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Review of a high-intensity muon source for fundamental high-energy physics experiments

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Diktys Stratakis[1]
Brookhaven National Laboratory
Upton, NY 11973, USA
E-mail: `diktys@bnl.gov`

Beams of accelerated muons are potentially of great interest for fundamental high-energy physics research as well as for various industrial and medical applications. Muons can be produced indirectly through pion decay by interaction of a charged particle beam with a target. The muon yield is fractionally small, with large angle and energy dispersion, so that efficient collection in all dimensions in phase-space is necessary. Here, we report on a compact muon collection system that can capture a large fraction of a divergent pion-muon beam and transport it further downstream with minimum losses.

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[1] Speaker

1. Introduction

Muon-based facilities [1] offer the unique potential to provide the next generation of capabilities and world leading experimental support spanning physics at both the Intensity and Energy Frontiers. Muon beams of high brilliance have been proposed as the essential ingredients of a Muon Collider (MC) [2] or a Neutrino Factory (NF) [3] since the 1960's. The MC addresses the high-energy frontier: looking at precise Higgs physics and beyond, while the NF addresses the precision frontier: looking at CP-violation in the neutrino sector. The present designs of a NF or a MC front-end (up to the beginning of the cooling section) are similar, as can be seen from the schematic layouts reported in Figure 1.

Muons are charged particles with mass between the electron and proton and can be produced indirectly through pion decay by interaction of a charged-particle beam with a target. To produce sufficient muons, a high-energy (multi- GeV), high-intensity proton beam is needed, implying the use of a linear accelerator to bombard a stationary target. The muon yield is fractionally small, with large angle and energy dispersion, so that efficient collection is necessary in all dimensions of phase-space. However, the short lifetime of muons – 2.2 μs in the rest frame – makes the transport of a muon beam very challenging technologically [4].

In this paper the production of pions, their decay into muons and the survival of muons during transport are studied. We present a method for manipulating the longitudinal and transverse phase-space in order to efficiently capture and transport a muon beam from the production target towards the accelerator chain. In that method, a set of properly tuned rf cavities captures the muon beams into strings of bunches and aligns them to nearly equal central energies, and a following set of rf cavities with absorbers cools them by a factor of three in transverse emittance. With the aid of numerical simulations, we show that our proposed muon collection scheme can simultaneously capture species of both signs with a notable rate of 0.12 muons per initial 8 GeV proton. We systematically analyze the sensitivity in performance of the channel against key parameters such as the number of cavities, accelerating gradient and magnetic field. The compact muon source we describe can be used for fundamental physics research in neutrino experiments.

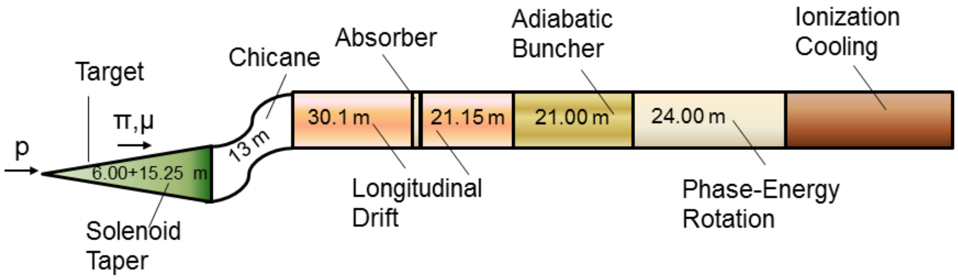
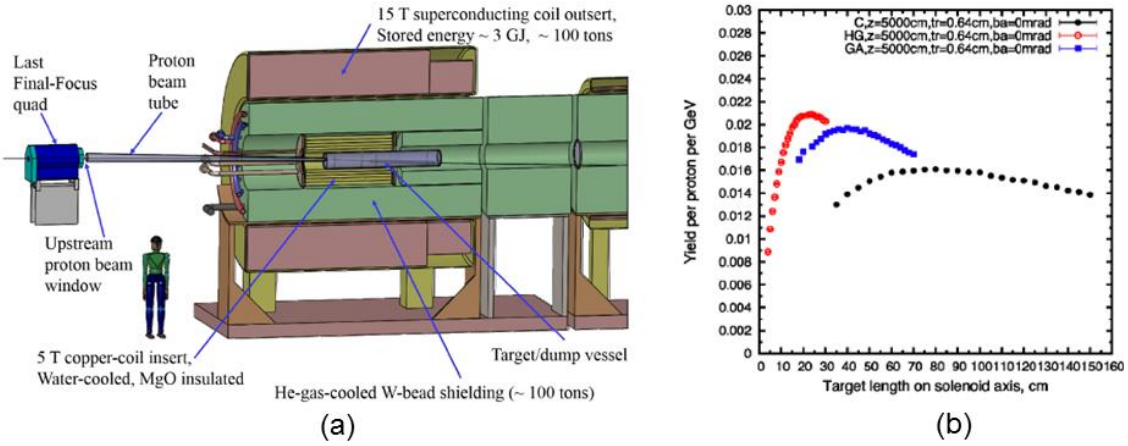


