A STUDY ON THE HYBRID COOLING SECTION OF THE FRONT END OF A NEUTRINO FACTORY

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Abstract

In this paper I describe two studies which I carried out during my summer at BNL. First, I optimize the parameters of a hybrid cooling section in the front end of a (IDS) Neutrino Factory. Second, I observe the effects of systematic and random errors of rf cavities and magnets in the cooling section.

INTRODUCTION

In the past decades, strides in neutrino physics have led us to discover that there are three types of neutrinos, and that these types oscillate between one another. However, despite advances, in our knowledge of neutrino physics there are still many things about neutrinos we don't yet know. For example, the mixing angle, θ_{13} , the amplitude in the neutrino oscillation probability formula, has yet to be precisely measured; Δm^2, the frequency of neutrino oscillation, is also still under investigation (Equation 1).

$$P(\nu_\mu - \nu_\tau) \approx \sin^2(2\theta_{13}) * \sin\left(\frac{\Delta m^2}{4} * \frac{L}{E}\right) \text{ (Equation 1)}$$

These studies have the potential to explain the apparent prevalence of matter over antimatter in our universe [1].

An efficient and effective method for studying neutrinos and their different properties is to mass produce them in a neutrino factory [2]. This can be done by sending a beam of protons towards a target, a jet of Hg. In this collision, a stream of pions (π±) is created. These pions would eventually decay into muons, which we would focus to form an intense, well collimated beam [3]. The muons would then decay into 2 neutrinos and a positron (Equations 2, 3); these neutrinos are then aimed towards a far away detector.

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu} \text{ (Equation 2)}$$

$$\mu^- \rightarrow e^- + \overline{\nu_e} + \nu_\mu \text{ (Equation 3)}$$

In this study, we focus primarily on the cooling channel in the front end (Figure 1).

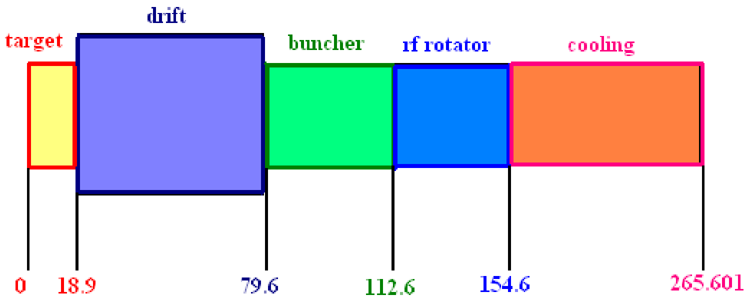


Figure 1: [color] Front end of the muon collider. The numbers represent the position of each section in meters—the cooling section is of the order of 111m with 144 RF cavities and 396 magnets.

In the original design of the Muon Collider's front end cooling section, vacuum RF-cavities were used [4]. Studies of the front end with vacuum cavities had shown that it was possible to produce a high intensity beam with a small transverse emittance. However, collaborators found experimentally that when a strong magnetic field was applied across the cavities, the 15MV/m gradient necessary for an efficient cooling could not be reached [6]. In the new model of the front end, the RF cavities are filled with high pressure H_2 gas [5]. This design can potentially solve the problem of the gradient break down, while maintaining the high intensity (Figure 2) and low emittance (Figure 3) of the muon beam.

Emittance is a measure of how disorderly a particle beam is in coordinate and momentum phase space. In particular, transverse emittance is a measure of that disorder in the two dimensions perpendicular to the beam; it can be approximated by $\varepsilon_\tau = \sigma_r * \sigma_p$, where σ_r represents an approximation of the beam's radius and σ_p represents an approximation of the beam's divergence. For a particle beam to be effective, it is important to give the particles in the beam small transverse emittance: the lower the transverse emittance, the better collimated and the smaller the radius of the beam will be.

