OVERVIEW OF A MUON CAPTURE SECTION FOR MUON ACCELARATORS*

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Abstract

We describe a muon capture section to manipulate the longitudinal and transverse phase-space to collect efficiently a muon beam produced from an intense proton source target. We show that this can be achieved by using a set of properly tuned rf cavities that capture the beam into a string of bunches and aligns them into nearly equal central energies, with a solenoidal chicane that filters high momentum particles, followed by a proton absorber that reduces the energy of all particles. This work explores the key parameters that are needed for successful muon capture, such as the required rf frequencies, rf gradients and focusing field. We discuss the sensitivity in performance upon the number of different rf frequencies and accelerating rf gradient.

INTRODUCTION

Attractive physics opportunities will accompany the production of intense muon beams. In particular, the electroweak physics at the energy frontier can be explored at a Muon Collider [1], and detailed studies of neutrino mixing, including CP violation can be pursued at a Neutrino Factory based on muon storage rings [2]. One key issue for these machines is the production and capture of copious pions that decay into the desired muons.

Commonly, the muons originate from the pions produced in the interaction of a proton driver beam with a high power target. Unfortunately, the created muons have diffuse energies and are spread in all directions from the target. Thus, the common task is to manipulate the longitudinal and transverse phase-space of the pion beam, so as to collect the resulting muon beam as efficiently as possible.

A number of studies [3-5] were developed for the capture, bunching, and phase-energy rotation of secondary beams from a proton source. In those studies, a proton bunch on a target creates secondaries that drift into a capture transport channel. A sequence of rf cavities forms the resulting muon beams into strings of bunches of differing energies, aligns the bunches to nearly equal central energies and initiates ionization cooling. Previous versions of this system have used 201.25 MHz bunch spacing as the final goal of the capture system [3]. We consider here a new muon capture system that matches to a 325 MHz cooling channel. There are several advantages of such a choice: First, it reduces the cost of the machine, since the cavities are shorter and are enclosed in coils with smaller radius. Second, since the rf gradient scales as the square of the frequency, the use of 325 MHz enables higher gradients, enabling a more compact system.

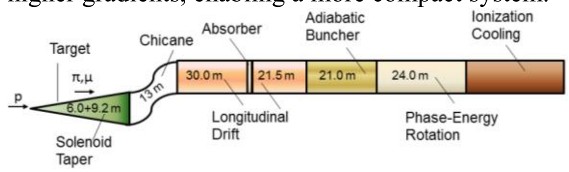

Figure 1: Schematic representation of the new front-end muon capture system.

SYSTEM OVERVIEW

The main components of the muon capture front-end are illustrated in Fig. 1. In the subsections below we describe its main components:

Target & Decay Channel

In the present configuration, the input beam is taken to be composed of a monochromatic 8 GeV proton beam with a 2 ns time spread incident on a liquid mercury target in the bore of a 20 T solenoid [6]. After the target, the field tapers from 20 T to 2.0 T over a distance of 6.0 m collecting both positive and negative particle species, continuing at 2 T. Then, continues at 2 T for another 15.25 m. A large flux of protons of all energies comes off the target as well as relatively low-energy electrons and pions are produced. A major change in the new design, is the use of a short field taper length compared to previous designs which use a 15 m long taper. Optimization studies have shown that this arrangement enhances the performance by more than 5%. This is because the short taper delivers a denser distribution of muon in longitudinal phase-space, which permits a more effective bunch formation in the buncher and phase-rotator sections further downstream [7].

Chicane and absorber

The aforementioned pion production results in a significant background of protons which may result in heat deposition on superconducting materials and activation of the machine preventing manual handling. In order to localize most losses as early as possible a solenoidal chicane and absorber system is placed at the end of the 15.25 m decay drift. The chicane bends out by 15. 0 deg. over 6.5 m and back by the same angle over 6.5 m more [Fig. 2(a)]. High momentum particles (> 800 MeV/c) are not strongly deflected by the bend solenoid and are lost in or near the chicane and collimated on shielded walls. The action of the chicane on the incident protons is displayed in Fig. 2(b). Lower momentum

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particles are strongly focused by the solenoid and follow the chicane with little orbit distortion. Subsequently, those particles pass through a 10 cm absorber which removes almost all of the remaining low energy protons.

The absorber was found to stop pions before they decay to muons and was therefore moved 30 m downstream of the chicane. An additional, 29.7 m are added after the absorber to extend the beam distribution and obtain the energy position correlation needed for bunching and phase-rotation.