Figure 1:Conceptual diagram of the proposed high-intensity muon source.

1.1 Target Optimization

The basic concept for the Target System for a Muon Collider as a solid or liquid-metal target that intercepts the proton beam inside a high-field solenoid magnet to capture both signs of secondary particles emerged already in 1995 [5]. The present concept is for a graphite (or carboncarbon composite) target and proton beam dump inside a 20-T solenoid field, which field tapers down to 2 T, used throughout the rest of the Muon Collider/Neutrino Factory Front End, over 5 m [6]. The yield of muons from the target is maximal at low kinetic energies, roughly 40 < KE < 180 MeV, which particles emerge at large angles to the proton beam, favoring a cylindrical target of small radius, and tilted slightly with respect to the magnetic axis to minimize reabsorption of particles if their helical trajectory passes through the target a second time. The feasibility Optimization of the graphite target and dump was performed via MARS15(2014) simulations. In an iterative procedure the best values of the target length, radius and tilt angle were determined, assuming that the proton beam is along the target axis at its center, z = 0 and that the rms beam radius is 1/4 the target radius. The figure of merit in the optimization was the number of muons at z = 50 m with kinetic energy in the range 40 < KE < 180 MeV. More details on these results can be found in Ref. 6.

A comparison of the yield from a graphite target with that from gallium and mercury free-liquid-jet targets is shown in Fig. 2, which indicates that higher-Z targets are favored. While the optimum graphite target radius is near 0.7 cm, there is little decrease in muon yield with a target of larger radius, which latter leads to a lower operating temperature of the radiatively cooled target. Hence a radius of 0.8 cm has been adopted for operation at 1 MW, and a radius as large as 1.2 cm might be favored for use at 4 MW. While a beam/target tilt angle of 65 mrad is optimal, it would be simpler for the Final Focus system of the Proton Driver [7] if the tilt angle were zero. This would imply a decrease of 15% in the muon yield.



(a) (b)

Figure 2:(a) Conceptual diagram showing the solid target module inside a high-field solenoidal magnet,and (b) Muon yield at z = 50 m as a function of target length for carbon, gallium and mercury targets.

Another aspect of the Target System optimization concerned the length of the “taper” of the solenoid field from 20 down to 2 T. For this, simulations using the ICOOL code were used, with input of the secondary-particle spectrum at the end of the target from a MARS15 simulation. It turns out the a longer, more adiabatic taper improves the transverse emittance of the muons, but increases the longitudinal emittance. The latter increase is unfavorable for capture of the muon beam into rf bunches, such that the optimum taper length is about 5 m.