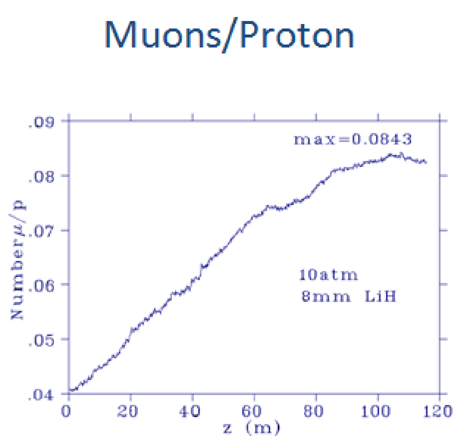


Figure 2: Number of muons/proton along the cooling section of the front end, shown for 10atm H_2 gas and with a LiH absorber of 8mm thickness.

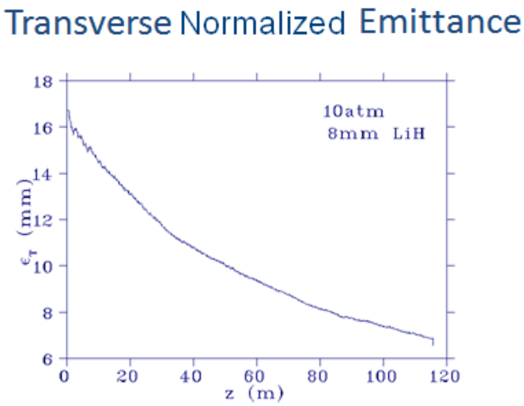


Figure 3: Transverse normalized beam emittance across the channel, shown for 10atm H_2 gas and with a LiH absorber of 8mm thickness.

With this new introduction of H_2 gas into the RF cavities of the cooling channel, there are many parameters which need to be systematically studied and adjusted. For instance, in the new design with the H_2gas, there will be more ionization cooling. Ionization cooling is the process through which muons lose energy by interacting with electrons via the Coulomb Force [2].

In our design, the muons will pass through a material, whether H_2 gas or LiH windows, and transfer some of their energy to the electrons surrounding the medium's nuclei. This energy breaks the electrons away from their respective nuclei, i.e, it ionizes them. Thus, the beam will be cooled, and the medium, though more energetic, will maintain its form. This will directly affect the thickness of the LiH absorbers, which no longer bear the entire burden of cooling the beam. Also affected is the pressure of the H_2 gas, the RF gradient and RF phase.

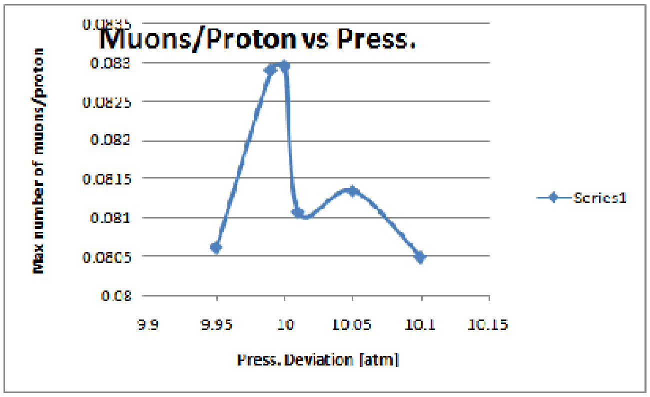
Subsequently, I studied some error parameters, such as magnet displacement, RF cavity failure, etc.

STUDY 1: PARAMETERS OF THE COOLING SECTION

In the present model of the cooling channel, a study of the run parameters previously described is crucial to the success of the front end cooling channel.

I. Pressure of H_2 Gas

As previously stated, H_2 gas has been introduced into the RF cavities of the cooling section. Because the pressure of the H_2 gas will determine how effectively our gradient is established, it is an important parameter that must be investigated. Using ICOOL, we ran several muon beam simulations through the front end at different pressures in an attempt to find the pressure which would produce the highest final ratio of muons/protons. Our results showed the optimal pressure was approximately 10atm (Figure 4), although there is an unexplained dip in the data at



10.01 atm.

Figure 4: Shown above, muons/proton vs pressure; ideal pressure at 10atm.

The effect of changes on the pressure of the gas needs further investigation; I will not pursue this here.

II. Thickness of LiH Absorbers

In the original model of the cooling channel, 1.1cm thick LiH absorbers played the main role in absorption of energy in the beam [3]. However, because the H_2 gas in the new design will absorb about 25% of the energy originally absorber by the LiH, we are able to decrease the original size of the absorbers. The results from simulations at different LiH thicknesses and 10atm are shown in Figure 5.

