider circulating colliders which have a luminosity which is proportional to the number of circulating turns within the collider rings. Finally, because of the suppressed synchrotron radiation, the energy spread of the colliding beams can be much reduced over that of electron colliders. Some machine scenarios contemplate energy spreads as low as 0.003%. This can be an important advantage when studying narrow resonances.

Muons, however, do possess a significant attribute which mitigates their usefulness, namely they decay with a lifetime of ~ 2 μsec when at rest. To overcome this problem, the muon collider collaboration adopts the strategy of producing prodigious amounts of muons via a chain of; 1) pion production from a robust proton beam impinging on a high-Z target, 2) conducting these pions down a solenoid based decay channel allowing the muons to appear as pion decay products and 3) conducting the resulting muons through an ionization cooling channel[1] in order to reduced their phase space to dimensions suitable for subsequent acceleration and to achieve a high luminosity at the subsequent collider (as an example, 7 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for a 1.5 TeV center-of-mass (CoM) machine[2]).

2 PION PRODUCTION

In order to achieve the design luminosity, 2 10^{12} muons per pulse (for the 1.5 TeV CoM machine) must be introduced into the recirculating collider (for each sign). We assume 1/4 survival rate due to aperture and decay losses in the ionization cooling and acceleration stages and a 50 % efficiency for the decay/phase rotation channel. This leads to the requirement that we produce ~ 2 10^{13} pions within the collection energy band (KE= 50-650 MeV) at the target.

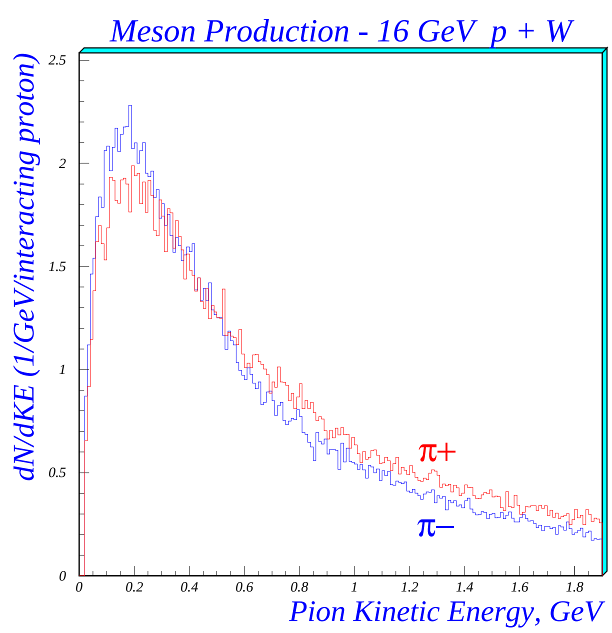

Figure 1: Meson production using the MARS code. Note that the most prolific portion of the pion energy spectrum lies below 600 MeV

Extensive modeling using three different Monte Carlo computer codes have been performed[3][4][5] resulting in the conclusion that we require a 4 MW proton beam (15

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Hz operation) impinging on a high-Z material target. In order to benchmark these codes in the important low-energy portion of the pion production spectrum, the muon collaboration has participated in an AGS experiment, E-910[6], where good efficiencies for detecting forward low-energy pions within a time projection chamber is realized. Data from this experiment is currently being analyzed.

3 TARGETS

Maintaining target integrity with beam powers at the level of 4 MW is difficult. Since about 10% of the proton beam energy is ultimately deposited into the target, this leads us to infer that the target must absorb 400 kW of sustained power and also withstand an instantaneous energy deposition of 30 kJ.

Water cooling via a thermal bath is not considered viable as it would lead to unacceptable losses due to the absorption of the produced pions. Radiative cooling is inadequate for these power levels in a compact target. We therefore consider moving targets as the best solution and choose as our baseline approach moving free-liquid targets where disruption due to shock damage from the single pulse energy deposition can be more easily contained.

Liquid targets have the additional advantage of being relatively easy to move and cool. Contained liquids are not preferred as they will expose the containment vessel to possible high-shock thresholds. Jets of liquid mercury have already been demonstrated[7] but without exposure to a high-power beam.

4 TARGETRY SYSTEM

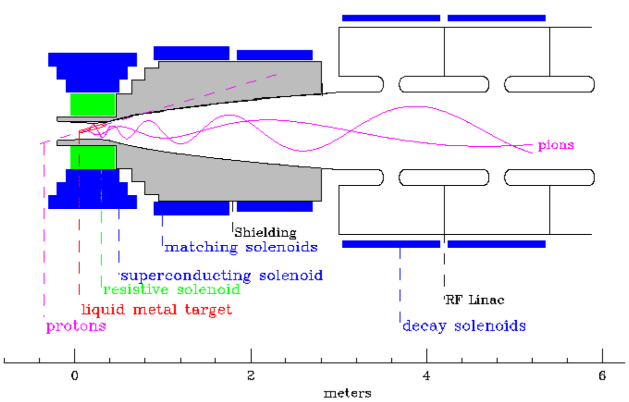

Figure 2: Schematic view of the muon collider targetry system. The proton beam is incident on a skewed target inside a solenoidal magnetic field which tapers from 20 T at the target to 1.25 T at the beginning of the rf linac.

