A COMPACT AND HIGH PERFORMANCE MUON CAPTURE CHANNEL FOR MUON ACCELERATORS

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Abstract

It is widely believed that a neutrino factory would deliver unparallel performance in studying neutrino mixing and would provide tremendous sensitivity to new physics in the neutrino sector. Here we will describe and simulate the front-end of the neutrino factory system, which plays critical role in determining the number of muons that can be accepted by the downstream accelerators. In this system, 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. For this, the muon beams are transported through sections containing high-gradient cavities and strong focusing solenoids. In this paper we present results of optimization and variation studies toward obtaining the maximum number of muons for a neutrino factory by using a compact transport channel.

INTRODUCTION

Recent experiments demonstrated that neutrinos can oscillate among their different flavors [1], indicating that they are massive bodies. Such results have important consequences for the standard model, the theory that describes fundamental particles and their interactions, wherein neutrinos were assumed to be massless particles. However, most observations so far have been of naturally occurring neutrinos striking the Earth from the Sun and from supernova. Over the past years there have been numerous developments on concepts and technologies for producing, capturing and accelerating a muon beam. Such progress has opened the gates for the construction of a neutrino factory [2] in which high-energy muons decay within the straight sections of a storage ring to produce a beam of neutrinos and antineutrinos. Such neutrino factory would deliver unparallel performance in studying neutrino mixing and would provide tremendous sensitivity to new physics in the neutrino sector.

In a neutrino factory, a 4 MW proton beam is focused onto a target to produce pions that decay into muons, which are then accelerated to energies up to a few tens of GeV. The muons are subsequently stored in a racetrack-shaped storage ring, where their decays provide intense beams of neutrinos. A key requirement in maximizing the final flux of neutrinos is that the phase space-volume of the muon beams must match the acceptance of the downstream accelerators. This demands a front-end channel (the part of the facility between the target and the first linear accelerator) for manipulating the beam in transverse and longitudinal phase-space [3]. For the latter, a series of rf cavities form the resulting muon beam into strings of bunches with different energies, and then align them into nearly equal central energies by phase-rotating the beam. To reduce the volume of transverse phase-space, the bunches are passed through a cooling channel, which reduces the beam's emittance using ionization cooling [4]. The cooling channel consists of absorbers, which lower the transverse and longitudinal momentum of beam particles, and rf cavities, which only restore the particle's longitudinal momentum, inside a magnetic channel. Since the cost of the front-end is roughly one third of the total cost of the factory complex, it is critically important to assure that its performance maximizes efficiency while reducing its risk.

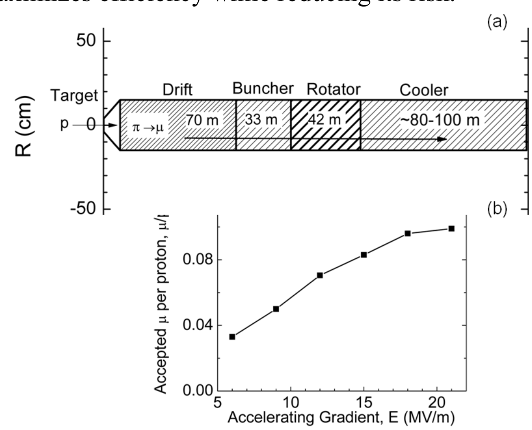

Figure 1: Muon accelerator front-end: (a) Schematic layout; (b) accepted muons vs. gradient in the cooler.

In the baseline configuration [4] the rf cavities in buncher and rotator are closed cell pillbox cavities placed within focusing solenoidal fields with nominal field of 1.5 T. Recent theoretical [5] and experimental studies [6] suggest that this configuration enhances the possibility of rf breakdown. It is considered likely that that the rf gradient will be limited by the magnetic field with the allowable gradient reduced with the increased field. This result will have dramatic consequences on the performance of a neutrino factory and this is illustrated in Fig. 1. The main goal of this work is to propose alternate strategies to mitigate this problem and particularly emphasize on the design of a cooling channel with magnetically insulated cavities.

FRONT-END OVERVIEW

Figure 1(a) schematically represents the IDS-NF front-end scheme. In this configuration, a 4 MW proton driver

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produces bunches with length in the range of 1-3 ns and 8 GeV in energy. The beam is directed onto a Hg jet target enclosed in a 20 T solenoid. The pions created are captured as they transverse a ~15 m long, tapered superconducting solenoidal magnet system, where the field profile drops adiabatically from 20 T to 1.5 T. Simultaneously, the radius of the beam pipe increases from 7.5 cm at the target up to ~ 30 cm at the end of the taper. This is followed by a 70 m drift section with a constant 1.5 T field, where the pions decay into muons, and the beam develops a time-energy correlation with a high-energy "head" and a low-energy "tail".