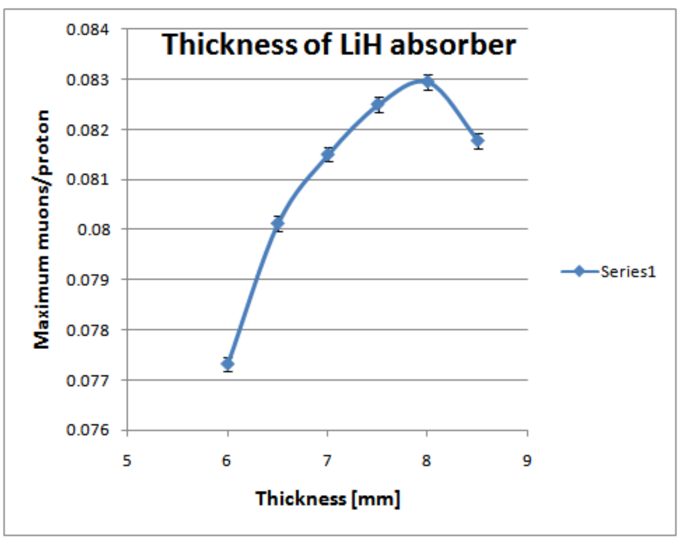


Figure 5: Simulation results at LiH thickness around 80% of original 1.1cm—ideal at 8mm.

As can be seen clearly from Figure 5 above, at a H_2 pressure of 10atm, the optimal thickness of the LiH absorbers, i.e., where the muons/proton ratio is greatest, is 8mm.

III. RF Gradient

An external power supply, a klystron, creates an electromagnetic field inside the RF cavities. This field can be modeled by the time dependent equation

$$E(t) = E_0 * \cos(\omega * t + \delta)$$

where E_0 represents the gradient of the field and δ represents the phase. The gradient E_0—15MV/m in the original design—was optimized using the new parameters described above through simulations in ICOOL. The results shown below in Figure 6 seem very noisy, but when plotted with a trend line, appear to follow a rough sort of Gaussian curve. The optimal gradient, according to these results, is approximately 16MV/m.

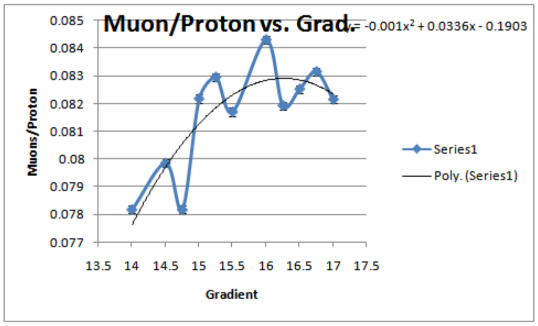


Figure 6: Muon/Proton vs. RF-Gradient, roughly fitted to a Gaussian distribution curve.

It is important to note that this test was run at 10atm, 8mm and constant rf-phase of 40 degrees. In reality, this is not entirely consistent because the gradient and the phase depend on each other. Similar to the pressure, these gradient results require additional investigation and more intricate analysis. I could not do these long term studies within the duration of my summer internship at BNL.

IV. RF Phase

The final of the cooling section parameter simulations I performed was one on the phase. As before with the gradient, the delta in the equation for the electric field shown above affects the gradient and vice versa—therefore this optimization of the phase, run at constant gradient of 16MV/m, is also not entirely correct. Optimal phase, according to the parameters used, was 40 degrees (Figure 7).

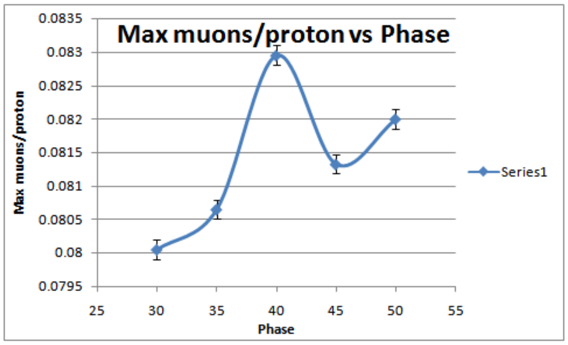


Figure 7: Muon/Proton vs Phase of Electric Field in RF Cavities.