We show in Figure 2, a schematic of our baseline targetry/capture system. The capture solenoid is a hybrid magnet consisting of a inner 6-T, water-cooled hollow-conductor magnet with an inner diameter of 24 cm and an outer diameter of 60 cm. There is space for additional shielding between this coil and the beam pipe. The outer coil is a superconducting magnet extending to an outer diameter of 80 cm. It will generate an additional 14-T field at the target.

The product of solenoid field (B) and the beam pipe radius (R) determines the maximum transverse momentum which the produced pions can possess and still be captured. On the other hand, the transverse emittance of the resulting captured beam is proportional to BR^2, hence we benefit by selecting a high-magnetic field coupled with a small bore radius. Our baseline parameters call for a solenoidal field of 20 T and a bore radius of 7.5 cm thus yielding a maximum transverse-momentum of p_t = 225 MeV/c for those pions which are conducted into the decay channel.

In order to realize maximum pion production efficiencies, we favor using high-density target material embedded within the high-field capture solenoid. Optimum target geometry calls for a small target diameter in order to reduce the effect of pion reabsorption after production. We find that it is advantageous to tilt the target slightly (100-150 mrad) to avoid having the pions spiral back onto the target and be lost through absorption.

The rf linac depicted in Figure 2 represents the beginning of the phase rotation channel. The phase rotation system is designed to contain and shape the longitudinal emittance parameters of the captured muon beam. The initial frequency is determined mainly by the longitudinal spread of the proton driver bunch ($\tau \sim 1$ to 2 ns) and the drift space from the target to the initial cavity. Based on a capture kinetic energy band of 50 to 650 MeV and a drift distance of 3 m, the initial frequency needs to be on the order of 100 MHz. Modeling of this system[8] has yielded typical phase rotation exit parameters of dE/E = 15% and an rms $c\tau$ of 1.5 m.

The 20-T capture magnetic field is tapered adiabatically down to a lower field in the phase rotation channel. We keep the total magnetic flux constant but reduce the axial magnetic field by a factor of 16 to a more manageable 1.25 T while increasing the beam bore radius by a factor of 4 to 30 cm.

Although we are exploring methods of separating the pions by charge state, our current baseline calls for producing pions of each sign with separate proton pulses. The solenoid channel will transport each sign with equal facility and the phase rotation can work equally well with each charge state provided the rf frequencies are configured to be odd multiples of a fundamental harmonic and the proton drive beam is delivered with a phase separation of $n\pi$ within the fundamental harmonic.

5 R&D PROGRAM

We have identified several critical issues which need to be addressed in order to insure the success of our program.

- Identification of the appropriate material for a liquid jet target.

- Performance of a liquid jet in a 20-T solenoidal field.
- Performance of a liquid jet in a 4 MW proton beam.
- Operation of a 20-T hybrid solenoid in a high-power proton beam environment.
- Operation of a rf cavity in a high-radiation environment.

Not so technically demanding but important to the eventual success of a muon collider is the optimization of the target parameters in order to maximize the pion capture efficiency.

We have embarked on an R&D program to address these and other important issues. Included in this program are:

- Study of liquid/proton beam interactions.
- Build prototype liquid jets.
- Study the effects of eddy currents on the liquid jet propagation through a 20-T field at the National High Magnetic Field Laboratory.
- Study the effects of a high-power proton beam on the liquid jets at Brookhaven's AGS.
- Conduct an experimental test of the proposed targetry system at Brookhaven's AGS.
- Build a 70 MHz rf cavity and operate it in a high-radiation environment.

The cornerstone of this R&D effort is found in our BNL proposal[9] in which we detail our plans to build and test the key components of our targetry scheme in a high-power proton beam environment. We show in Figure 3 the layout of our proposed experiment.

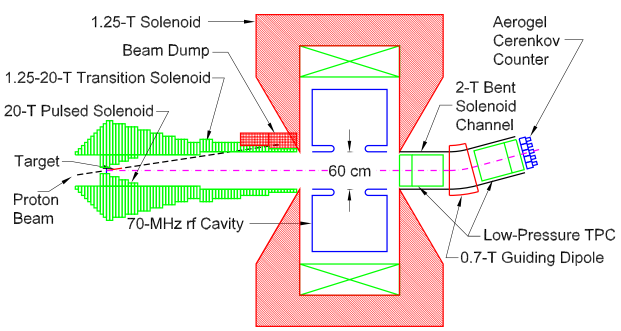

Figure 3: Schematic view of the proposed targetry experiment at the Brookhaven AGS.

In order to minimize cost while retaining the essential functionality of a 20-T solenoidal field at the target, we have chosen to build a pulsed resistive based solenoid in which we will sacrifice repetition rate for cost savings. Additional cost savings may be realized by using an iron-dominated resistive solenoid to surround the rf cavity.

The bent solenoid channel at the end of the experimental setup will serve as a spectrometer to measure the pions/muons spectra and evaluate the pion/muon yield achieved by the chosen target configuration.

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