A FEW LOW-FREQUENCY PHASE-ENERGY ROTATION AND CAPTURE SCENARIOS FOR A NEUTRINO FACTORY OR MUON COLLIDER

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Abstract

A short study was conducted to evaluate the possible performance of a few low-frequency, phase-energy rotation and capture scenarios for the front end of a neutrino factory of muon collider. The study compares the general requirements necessary for designs implimenting standard vacuum RF cavities with designs implimenting high-pressure, gas-filled RF cavities. The study also shows that if very large gradients can be achieved with low-frequency, gas-filled cavities, which we believe is possible based on recent experimental results, then competitive designs can be developed at high-pressure.

INTRODUCTION

Until recently, the designs for RF capture in the front end of a neutrino factory and those for a muon collider have differed significantly. These differences have stemmed from the two major differences between the requirements for each machine: neutrino factories require high muon flux, and muon colliders require high luminosity. The most significant result of this difference is that neutrino factories do not, in principal, require longitudinal cooling and/or an intense single-bunch beam, as is required for a muon collider. Recently, a concensus has been reached that a multi-bunch front-end for a muon collider will be necessary in order to eliminate beam-loading and space-charge effects that would be evident in a low-energy, single-bunch beam after *extreme cooling*[1]. Therefore, it is believed that a front-end design that captures into $\sim$10, $\sim$300 MHz bunches will be common to both machines.

This study explores a few different scenarios for a front-end design that captures muons into 325 MHz RF. The first scenario considered is a single-frequency, phase-energy rotation scheme with vacuum RF cavities. We consider the effects of various gradients in such low-frequency RF cavities. The second scenario considers the effects of using high-pressure, gas-filled RF cavities in a similar single-frequency design, and we consider the effect of various gradients in both the phase-energy rotation section and the 325 MHz buncher section. The third, and last, scenario considers a multi-frequency vacuum-cavity alternative, an option that may be feasible if the single-frequency vacuum-cavity design proves impractical.

[1] *Extreme cooling* implies cooling to transverse emittances on the order of 1 μm.

TARGET AND INITIAL BEAM

For all of the following scenarios, we consider the same initial beam, generated from 8 GeV protons incident on a high-Z target. For simplicity, a SuperInvar target with 1 cm diameter and 30 cm length was chosen for these simulations. SuperInvar shows promise as a solid, high-Z target option, and it would be cheaper and easier than liquid target configurations. If extreme muon cooling can significantly reduce the demand on the required incident proton beam power, then heat deposition into the solid target could be kept acceptably low. However, if solid targets are not shown to be feasible, then similar yields can be achieved with the liquid mercury target.

To avoid dumping the proton beam into the near RF cavities, the target was tilted at an angle of 100 milli-radians with respect to the central axis of the channel, and the incident proton beam is aligned with the axis of the target. Some degradation in the captured pion yield was noticed if the target was tilted less or more than 100 milli-radians, but the losses over a range of ± 50 milli-radian are small.

The charged pions produced from the target are captured in a large, 20 T solenoid which adiabatically tapers to 2.22 T over 10 m. At 10 m from the target, a lattice of closely-spaced solenoids follows, maintaining a uniform 2.22 T longitudinal field down the length of the phase-energy rotation and 325 MHz buncher channels.

The longitudinal distribution of the beam at the end of the taper, 10 m from the target, can be seen in Figure 1, generated with MARS15[1]. This initial beam is identical in all of the scenarios considered in this article, and we define the origin of the z-axis to be the end of the taper (10 m from the target).

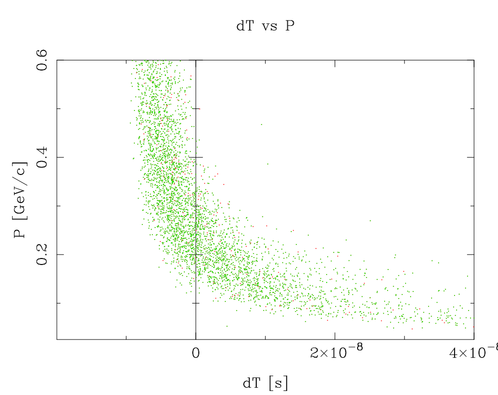

Figure 1: The longitudinal distribution of the $\mu + \pi$ beam at the end of the 10 m tapered solenoid, $z = 0$.