STUDY 2: ERROR PARAMETERS

In the previous section, I discussed different run parameters of the front end cooling channel which had to be re-examined with the introduction of H_2 gas. We concluded that the channel would perform most optimally with the values shown in Table 1. With these factors accounted for, we next began to take into account some of the systematic errors that could occur. All simulations were run using ICOOL.

PARAMETER	VALUE
Pressure of H2 gas	10 atm
Thickness of LiH	8 mm
RF-phase	40 degrees
RF-gradient	16 MV/m

Table 1: Summary of different parameters optimized in Study 1.

I. Magnetic Displacement [x direction]

The first error study we did by randomly moving all 396 magnets according to different standard deviations of a Gaussian distribution. We found that within the first couple millimeters of displacement, the channel managed to maintain its relatively high production ratio of Muons/Protons (Figure 8)—approximately 0.082. At larger deviations such as 1 cm, however, we found that our final ratio had decreased by approximately 50%--this kind of drop would be devastating to the actual experiment; luckily it is not all too difficult for our survey devices to keep the positions of the magnets within a millimeter or so of error.

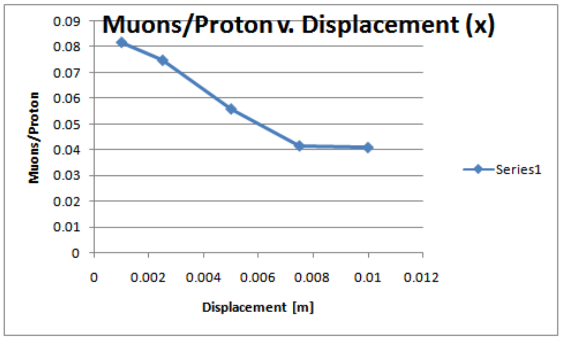


Figure 8: Drop in Muon/Proton count over standard deviation of a Gaussian distribution displacements.

II. Magnetic Tilt

ICOOL can't tilt the magnets to simulate angular error, but it can tilt the beam of particles. It should be noted that although this test was run through ICOOL with a tilted particle beam at random locations along the channel, no correction for tilt was issued anywhere else in the beam line. Therefore this test is merely a rough case study of tilt, rather than a true indication of output results under said conditions. From this inherently flawed run design comes Figure 9. In Figure 9 we can see that within about a tenth of a degree of the desired tilt, our magnets will enable us to obtain the desired ratio of muons/proton.

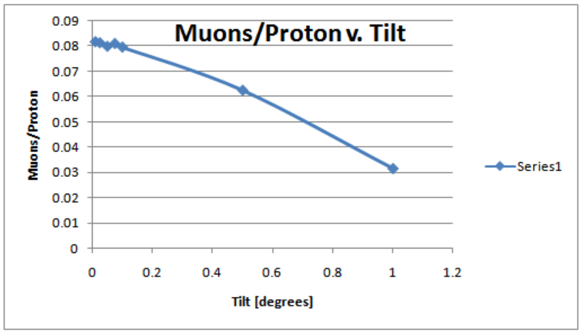


Figure 9: Drop in ratio over standard deviation of a Gaussian distribution tilts. At about 1 degree, more than 50% drop in Muon/Proton ratio, according to the applied parameters.

III. RF-Cavity Failure

RF cavities need to be built with very precisely defined, smooth surfaces, usually machined to very high tolerances. If there is a scratch or a dent on the surface in the presence of an electric field, a high voltage buildup at the point of the anomaly can cause the surface to arc; this degrades and eventually destroys the surface. Similarly, if a very high-current beams mis-steers, it can hit the surface, pitting it and rendering the cavity useless.

There were two separate error studies performed on the RF-cavities, in the event that something like the above should occur. First, various clusters of cavities were turned off at the beginning of the channel only (Figure 10). Our results were particularly interesting. With a Voltage of essentially 0 across the first 25 of 144 cavities in the cooling channel, these results tell us that we maintain more than half the original number of particles at the end of the run. So according to these results, we might as well just get rid of the first 15 cavities! They are, apparently, unnecessary.

