# TOWARDS A GLOBAL OPTIMIZATION OF THE MUON ACCELERATOR FRONT END *

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*Abstract*

The baseline design for the Front End of a Neutrino Factory and Muon Collider consists of a five major components, namely the Target System, Decay Channel, Buncher, Phase Rotator, and the Ionization Cooling Channel. Although each of the mentioned systems has a complex design which is optimized for the best performance with its own set of local objectives, the integration of all of them into one overall system requires a global optimization to insure the effectiveness of the local objectives and overall performance. This global optimization represents a highly constrained multi-objective optimization problem. The objectives are the number of muons captured into stable bunches of specified transverse and longitudinal emittances, as constrained by the momentum-and dynamic-acceptance of the subsequent acceleration systems in addition to the overall cost. A multi-objective global evolutionary algorithm is employed to address such a challenge. In this study a statement of optimization strategy is discussed along with preliminary results of the optimization.

## INTRODUCTION

The capture efficiency of muon Front End [1] of a Neutrino Factory and Muon Collider [2] determines the luminosity of both machines. In the Neutrino Factory scenario only a 4D transverse Cooling Channel is considered, while in the Muon Collider a charge separation follows the Front End before the 6D Ionization Cooling.

The muon beam is produced by bombarding a pion-production target with a 4-MW proton beam that is pulsed at 50 Hz. Produced pions travel through a constant-field solenoid Decay Channel where they decay into muons. Following the Decay Channel, muons go through bunching, phase rotation, cooling, and acceleration sections. Previous studies [3] have shown that using the global Front End performance as the figure of merit in the optimization of local systems improves the performance in a significant way. In this study we identify the parameters in each of the major subsystems of the Front End major that have an impact on the integrated performance, then we optimize the design accordingly.

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## TARGET AND MUON FRONT END

The Target System is designed to deliver intense muon beam of $10^{14}$ muons/sec from an incident beam of $10^{15}$ protons/s. In the baseline design a liquid-mercury jet target intercepts the 8-GeV proton beam inside a solenoid field that peaks at $B_i = 20$ T at the target and tapers down to $B_f = 1.5$ T over a distance of $L_{\rm taper} = 15$ m. The portion of the mercury jet disrupted by the proton beam is replaced before the arrival of the following proton pulse. This baseline configuration produces 0.8 muons/proton at the end of the Target System.

After the particles leave the tapered target solenoid they are transported in the Decay Channel, Buncher, and Phase Rotator in a constant solenoid field, nominally 1.5 T. At the end of the Decay Channel, $\approx$ 70 m from the target, most pions have decayed into muons and the beam is about 15 m long. The beam is then bunched over $\approx$ 33 m in a sequence of RF cavities with frequencies from 320 to 230 MHz that capture muons with kinetic energy ranging from 50-400 MeV. The bunching cavities RF voltage increases linearly along the channel from 3.4 to 9 MV/m.

In the 42-m-long phase-rotation section, lower-energy muons are accelerated and higher-energy ones are decelerated, until at the end of the Rotator the central momentum is 232 MeV/c, and the original 15-m-long bunch of muons of both signs has been formed into a 48-m-long train with 33 bunches of $\mu^+$ interleaved with 33 bunches of $\mu^-$. The muon beam is then matched into the alternating, 2.8-T solenoid field in the Cooling Channel.

## OPTIMIZATION STRATEGY

In this section we identify the parameters in each subsystem that we consider in the global optimization. In the next section we will show the improvement on the performance after optimizing each of those parameters.

### *Capture Solenoid*

The target-solenoid field is parameterized in three variables, the peak initial field at the target location, the taper length, and the end solenoid field. For this study the peak field was either 20 or 15 T The effect of solenoid field profile on the phase space density and distribution of the captured muons was studied by simulating the particles produced at the target and transported through the rest of the Front End. The target-solenoid field profile was shown to

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have a significant effect on the performance of the front end [4]. Here, we consider optimizing the capture efficiency as a function of the final asymptotic end field and the length of the taper as well.

### *Decay Channel, Buncher and Phase Rotator*

Muons are confined in the Decay Channel, Buncher, and Phase Rotator by a series of constant-field focusing solenoid coils.