1.2 Energy Deposition

In addition to the desirable pions which will eventually decay into muons, there are a number of other particles, in particular protons, which will be focused by the downstream solenoid channel. Without collimation, this flux is lost on the front end apertures at kW/m levels, much larger than the approximately 1 W/m desired to ensure “hands-on” main- tenance. An absorber can reduce the uncontrolled energy deposition in the downstream channel from these particles, but making an absorber thick enough to eliminate the high energy protons would also significantly reduce the pion and muon flux. To circumvent this difficulty a solenoid chicane is proposed [8] to eliminate the high energy protons, leaving the absorber to deal with the remaining low energy protons. The chicane is a bent solenoid system. Lower momentum particles are strongly focused by the solenoid and follow the chicane with little orbit distortion. High-momentum particles are not strongly deflected by the bent solenoid and are lost in or near the chicane, and collimated on shielding walls. The action of the chicane is illustrated in Fig. 3.

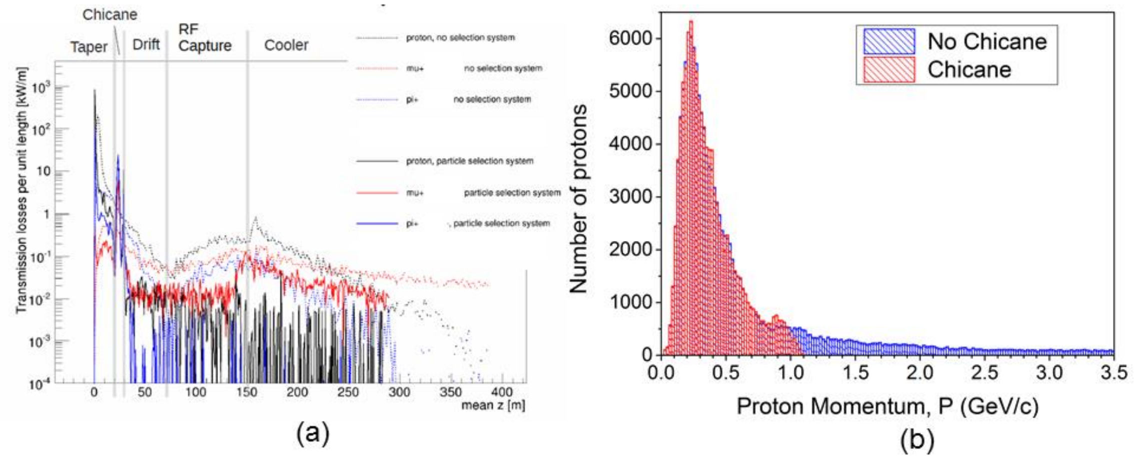
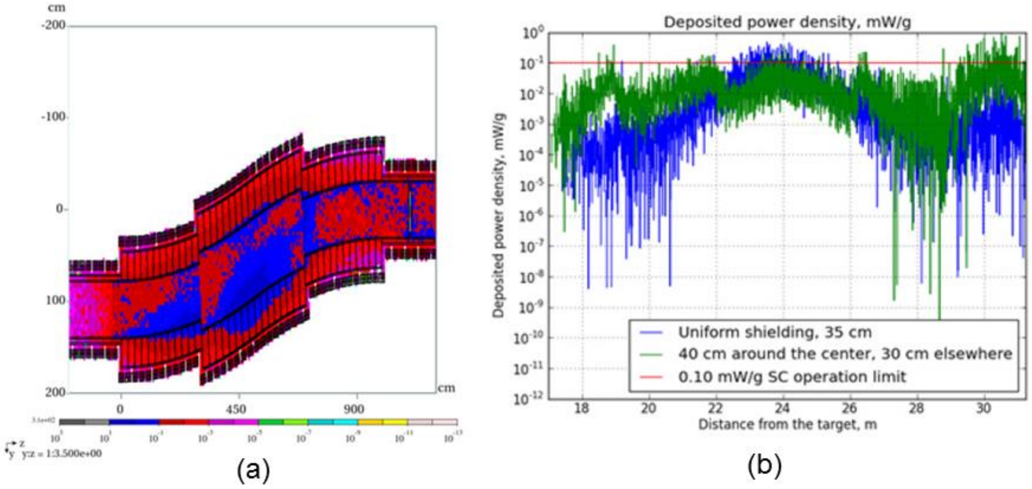


Figure 3: (a) Energy deposition with and without the chicane, and (b) momentum distribution for protons with and without chicane.