The decay channel is followed by a 33 m buncher section [Fig. 2(a)] in which the gradient of the rf system gradually increases and the beam is captured into a string of bunches with different energies. The rf frequency decreases along the length of the buncher, with the constraint that the phase difference between two reference particle momenta, p_1 and p_2, remains a fixed number N_B of wavelengths as the beam propagates through it. Following this procedure, the reference particles and all intermediate bunch centers remain at zero crossings of the rf wave throughout the buncher. For the present IDS-NF baseline design [4], $p_1 = 233$ MeV/c and $p_2 = 154$ MeV/c and N_B =10. With these parameters, the rf frequency at the beginning of the buncher section is 325.6 MHz and at the end falls to 232.0 MHz. In the bunching system, 44 normal-conducting rf cavities are employed, each having a different frequency and the rf gradient E_B increases linearly up to 9 MV/m.

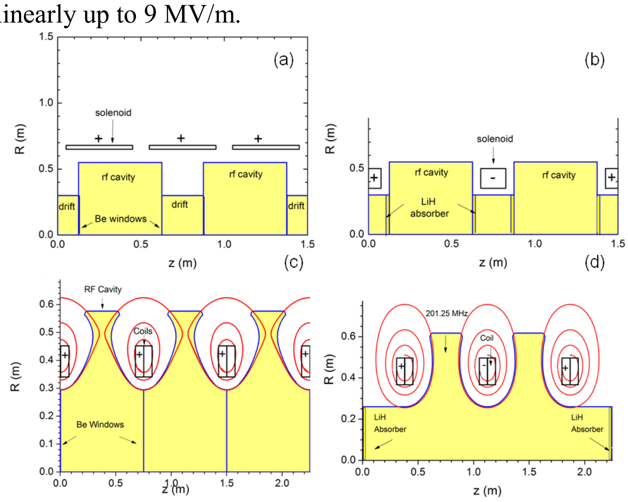

Figure 2: A neutrino factory front-end: (a) buncher and rotator with pillbox cavities; (b) cooler with pillbox cavities, (c) rotator with MI cavities, and (d) cooler with MI cavities

In the baseline configuration, the pillbox shaped rf cavities have nominal lengths of 0.5 m and are separated by a 0.25 m spacing. To keep the muon beam focused, a constant 1.5 T solenoidal field is maintained through the buncher. Once the beam leaves the buncher, it consists of a train of bunches with different energies. The beam then is phase-rotated with a second string of 56 cavities with decreasing frequencies, but with constant accelerating gradient. The frequencies are chosen so that the centers of the low- energy bunches increase in energy, while those of the high-energy bunches decrease. The algorithm used for setting this condition is to keep the first reference particle at fixed momentum while uniformly accelerating the second reference particle through the rotator section, so that it attains the first particle's energy at the end of the channel. This is accomplished by increasing slightly the phase shift between the reference particles by $N_R = N_B + 0.05$. With this condition, the bunches are aligned into nearly equal energies over the 42 m length of the rotator. The rf gradient is kept fixed at 12 MV/m while the rf frequency drops from 232- to 202-MHz. Similar to the buncher, the cavities occupy 0.5 m over a 0.75 m long cell and a 1.5 T solenoidal field continues throughout the section.

Upon exiting the rotator, the muons enter a ~80-100 m long cooling channel consisting of rf cavities, LiH absorbers for ionization cooling, and alternating 2.8 T solenoids for focusing. Fig. 2(b) depicts the cooling channel configuration. The cooling section has 0.75 m long cells and is identical to the cooling scenario used for the International Scoping Study [2]. Each cell has a 0.5 m long, 201.25 MHz rf pillbox cavity with a gradient of 15 MV/m. The 1.1 cm thick lithium hydride (LiH) absorbers are part of the cavity windows. The side of the absorber facing the rf cavity is covered by a thin 300-μm Be layer.

The performance of the front-end channel is evaluated by counting the number of simulated particles that fall within a reference acceptance, which approximates the expected acceptance of the downstream accelerator. Based on simulations with the ICOOL code, at the end of the cooling channel we expect that the system accepts ~0.083 muons per 8 GeV incident proton, while the transverse rms normalized emittance falls by a factor ~3 to $\varepsilon_t \approx 6.3$ mm. The accepted rms longitudinal emittance is $\varepsilon_l \approx 61.1$ mm.