The muon/pion bunch lengthens as it drifts through the Decay Channel, developing a high-energy head and a low-energy tail which depends on the Channel length. We considered a multivariable optimization of the target-solenoid taper length, RF phase and the Decay Channel length at various taper end-field values. Figure 1 shows the process of optimizing the Decay Channel length with the figure of merit being the total number of muons within the acceptance cuts of the accelerator [5].

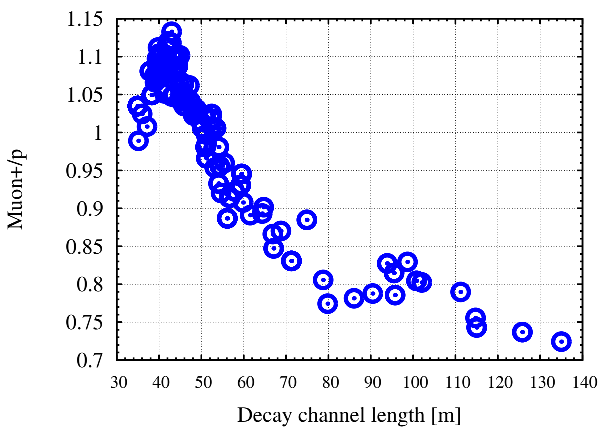


Figure 1: Optimizing the Decay Channel length using a differential evolution algorithm.

The effect of the solenoid field strength on the performance of the Front End was studied, including dynamic losses due to resonances (“stop bands”) in the periodic field structure. The coil design was optimized to suppress those dynamic losses.

As the taper length of the target solenoid was optimized, the RF phases of the Buncher and Phase Rotator were also varied to find the optimal working point. Figure 2 illustrates an optimization of overall RF phase.

### *Broadband Match to Ionization Cooling Channel*

While the muons are confined with a constant solenoid field starting from the Decay Channel to the end of the Rotator, the field in the Cooling Channel is generated by alternating solenoid coils of $\pm 2.8$ T strength. The muon-beam phase-space ellipse would experience filamentation and emittance growth without matching between the region regions of constant and alternating solenoid fields. The muon beam out of the Phase Rotator has a large momentum spread, as shown in Fig. 3. A set of 9 solenoid coils

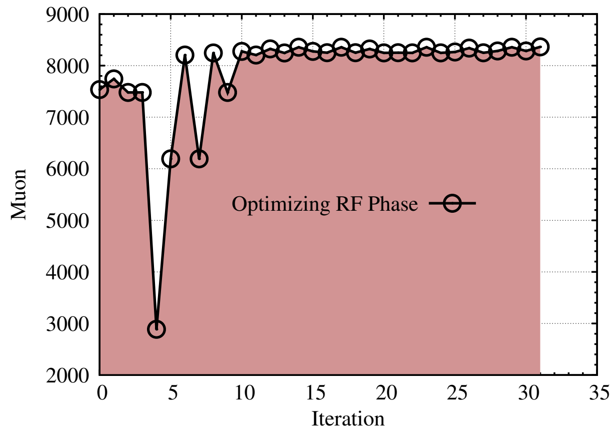


Figure 2: Optimization of the phase of the Buncher and Rotator RF cavities. Each iteration represent a trial value of the RF phase.

were considered to perform the match between the Rotator and the Cooling Channel. The objective of this optimization was constructed as a sum of the emittance magnification factor [6], eq. (1), at various momenta weighted by the number of muons within the vicinity of a central momentum,

$$EM = \frac{1}{2}\left[\frac{\beta_b}{\beta_s} + \frac{\beta_s}{\beta_b} + \left(\sqrt{\frac{\beta_b}{\beta_s}}\alpha_s - \sqrt{\frac{\beta_s}{\beta_b}}\alpha_b\right)^2\right], \quad (1)$$

where $\beta_b$ and $\alpha_b$ are the beam ellipse parameters and $\beta_s$ and $\alpha_s$ are the periodic solution for the Cooling Channel. Figure 4 shows the number of accepted muons along the Front End before and after the match.