The higher-energy particles (mostly protons) which leave the beam in the chicane would pass through the coils of the bent solenoids unless the latter have adequate internal shielding. As for the superconducting coils of the target-system upstream of the chicane, we desire that the maximum energy deposition in the coils be less that 0.1 mW/g to permit an operational lifetime greater than 10 years of 10^7 s. This criterion is taken from studies conducted for the ITER project. To evaluate the amount of shielding required for the magnets of the Decay Channel chicane, we used a MARS15(2012) simulation with field maps generated by G4beamline. A preliminary version of these studies was reported in [9, 10].

In a first study [9] of possible shielding configuration for the chicane, the beampipe was assumed to have radius 42 cm, and the thickness of the tungsten-bead shielding was 35 cm. Figure 1 shows a “horizontal” section of the model of the chicane. The average power deposition in the superconducting coils of the chicane, averaged over azimuth, for the model of Fig. 1 is shown to be less than the “ITER” limit of 0.1 mW/g. To estimate the peak energy deposition in the coils, the MARS model was segmented azimuthally, leading to the results shown in the blue curve of Fig. 4(b) , where the deposition in a few regions remains above the “ITER” limit. In a second iteration of the study, only the central 4 m of the chicane was modeled with a beampipe of 40 cm radius, with the outer segments having a beampipe of 30 cm radius, as shown in Fig. 4(a) . The thickness of the shielding in the central portion of the chicane was taken to have 40 cm thickness, while the thickness of the shielding was only 30 cm in the outer portions of the chicane. Next steps in the studies are to introduce a beampipe which changes its cross section from circular to elliptical and back to circular along the chicane, along with shielding whose inner surface matches the beampipe and whose outer surface is circular, and with thickness that varies along the chicane.



(a) (b)

Figure 4: (a) MARS15(2012) simulation of energy deposition in a model of the chicane with non-uniform beam-pipe of 42 cm radius around the central part of the chicane and 30 cm elsewhere, surrounded by 40 cm of tungsten-bead shielding around the central part of the chicane and 30 cm elsewhere; and (b) Simulated peak energy deposition in the superconducting coils of the chicane, based on an azimuthally segmented model.

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Regarding the optimization of the particle selection system we scan the geometric parameters of the chicane and look for solutions with the best transmission that remove almost all the protons above a given energy (the “maximum proton kinetic energy”, which we will henceforth denote with K). We use this to express the parameters of the chicane geometry in terms of K. We choose several of these optimal geometries and add a beryllium absorber downstream of the chicane, put it at two different positions, vary its thickness, and examine the muon transmission and the effectiveness of the system at removing protons. We scan in 20 mrad steps and L in 0.5 m steps. Our performance criteria are K and the muon transmission, without an absorber, at a position 44.1 m downstream from the start of the chicane. K is computed by finding the lowest proton energy such that the sum of the kinetic energies of all protons with that energy and higher is less than 2 W per MW of proton power hitting the target. The muon transmission is the number of the muons with kinetic energies between 80 and 260 MeV and pions with kinetic energies between 80 and 320 MeV, divided by the same quantity without a chicane.

Figures 5 shows the results of that parameter scan. Chicanes with very different parameters can have similar K but different transmissions. We chose some parameters which were on the high transmission edge of the points in Fig. 5(a). Those points are colored in the figure, and their θ and L are plotted in Fig. 5(b). We then fit those points to the functional form L=L0+L1 K and θ=θ0+θ1/K. The resulting parameters are L0 = 1.6 m, L1 = 9.1 m/GeV, θ0 = 69 mrad, and θ1 = 28 mrad GeV.