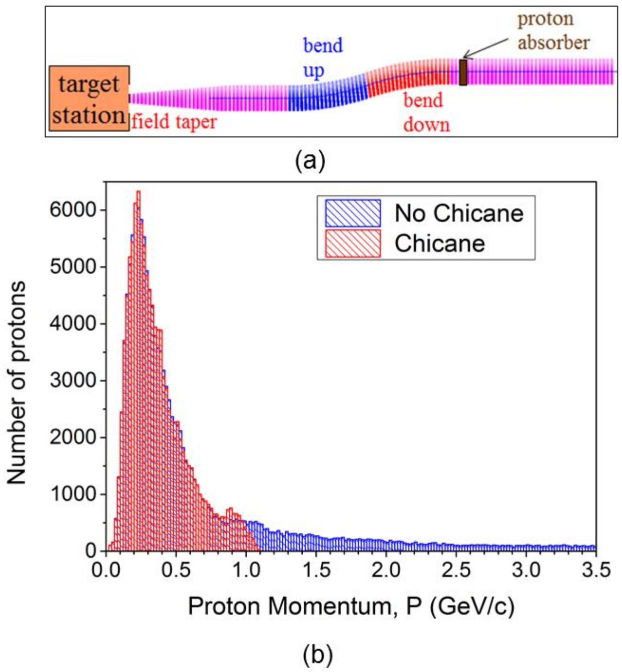

Figure 2: Secondary particle removal with a bend chicane.

Buncher& Phase Rotator

The drift channel is followed by a buncher section that uses rf cavities to form the muon beam into a train of bunches, and a phase-energy rotating section that decelerates the leading high-energy bunches and accelerates the later low-energy bunches to the same mean energy. To determine the buncher parameters we consider two reference particles at P_0 =250 MeV/c and P_N =154 MeV/c with the intend to capture particles within the 50 to 400 MeV energy range. The rf frequency and phase are set to place these particles at the center of bunches while the rf voltage increases along the transport. This can be achieved if the wavelength increases along the buncher by :

$$N\lambda_{rf}(L) = L\left(\frac{1}{\beta_N} - \frac{1}{\beta_0}\right) \quad (1)$$

where β_0 and β_N are the velocities of the reference particles at momentum P_0 and P_N. For the 325 MHz case, N=12 and the buncher length L is 21 m. The rf frequency decreases from 490 MHz to 365 MHz along the 21 m long buncher while the rf gradient increases from 0 to 15 MV/m. In the baseline design, the buncher consist of 28 cells, 0.75 m each containing two 0.25 m long cavities. To keep the muon beam focused, a constant 2.0 T field is maintained through the section. In the bunching system 56 normal conducting pillbox-shaped rf cavities are employed, each having a different rf frequency. At the end of the buncher the beam is formed into a train of bunches with different energies.

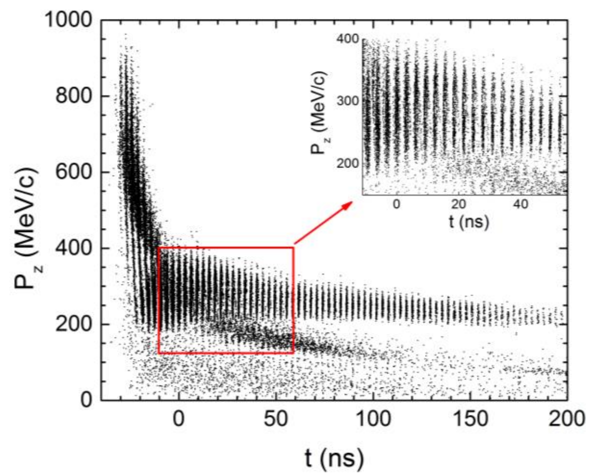

Figure 3: Beam distribution at the phase-rotator exit.

Table 1: Buncher and phase-rotator rf requirements for the muon accelerator front-end.

Buncher Frequency (MHz)	Buncher Gradient (MV/m)	Rotator Frequency (MHz)	Rotator Gradient (MV/m)
493.71	0.30	363.86	20
482.21	1.24	357.57	20
470.27	1.95	352.20	20
458.40	3.38	347.59	20
448.07	4.45	343.65	20
437.73	5.52	340.27	20
427.86	6.60	337.39	20
418.43	7.67	334.95	20
409.41	8.74	332.88	20
400.76	9.81	331.16	20
392.48	10.88	329.75	20
384.53	11.95	328.62	20
376.89	13.02	327.73	20
369.55	14.30	327.08	20
		326.65	20
		326.41	20