Needless to say, this seems peculiar and should be further investigated.

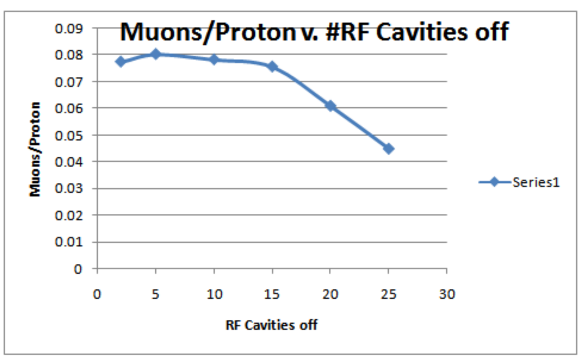


Figure 10: Ratio of Muons/Proton vs. different clusters of deactivated RF-cavities at beginning of channel. The only 50% drop in particles at 25 cavities is unexpected.

The second RF-cavity study involved turning the same number of RF-cavities off throughout the channel, but at random instead of in clusters. Although this arrangement produces a slightly higher final ratio of muons/proton than does the clusters of failed RF-cavities, it doesn't do so by much (Figure 11). Again, these studies should be further investigated.

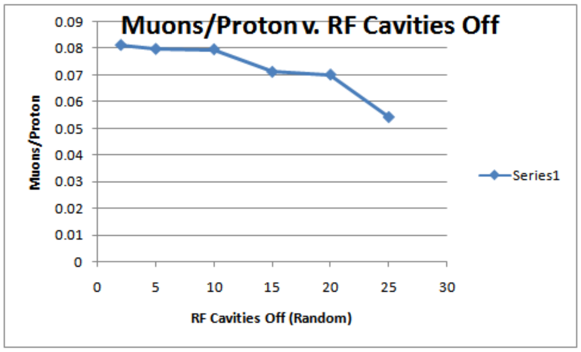


Figure 11: Ratio vs. Random RF cavities throughout channel deactivated. These results too closely resemble the clusters—should be further examined.

IV. Magnetic Field Change

There are several ways in which electromagnets (like solenoids) can be damaged. For example, in the case of superconducting magnets, should the mechanism keeping the magnets cold fail (even slightly), the magnets will quench. A quench puts enormous physical strain on the coils, as their changing current reacts with the initially still-present magnetic field. If the current isn't quickly eliminated, the coils will move, and the magnet will be potentially destroyed. The following two tests were done with this sort of situation in mind.

In the first study, 20 magnets along the cooling channel were set to different percentages of the original magnetic field in corresponding simulations. This was an attempt to mimic the aftermath of one of the above situations. We found, as expected, that as the percentage of 'broken' magnets increased, the final number of particles decreased (Figure 12). Within a couple percent of the full field value, we attained satisfactory ratio results.

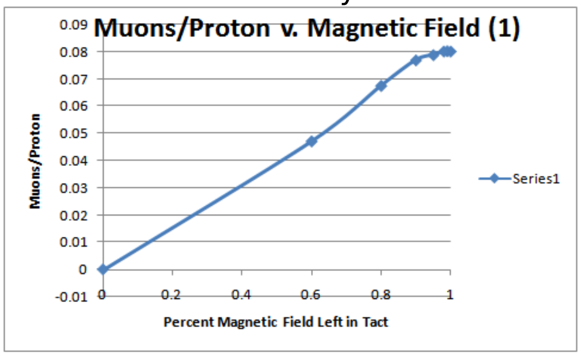


Figure 12: Magnet failure and its effects on the final count of muons.

In the second study, we performed the same kind of test with a small difference. The way the cooling channel has been put together, there is a cluster of 8 cells and then 1 cell repeated throughout the section, with each cell containing two magnets.

In the original test, we changed the magnets in all the single cells. In this test however, we changed all the magnets in the groups of 8 (Figure 13).