SINGLE-FREQUENCY, VACUUM-CAVITY ROTATION

The first scenario for capture into 325 MHz RF is a single-frequency, vacuum RF cavity approach. Evenly-spaced 25 MHz vacuum RF cavities are considered down the channel to provide phase-energy rotation, starting immediately after the 10 m taper. To find the optimal gradient for the rotation, we count the number of $\mu^+ + \pi^+$ that lie within an acceptable momentum band, 200-300 MeV/c, [2] as a function of distance down the phase-energy rotation channel for various gradients. The results, generated in ICOOL, are shown in Figure 2 and suggest that the optimal gradient is $\sim$3 MV/m.

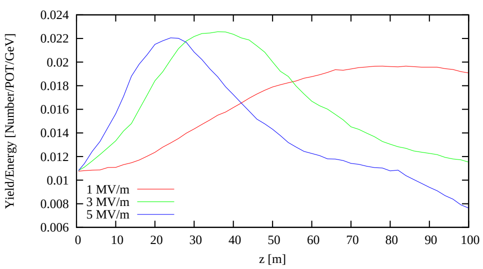

Figure 2: Comparison of $\mu^+ + \pi^+$ yields per unit proton energy within the acceptable 200-300 MeV/c momentum band as a function of distance down the phase-energy rotation channel with various real-estate gradients.

To improve capture, we consider adding higher-order mode (HOM) cavities to the rotation channel. We do this by substituting every 5th 25MHz cavity with a 50 MHz cavity that has the same gradient but is $180°$ out of phase. One can see the effect of the higher-order mode cavities on the yield in Figure 3. One can see that the HOM cavities increase the length of the optimal rotation channel by 15 m, but the number of $\mu^+ + \pi^+$ rotated into the given momentum range is increased by $\sim$10%. Figure 4 shows the longitudinal distribution of the beam after 25 MHz, 3 MV/m phase-energy rotation of 50 m and 34 m, with and without HOM cavities, respectively.

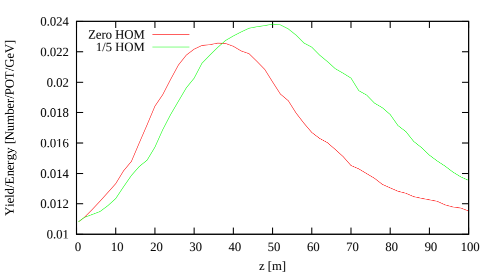

Figure 3: Comparison of $\mu^+ + \pi^+$ yields per unit proton energy within the acceptable 200-300 MeV/c momentum band as a function of distance down the phase-energy rotation channel with (green) and without (red) higher-order mode cavities.

[2] This momentum range is compatible with the admittance of the helical cooling channel.

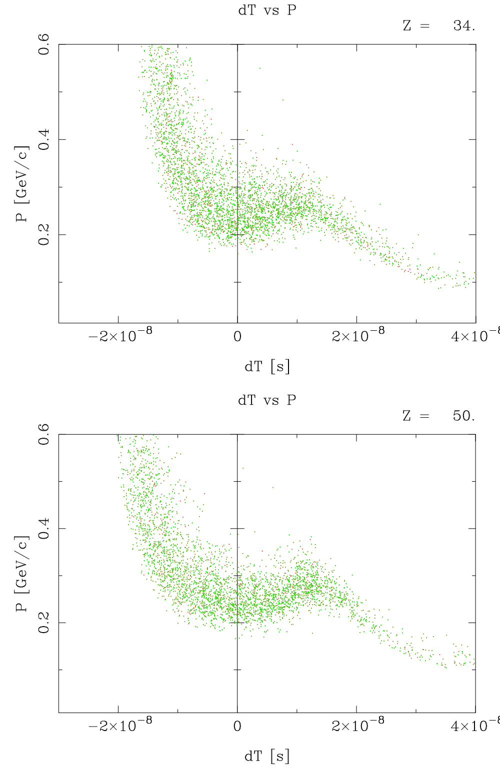

Figure 4: Comparison of $\mu + \pi$ longitudinal distributions after 25 MHz, 3 MV/m phase-energy rotation with (bottom) and without (top) higher-order mode cavities.