FRONT-END WITH MAGNETIC INSULATION

Recent experiments indicated that operating rf cavities in magnetic fields can cause a decline in their maximum achievable gradient. According to a recent theory [5], this drop in gradient likely occurs after the electrons from a field-emission site are focused by the magnetic field, and damage a surface with high electric fields. Such damage would be caused by fatigue from cyclical strains induced by local heating from the electrons. This theory agrees reasonably well with numerical simulations [5] and with experimental data [6]. Assuming that emitted electrons that are accelerated and focused on other surfaces trigger the breakdown in magnetic fields, the process could be suppressed if the magnetic fields were parallel to all emitting surfaces. Hence, instead of focusing the electrons, the field would return them with little energy to near their points of origin. This idea was numerically investigated in Ref. 7 and recently experimentally tested with a box 805 MHz rf cavity [8]. Compared to the case where there was a component of a 0.2 T field parallel to the rf electric field, the first preliminary results showed a 30% larger maximum gradient threshold when the magnetic-field was introduced at right angles to the rf electric field. Since the IDS-NF baseline employs magnetic fields that have parallel components to the rf electric field that in many cases exceed 0.2 T, there is an argument for considering a lattice with magnetically insulated cavities as an alternative option.

In order to design a magnetically insulated (MI) lattice, we propose placing the primary focus coils in the irises of open multi-cell cavities, and shaping the walls of the cavity to follow the magnetic field lines. Figure 2(c) shows three cells of our proposed buncher channel. Three cells of the proposed MI cooling channel are shown in Fig. 2(d). The total length of the channel is 115 m. As in the baseline design, the lattice consists of a sequence of identical 0.75 m long cells, with 201.25 MHz rf cavities operating at 15 MV/m. One noteworthy difference is that we removed a cavity every third cell, and we extended the ends of the two adjacent cavities. A 2.7 cm LiH absorber with a 25-μm thick Be coating on both sides is located at the center of the empty cell. Both the current density and position of the coil are like the baseline and generate a 2.8 T peak field that varies sinusoidally within the channel and provides a minimum transverse beta function $\beta_{\perp} \approx 0.77$ m.

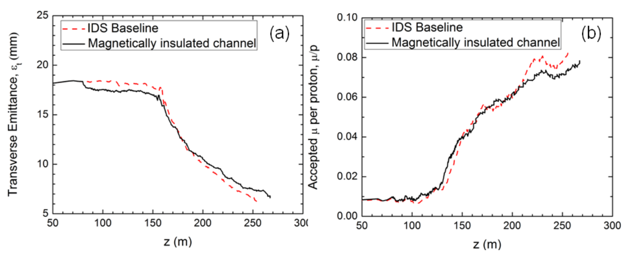

Figure 3: Performance of a front end channel with pillbox and magnetic insulated cavities.

Simulations of the overall performance of our proposed MI front-end lattice is displayed in Fig. 3 (solid line) and summarized in more detail in Table I. We compare these data against the baseline in Sec. II (dashed line). Figure 3(b) shows the number of produced muons per incident proton that fit into the transverse and longitudinal acceptance. Figure 3(a) illustrates the cooling in normalized transverse emittance along the channel. The cooling channel produces a final value of 6.7 mm, i.e., almost a factor of three less than its initial value. In addition, the channel achieves ~0.078 muon per proton for each sign of muons. The final values of ε_t and μ/p meet the IDS-NF requirements. A more detailed description can be found in Ref. 9.

One possible difficulty that might arise is multipactoring. With magnetic insulation the energy of the impacted electrons for all rf phases is below 0.8 keV, which corresponds to the peak secondary emission yield for Cu. However, small changes in the cavity alignment or in the magnetic field configuration could lead to increased impact energy and to a resonant condition for the emitted electrons. Thus, multipactor is a very complex phenomenon and should be investigated in more detail in future studies.

SUMMARY

It has been suggested computationally and experimentally that the maximum achievable gradient is enhanced by introducing an external magnetic field at right angles to the rf electric field since it suppresses field-emission processes. Here, we have discussed a possible scheme for extending the concept of magnetic insulation to capture, transport, and cool muons in a neutrino factory. We incorporated this idea into a new lattice design where the rf cavities are shaped so that their walls were tangential to the magnetic-field lines. We showed that, with magnetic insulation, the field-emitted electrons impact the cavity surface with energies four orders-of-magnitude less than in conventional pillbox cavities; consequently, damage from field-emission is suppressed significantly. While demanding in terms of power requirements, this neutrino factory lattice showed satisfactory performance in both cooling and collecting the accepted muons within the requirements for the IDS-NF. Optimizations were also made to reduce heating on the absorber windows minimizing losses in the accepted muon fluxes. The next step for verifying these ideas should be an experimental demonstration of a single muon accelerator magnetically-insulated rf cavity [7]. A successful demonstration will provide us with a new versatile tool for a future muon accelerator.

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