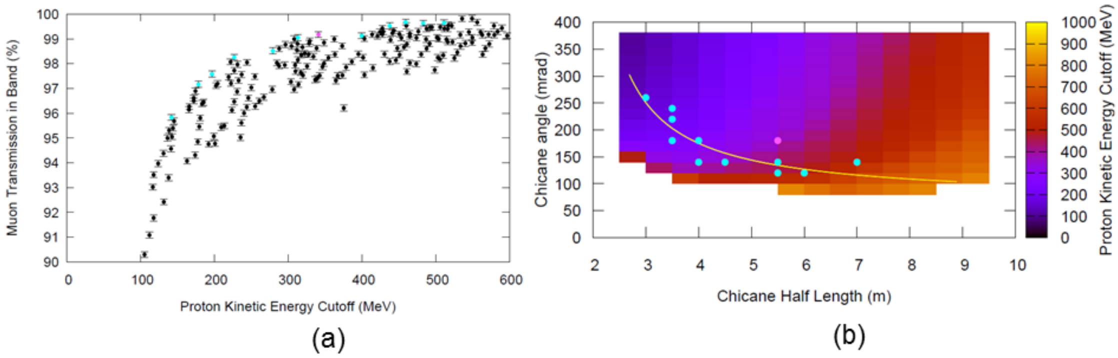

Figure 5: (a) Muon and pion transmission and K for the chicane parameters we scanned; (b) K downstream of the chicane as a function of L and θ. Points correspond to the colored points in Fig. 5(a).

1.3 Buncher & Phase Rotator

In order to reduce the near 100% dp/p [see Fig 6(a)] of the muons out of the target, the beam is phase rotated into a longer string of bunches with lower momentum spreads. First the muon beam is allowed to lengthen and develop a time-energy correlation [see Fig. 6(b)]. Then, over a distance of 21 m, it is bunched into a train. This is done while maintaining the time energy correlation, using rf cavities whose frequencies vary with location (from about 500 MHz to 360 MHz). The lattice consists of 0.5 m long cavities placed within 0.75 m long cells, focused by 2 T solenoids outside the rf. The rf gradient is slowly increased from cell to cell, rising to 15 MV/m. This adiabatically captures the muons into the string of rf buckets (see Fig. 6(c)], with minimum phase-space dilution. Over the next 24 m, by phase and frequency control, the rf accelerates the late low energy bunches, and decelerates the early high energy ones, to give a monoenergetic train with 325MHz spacing [see Fig. 6(d)]. The muons of both signs are bunched and phase rotated simultaneously into interleaved bunches. The best 21 bunches will be used. At the end of the phase rotation channel there are 0.2 muons of each sign per incident 8 GeV proton on target.

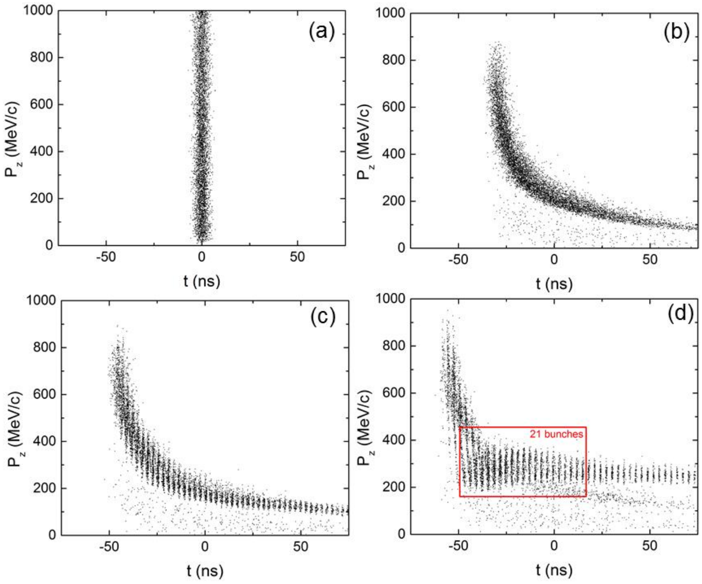

Figure 6: Evolution of the longitudinal phase-space along the muon source.