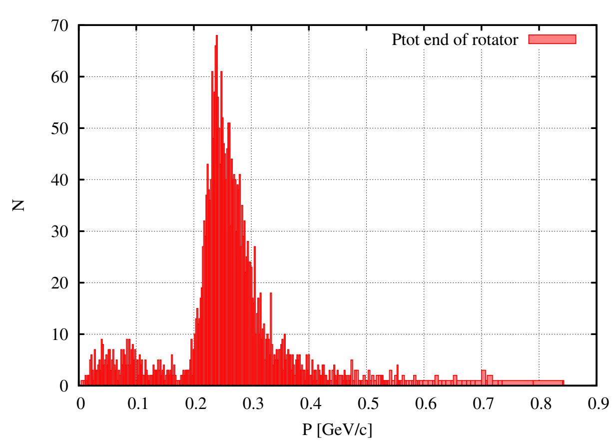


Figure 3: Muon beam momentum distribution at the end of the Phase Rotator.

## HIGH PERFORMANCE COMPUTING OPTIMIZATION TECHNIQUES

A set of parallel, differential-evolutionary-optimization algorithms working on a CRAY based architecture [7] were

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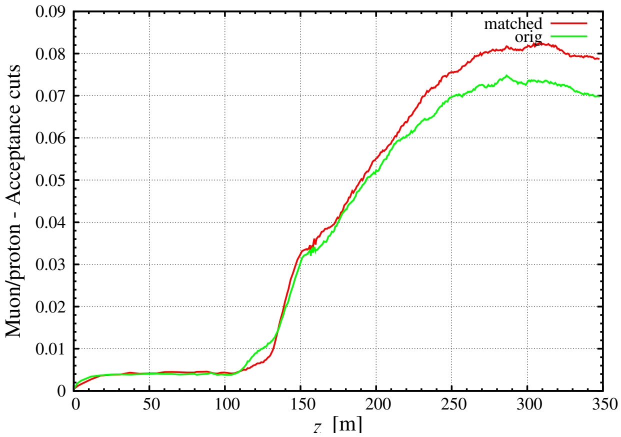


Figure 4: Performance of the Front End before and after optimizing the $B = 2.5$ T match to the $\pm 2.8$ T alternating solenoid field in the Ionization Cooling Channel. The matching coils are located at $z \approx 150$ m from the target.

utilized and integrated with a parallel, Monte-Carlo-based, ionization-cooling-and-transport code ICOOL [8].

## RESULTS

A first round of the global optimization of the Front End (which included parameters from the target solenoid taper, Buncher and Rotator RF phases, Decay Channel length and field strength, broadband matching to Cooling Channel) showed significant improvement of the performance of the Front End. Figure 5 shows the optimized performance of the Front End *vs.* the constant solenoid field, with an improvement of $15\%$ above the unoptimized baseline field of 1.5 T, increases to $60\%$ improvement at 3.5 T. An increase of the focusing field from 1.5 T to 2 T would improve the performance by $40\%$ which represents a substantial increase in the performance of a mild rise in the cost.

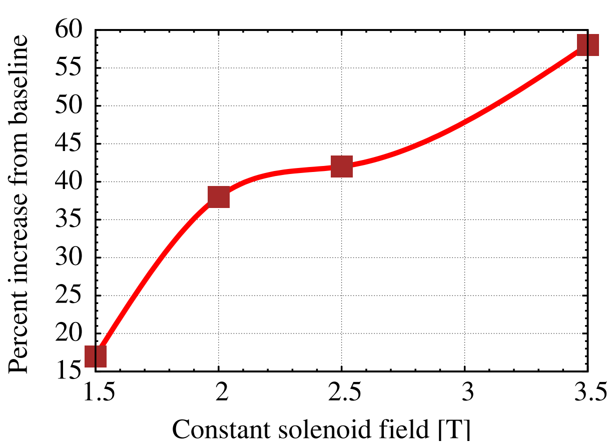


Figure 5: Optimized performance of the Front End *vs.* the constant solenoid field in the Decay Channel, Buncher, and Phase Rotator.

## SUMMARY AND FUTURE WORK

A global optimization strategy for the muon Front End was presented. The first round of the multivariable optimization showed improvement by $15 - 60\%$ over the current baseline. Future work will include optimization of parameters of the Ionization Cooling Channel (focusing field, RF phase and RF gradient, absorber configuration).

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