After phase-energy rotation, the beam is bunched into 325 MHz buckets. To capture the beam without increasing the energy spread, the bucket height of the 325 MHz RF is chosen to closely match the 200-300 MeV/c momentum spread. This corresponds to a gradient of $\sim$4 MV/m. The capture is not perfect, however, as a significant number of particles that lie on the edge and between the 325 MHz buckets are eventually lost. To improve capture, every 4th cavity is replaced with a 650 MHz HOM cavity. One can see the captured yield per unit proton energy in Figure 5. About 20% of the particles are lost in the first 5 m of capture into 325 MHz. However, the resulting yield per unit proton energy captured into 325 MHz is a factor of 2 greater than that found in recent Neutrino Factory front-end designs[2], which captured 0.007 μ/POT/GeV into 200 MHz. Also shown in Figure 5 is a similar 325 MHz capture scheme with only 1 MV/m gradient in the phase-energy rotation section. With vacuum cavities, it may not be possible to achieve real-estate gradients much larger than 1 MV/m. With 1 MV/m, the yield per unit proton energy is still 50% larger than the Study 2b results.

Figure 6 shows the longitudinal distributions of the beam after rotation with 1 MV/m and 3 MV/m phase-energy rotations and capture into 325 MHz RF.

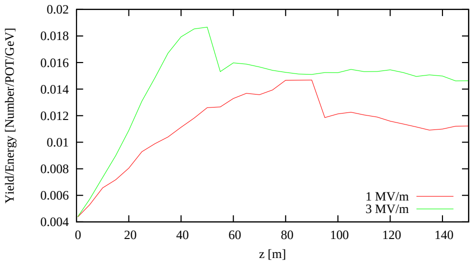

Figure 5: Comparison of $\mu^+ + \pi^+$ yields per unit proton energy within the separatrix of 325 MHz, 4 MV/m buckets along the channel for 1 MV/m (red) and 3 MV/m (green) real-estate gradients in the 25 MHz phase-energy rotation channel.

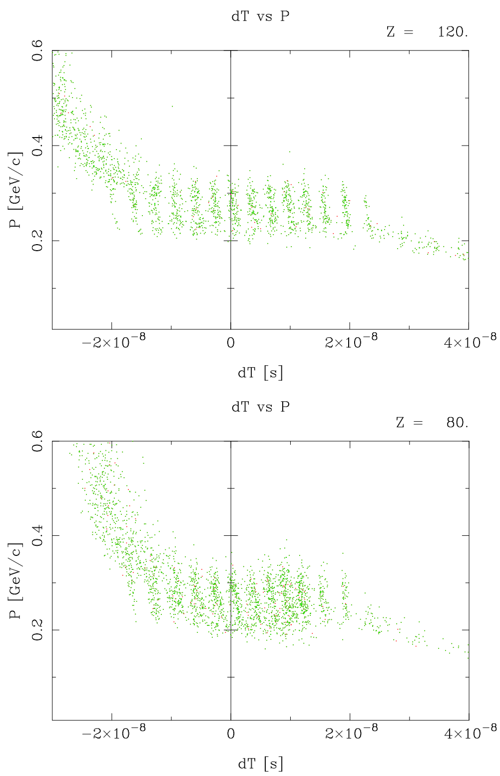

Figure 6: Comparison of $\mu + \pi$ longitudinal distributions after 25 MHz phase-energy rotation channels with 1 MV/m (top) and 3 MV/m (bottom) real-estate gradients after 30 m of transport in 325 MHz, 4 MV/m RF buncher.

SINGLE-FREQUENCY, HIGH-PRESSURE, GAS-FILLED-CAVITY ROTATION

In this scenario, we consider the effects of high-pressure hydrogen gas in the cavities.

High-pressure gas-filled cavities have several advantages. First, the high-pressure gas has been seen to suppress breakdown in the cavities, allowing for higher gradient, even in the presense of strong magnetic field. Second, the high-pressure gas acts as an absorber which, with re-acceleration with RF, exhibits transverse ionization cooling.