In the rotator section the frequencies are chosen so that the centers of the low energy particles increase in energy while those of high-energy bunches decrease. Thus, the lower energy reference particle is moved to an accelerating phase as the wavelength separation is also lengthened (12 → 12.045). At the end of the 24 m rotator the reference particles are at the same momentum ~245 MeV/c and the rf frequency is matched to 325 MHz. The gradient is kept fixed at 20 MV/m while the rf frequency drops from 364 MHz to 326.5 MHz. Similar to the buncher, the rotator cell is 0.75 m in length and contains two rf cavities 0.25 m long each. It employs a total of 64 cavities. The 2.0 T field continues throughout the rotator section. The longitudinal phase-space distribution of the beam at the exit of the phase-rotator is shown in Fig. 3. 21 bunches (red box) are used for subsequent cooling.

The present baseline assumes a continuously decreasing frequency where each cavity is different resulting to a total of 120 rf frequencies. For a realistic implementation, we attempted to group 4 or 8 cavities into a single frequency. The lattice efficiency can be calculated by counting the number of simulated particles that fall within a reference acceptance, which approximates the expected acceptance of the downstream accelerator. For the Neutrino Factory, the accelerator transverse normalized acceptance is 30 mm and the normalized longitudinal acceptance is 150 mm.

Figure 4 displays the muon yield when the cavities are grouped into 1-pair baseline, 4-pair and 8-pair. The simulations suggest that if the cavities are grouped into a pair of four, which corresponds to 30 discrete frequencies, the relative muon yield is reduced by ~8%. Table 1 has the required frequencies and rf cavity gradients to achieve this goal.

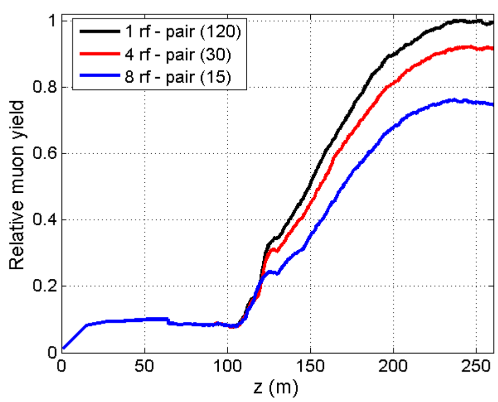

Figure 4: Cavity grouping to discrete frequencies: one cavity per frequency (black), four cavities per frequency (red) and eight cavities per frequency (blue).

Matching Section

While the magnetic field is constant at 2.0 T in the buncher and phase-rotator, the field of any subsequent cooling channel either 4D or 6D is generated by alternating solenoid that peak at ±3 T on axis. This will require a matching section to smoothly transport the beam from the exit of the phase-rotator to the cooler entrance. We consider a sequence of 9 solenoids to carry out the match to the cooler. The magnet settings were optimized using a standard Nelder-Mead algorithm [8] with the objective to maximize the muon yield at the cooling channel. The performance of the channel with and without optimization is shown in Fig. 5. Clearly, with optimization an additional 5% is added to the total gain.

Cooling Section

The baseline channel consists of a sequence of identical 1.5 m long cells. Each cell contains four 0.25 m long cavities with 1.1 cm thich LiH blocks at the ends of each cavity and a 0.25 m spacing between cavities with solenoidal focusing coils. The LiH provides the energy loss material for ionization cooling. The total length of the cooling channel is ~ 100 m (~70 cells). Based on the simulation results, the cooling channel reduces the transverse emittance by a factor of 2.5.

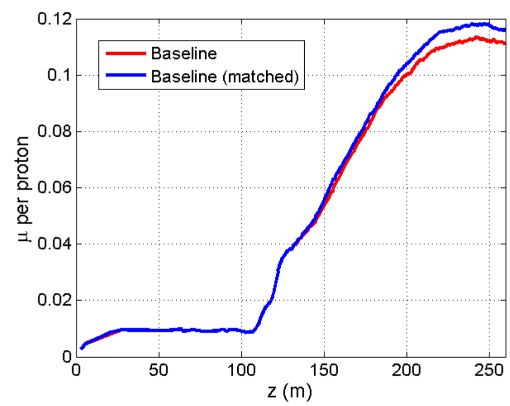

Figure 5: Lattice performance before and after optimization of matching.

CONCLUSION

We have designed and simulated a concept to capture muons from an intense muon source. Using this concept we can capture muons from a broad momentum spectrum, and then bunch and phase-rotate them by using a carefully tuned rf system. This method has potential applications to muon accelerators. Thanks to K. T. McDonald and R. B. Palmer for many discussions.

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