1.4 Future Plans

The main goal of this portion of the proposal is to continue to develop the key concepts required for a compact and efficient muon production and capture system based on an incoming proton beam that can provide an intense muon source. This production and capture system consists of a target within a capture solenoid, a decay channel, a chicane followed by an absorber to remove unwanted particles, and a buncher and phase rotation system to manipulate the longitudinal beam phase space into a desired form.

An intense muon source based on protons remains the only identified path to the high intensity muon beams required for high energy physics applications. Since the P5 report emphasizes having Fermilab becoming the world-leading facility for neutrino beams, the importance of the proton driver interface as the Fermilab facility plan evolves cannot be overlooked. Long-range planning toward a Neutrino Factory is essential for the post-LBNF era. Thus this research area includes exploring concepts to deliver MW-class proton beams consistent with the planned evolution of the proton complex at Fermilab.

One of the most significant challenges for a muon source is energy deposition from unwanted particles in the accelerator components. Concepts have been identified that could mitigate the impact of this energy deposition (in particular a chicane and a downstream absorber). We will explore these concepts to determine the efficacy of approaches that control halos, beam loss, and energy deposition. We will deliver the specifications for and performance evaluation of a source incorporating these elements.

One promising method for achieving the highest gradients in RF cavities, in particular those that are in magnetic fields, is to fill the cavities with pressurized hydrogen gas [12]. While vacuum RF cavities would be preferred and novel solutions to circumvent the rf in magnetic field challenge have been published [13], pressurized cavities are an important option for ensuring feasibility and possibly improving performance. The impact of this technique on the buncher and phase rotation systems of these muon sources will be studied [14] to understand its consequences.

An additional goal of this topical area is to identify possible applications that would benefit from such an intense muon source. Indeed, muon sources could have many applications in diverse fields, including fundamental science (such as Mu2e and g-2) and areas of societal interest. For example, scientists involved in homeland security have proposed using muon sources to interrogate cargo vessels for illicit nuclear material. Many applications have an interest in having a polarized muon beam. In addition to identifying applications for which muon sources are of interest, we will examine methods for increasing the polarization of high intensity muon sources. Primary deliverables of the envisioned future effort will include:

- Design specifications for the systems required to control particle loss in the muon production and capture sections of our proton-based muon source along with the corresponding performance specifications of those systems;
- A design concept for an optimized buncher and phase rotation system utilizing gas-filled RF cavities along with its performance specifications;
- If time allows, Design specifications for the system modifications required to provide a more highly polarized source of muons along with the corresponding performance specifications.

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1.5 Summary

Beams of accelerated muons are of great interest for fundamental high-energy physics research as well as for various industrial and medical applications. Muons are produced indirectly through pion decay by interaction of a charged particle beam with a target. However, the muon yield is fractionally small, with large angle and energy dispersion, so that efficient collection in all dimensions in phase-space is necessary. Here, we have described a fast method for manipulating the longitudinal and transverse phase-space with the purpose to efficiently capture and transport a muon beam from the production target towards the accelerator chain. In that method, a set of properly tuned rf cavities captures the muon beams into strings of bunches and aligns them to nearly equal central energies, and a following set of rf cavities with absorbers cools them by a factor of three in transverse emittance. With the aid of numerical simulations we found that our present muon collection scheme is capable of capturing simultaneously muons of both signs with a notable rate of 0.12 muons per initial 8 GeV incident proton. In addition, we discussed a conceptual design of a handling system for the removal of unwanted secondary particles from the target region (such as electrons and protons). We showed that such a system can successfully remove particles with momentum > 1 GeV/c and thus significantly reduce activation of the machine. The compact muon source described here can be used for fundamental physics research in neutrino experiments, muon radiography to study industrial machinery and medical research such as functional brain studies through muon-spin relaxation technique.

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