High-pressure gas also presents certain challenges when used in the front-end. First, it allows for strong interactions with the pions, which contribute to pion losses and fewer captured muons. Second, it requires that the RF cavities be phased appropriately to re-accelerate the particles, which results in less efficient capture into higher frequency due to the gaps between the non-zero phased buckets. Third, without longitudinal cooling present, the gas makes the phase-space motion of the particles unstable[3], and particles within the buckets will eventually spiral out if not transfered quickly to a channel with longitudinal cooling.

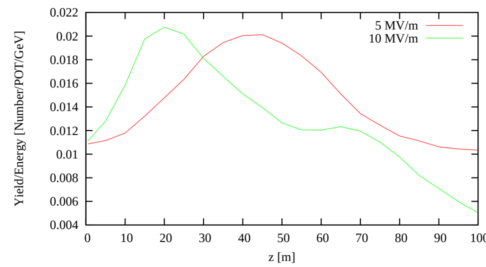

Figure 7: Comparison of $\mu^+ + \pi^+$ yields per unit proton energy within the acceptable 200-300 MeV/c momentum band along the gas-filled 25 MHz phase-energy rotation channel for 5 MV/m (red) and 10 MV/m (green) gradients.

For this study, hydrogen gas at 50 atm is used to fill the same channel. The energy loss per unit length in the gas is $\sim$1.9 MeV/m. To maximize the length of the bucket and still re-accelerate to compensate for energy loss in the gas, we must keep the phase of the cavities small, which means keeping the gradient of the cavities much larger than 1.9 MeV/m. We consider two real-estate gradients, 5 MV/m and 10 MV/m, and the resulting phase-energy rotation into the acceptable 200-300 MeV/c momentum band can be seen in Figure 7. The yields at both real-estate gradients are comparable, so we consider using the lower of the two real-estate gradients for capture. Figure 8 shows the longitudinal distribution of the beam after rotation with both gradients.

Next, we attempt to capture into gas-filled 325 MHz RF, and, again, we must apply enough gradient to compensate for energy loss and keep the phase of the cavities small. Therefore, we consider 25 MHz, 5 MV/m phase-energy rotation and capture into 325 MHz cavities with real-estate gradients of 5 MV/m and 10 MV/m. The resulting yields per unit proton energy into the 325 MHz buckets are shown in Figure 9. With a 10 MV/m real-estate gradient buncher, the yields are competitive with the vacuum cavities designs described in the previous section. The longitudinal distributions of the beam 30 m into the 325 MHz buncher, at both gradients, is shown in Figure 10. Many of the shown particles (red) are lost by the end of the simulation, and

[3] For particles with momenta greater than $\sim$400 MeV/c, energy loss in the gas results in natural longitudinal cooling. However, particles at these momenta are either not captured or are quickly rotated to lower momentum.

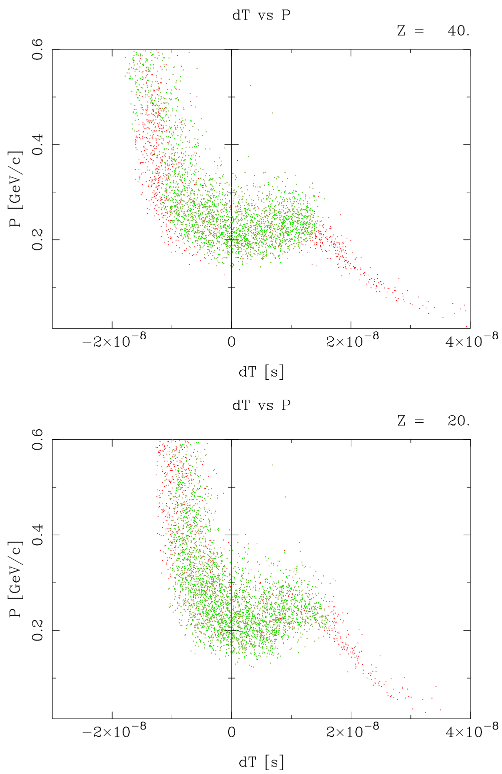

Figure 8: Comparison of $\mu + \pi$ longitudinal distributions after the gas-filled 25 MHz phase-energy rotation channel with 5 MV/m (top) and 10 MV/m (bottom) real-estate gradients.