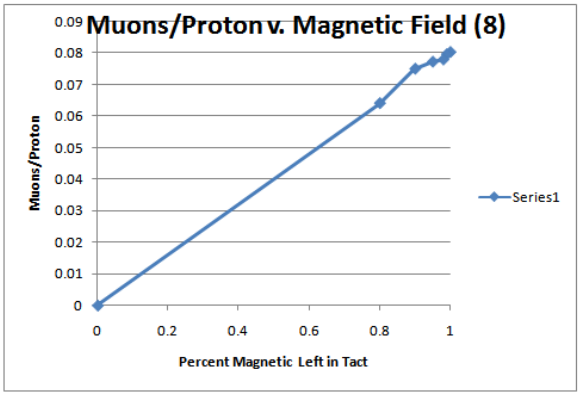


Figure 13: Ratio of muons/proton as a function of magnetic failures over clusters of 8 cells throughout the cooling channel.

As can be seen from the figure above, as the field breaks down across all the clusters of 8 cells, not much changes from when it broke down across the single cells. This, like the previously described RF cavity anomaly, is unexpected because the clusters of 8 cells should (one would think) more drastically affect the final count of muons/proton than the single cells would. But they are approximately the same. This study should be further examined.

V. Random Phase Change

This final study was done on random phase changes in the RF-cavities. The optimal phase, as obtained previously in study 1, was about 40 degrees. In this study, we changed the phase by different values and applied those new phases to 2, 5, 10, 20 and 25 randomly selected cavities throughout the cooling channel. As can be seen below in Figure 14, all 4 varied phases over the different numbers of cavities manage to produce a relatively steady Muon/Proton ratio, with respect to an optimal value represented by the black line. Although at 30 and 35 degrees the ratio seems to oscillate, it remains within ~5% of 35 degrees' peak value. 45 and 50 degrees appear to maintain a relatively smooth and consistent muon/proton value.

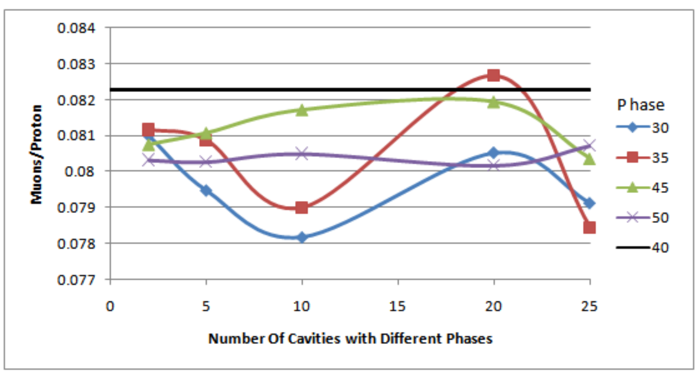


Figure 14: [color] Ratio to number of cavities with affected phases. The colored curves represent the different phases I performed this test at. The black line is simply a baseline, and is present simply for comparison purposes with the other curves—it has constant phase over all cavities.

These results seem to tell us that so long as we are able to maintain a relatively consistent phase over most of our cavities, our Muon/Proton ratio will not be too adversely affected.

CONCLUSION

For as many years as we've known about the existence of the neutrino, we know surprisingly little about them. Neutrinos are charge-less and interact very weakly; they are therefore fairly difficult to detect without gigantic detectors and tens of thousands of tons of water or mineral oil. One way to shy away from these gigantic detectors is to mass produce neutrinos in a neutrino factory [5]. This would enable us to increase the number of neutrinos entering our detector by order of magnitude; this would then also increase the number of observable neutrino interactions in the detector. More data means more answers.

In this study, the cooling channel of the front end of a muon collider neutrino factory was examined. With the introduction of H_2 gas into the model, parameters needed to be reviewed and accordingly adjusted. The pressure of the gas (10atm), thickness of absorbers (8mm), phase (40 degrees) and gradient (16MV/m) were all re-studied and updated. RF-cavity and magnet errors were also reviewed in attempt to offer some guidance on tolerance during the building stage of the experiment. Though many of those results were intuitive, the RF cluster/random distribution of broken cavities is an anomaly and should be further examined as should some of the parameters of the front end. These include the pressure of the gas and the RF-gradient.

ACKNOLEDGMENTS

I would like to acknowledge Juan Gallardo for the ideas and many useful discussions and suggestions that made this paper possible. This work is supported by the Diversity Department of Human Resources and Occupational Medicine Division at Brookhaven National Laboratory.

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