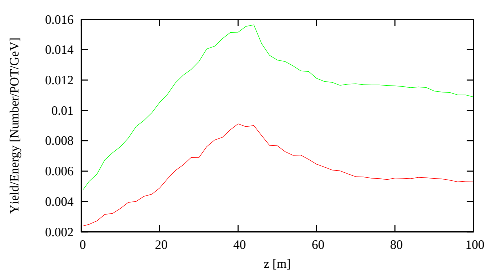

Figure 9: Comparison of $\mu^+ + \pi^+$ yields per unit proton energy within the separatrix of 325 MHz buckets along the gas-filled 25 MHz, 5 MV/m phase-energy rotation channel and the 5 MV/m (red) and 10 MV/m (green) real-estate gradient buncher.

gradual particle loss occurs as the particles undergo synchrotron rotations within the gas-filled buckets.

The beam should experience transverse cooling in the presense of high-pressure, gas-filled RF. The amount of transverse cooling can be seen in Figure 11 which compares the transverse emittance, calculated with ECALC9, of the optimal vacuum-cavity rotation scheme from the previous section[4] with the 25 MHz, 5 MV/m high-pressure, gas-filled rotation and 325 MHz, 10 MV/m capture scheme

[4]Specifically, we consider the 25 MHz, 3 MV/m rotation section with capture into 325 MHz, 4 MV/m RF.

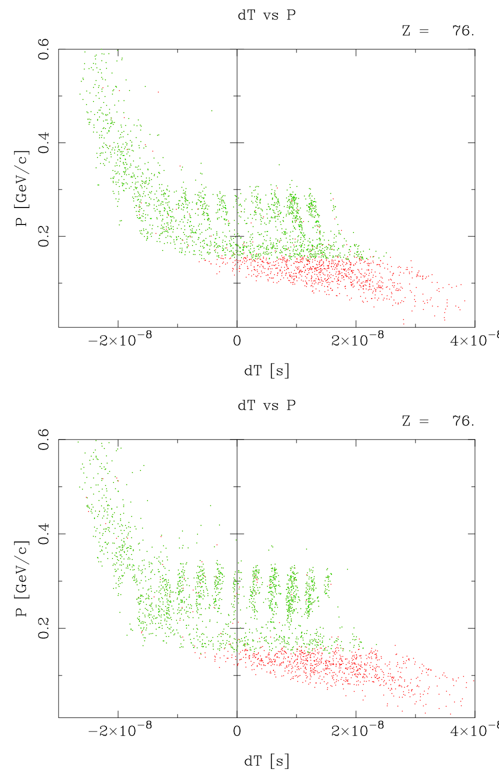

Figure 10: Comparison of $\mu + \pi$ longitudinal distributions after gas-filled 25 MHz, 5 MV/m phase-energy rotation and 30 m into the 325 MHz buncher with 5 MV/m (top) and 10 MV/m (bottom) real-estate gradients. Particles in red are eventually lost in the simulation.

described in this section. One can see that the gas-filled scheme captures particles that initially start with higher transverse emittance, and then cools them to approximately 70% of transverse emittance captured by the vacuum cavity design.

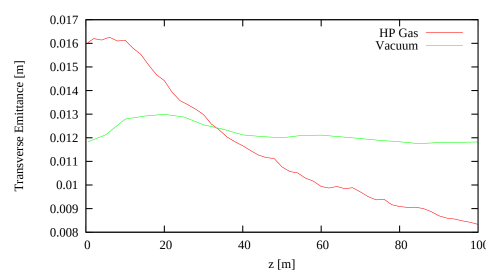

Figure 11: Comparison of the transverse emittance of the beam from the optimal vacuum-cavity scheme to the beam from the optimal gas-filled cavity scheme.

MULTIPLE-FREQUENCY, VACUUM-CAVITY ROTATION

The last scenario in this study considers an alternative approach to designing a vacuum-cavity phase-energy rotation channel. The peak gradients in vacuum RF cavities are significantly degraded in the presense of strong magnetic fields, unlike high-pressure, gas-filled RF cavities. The challenge, then, is to design a phase-energy rotation channel that does not demand large gradients with vacuum RF. In an attempt to achieve this, we consider a phase-energy rotation scheme that starts with higher frequency, which can attain higher gradient, and steps down to lower frequency and lower gradient over the length of the channel.

The first stage of this scheme is a 75 MHz rotation section with 4 MV/m real-estate gradient. After approximately one quarter phase-energy rotation, we begin a second stage with 50 MHz and 2 MV/m, which is followed by a stage with 25 MHz and 400 kV/m. This is then followed by 325 MHz, 4 MV/m RF, as in the previous vacuum-cavity scenarios.

The $\mu+\pi$ yield per unit proton energy into the 325 MHz buckets is shown in Figure 12. The 325 MHz cavities begin at $z = 90$ m, which shows that the the phase-energy rotation section is longer than in any of the other scenarios. However, the real-estate gradients are more realistic, even though the presense of strong magnetic fields may still degrade them. The captured yield is competitive with other designs, as well.

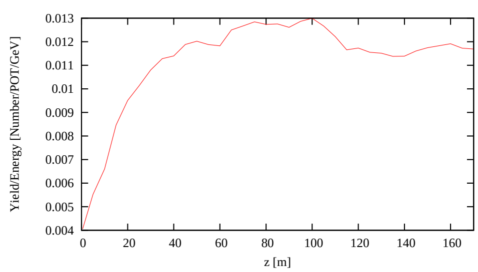

Figure 12: Yields of $\mu^+ + \pi^+$ per unit proton energy within the separatrix of the 325 MHz buckets as a function of distance along the multi-frequency phase-energy rotation and capture channel.

The longitudinal distribution of the beam at the end of the phase-energy rotation channel and 30 m into the 325 MHz capture channel are shown in Figures 13 and 14, respectively.

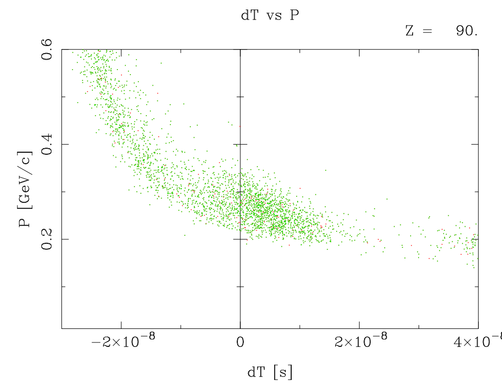

Figure 13: Longitudinal distribution of $\mu + \pi$ after the multi-frequency phase-energy rotation channel.

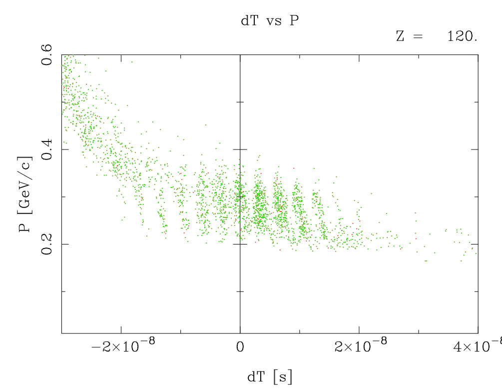

Figure 14: Longitudinal distribution of $\mu + \pi$ after 30 m of 325 MHz, 4 MV/m capture following the multi-frequency phase-energy rotation channel.

CONCLUSIONS

This studied has explored three possible options for the design of a phase-energy rotation and buncher channel for a muon collider or neutrino factory. There are many designs that have not been considered here, but the results of these few designs show significant promise for future investigations.

This study has shown that alternate designs with competitive performances can be developed with high-pressure, gas-filled RF as well as with vacuum RF. RF gradient in the presense of strong magnetic field may yet present a problem for vacuum-cavity designs, which may put more favor on the gas-filled designs. Many other design options have yet to be explored, which we hope to accomplish in the next years.

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[2] J. C. Gallardo, J. S. Berg, R. C. Fernow, H. G. Kirk, R. Palmer, D. V. Neuffer and K. Paul, “New and efficient neutrino factory front-end design,” *Prepared for Particle Accelerator Conference (PAC 05), Knoxville, Tennessee, 16-20 May 2005.*
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