DESIGN AND SIMULATION OF A HIGH INTENSITY MUON BEAM PRODUCTION FOR NEUTRINO EXPERIMENTS. *

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Abstract

The production of pions which then decay into muons, yields a muon beam with large transverse and longitudinal emittances. This beam requires phase space manipulation to reduce the total 6D emittance before it can go through any acceleration stage. The design of the muon beam manipulation is based on a Neutrino Factory Front End design. In this study we report on a multi objective - multivariable global optimization of the Front End using parallel genetic algorithm. The parallel optimization algorithm and the optimization strategy will be discussed and the the optimized results is presented as well.

INTRODUCTION

The baseline design for the Front End of a Neutrino Factory consists of a five major components, namely the Target System, Decay Channel, Buncher, Phase Rotator, and the Ionization Cooling Channel. Although each of these 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-variable 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. Downstream of the target station a Chicane was placed for filtering out residual high energy protons. The Chicane design parameters are included in the optimization. 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.

GENETIC ALGORITHM WITH MULTI-LEVEL OF PARALLELISM

A multi-objective global evolutionary genetic algorithm was utilized to optimize the performance of the muon source Front End. Due to the stochastic nature of the pion beam production process and the energy loss in the Ionization Cooling Channel, a tracking of large number of initial particles ($> 10^6$) has to be carried out to limit the statistical fluctuations from influencing the optimization process. In oder to be able to perform such tracking the average evaluation of one run may take up to few hours. We utilized a parallel MPI [1–4] tracking code which reduces the running time of each run to 2 minutes. The genetic optimization algorithms usually require large number of cost function evaluations before converging, the number of cost function evaluations has a dependence on the number of variables and initial population size. For a complicated optimization task that we are considering in this study it may take few days of running to reach a set of optimal solutions. To overcome this problem we developed a two layers of parallelism algorithm, where the genetic algorithm runs in parallel mode and each function evolution is evaluated using MPI - parallel tracking code (parallel - Icool [2]). In previous efforts [4] we were able to implement an integrated MPI-code where the control of parallel cores was managed by the MPI-genetic algorithm and the tracking code was called as an MPI function. Those efforts proved to be tedious in terms of code management and limited capability to run various codes for each runs (*e.g*, running MARS or GEANT4 for particle production and Icool for tracking). To solve this problem, we separated the optimization task into three separate blocks: the first block is the genetic algorithm which generates an array of size $n \times m$, where n is the number of variables and m is the population size. Then this array is passed to the second block where it launches a set of m MPI jobs. Each job runs independently where the second block has to wait for all of the MPI-jobs to finish before collecting the results and sending an array of size m back to the genetic algorithm for processing and generating the second batch of n variables. For the algorithm to be robust we implemented a technique to detect failed function evaluations and either discard the result or if crucial it repeats the function evaluation.

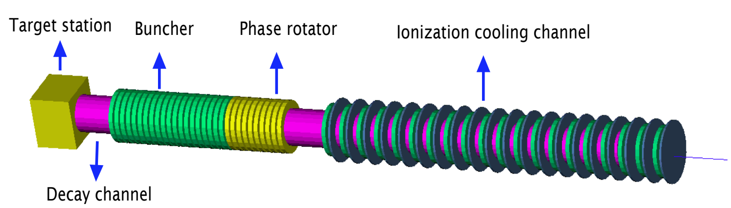

Figure 1: Schematic layout of the Muon Accelerator Front End based on [5].

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PION PRODUCTION TARGET AND MUON PHASE SPACE MANIPULATION

The target station under consideration of this study consists of Graphite target rod in a strong focusing solenoid field of 20 T. The solenoid filed tapers down to an end field which takes values from 2-4 T over a distance that we call "the taper length" L_{taper}. After the particles leave the tapered target solenoid they are transported in the Decay Channel, Buncher, and Phase Rotator in a constant solenoid field. At the end of the Decay Channel, most pions have decayed into muons and the beam is about 15 m long. The beam is then bunched in a sequence of RF cavities with frequencies from 490 to 325 MHz that capture muons with kinetic energy ranging from 50-400 MeV. The bunching cavities RF voltage increases linearly along the channel. The Buncher cavities frequencies decreases adiabatically. The RF frequencies and gradients are used as free parameters to be optimized in the optimization process. In the energy phase-rotation section, lower energy muons are accelerated and high energy ones are decelerated, until at the end of the Rotator all the bunches have the same central momentum, and the original long bunch of muons of both signs has been formed into a series of microbunches with 21 bunches of μ^{+} interleaved with 21 bunches of μ^{-}. The muon beam is then matched into the alternating, 2.8-T solenoid field in the Ionization Cooling Channel. A schematic of the Muon Front End is shown in Fig. 1.

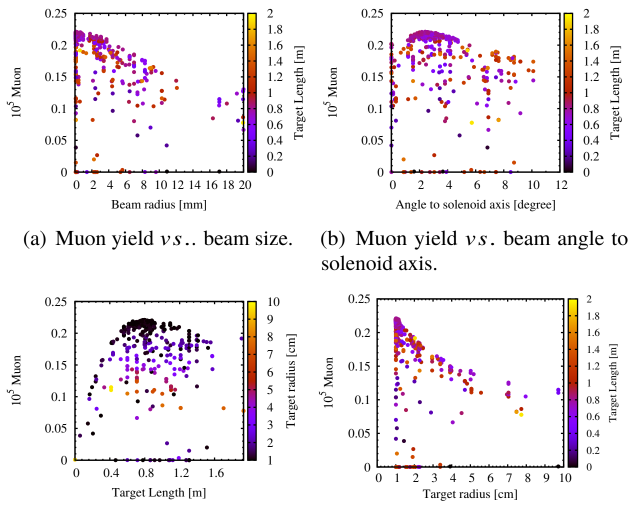
LOCAL SYSTEM OPTIMIZATIONS

We will start by optimizing each of the local systems individually starting from the target, particle selection Chicane, and Be absorber. Later we include the mentioned systems with the rest of the Muon Front End including the Buncher, Energy Phase Rotator, matching to transverse Ionization Cooling Channel, and the Ionization Cooling Channel parameters in a global optimization to be discussed in the following section.

The target geometry and capture section

The pion production target yield depends on the proton driver beam parameters, target geometrical parameters, and the capture field. We first started by looking at the impact of beam and target geometrical parameters on the muon yield. Fig, 2. In this study both the proton beam and the target are set to be collinear. GEANT4 was used for particle production and the muon yield was recorded at the end of the Decay Channel, we only counted muons which fall within the acceptance of the Buncher and Energy Phase Rotator. The tracking included the capture section, Chicane and Decay Channel. The target material considered in this optimization is graphite. The aperture surrounding the target was also included in the optimization. Fig. 4 shows the muon yield for different end fields counted at the Decay Channel. Notice that the capture efficiency saturates at 7 T.

Table 1 shows the optimal parameters for the target geometry.



(a) Muon yield $vs.$. beam size. (b) Muon yield $vs.$ beam angle to solenoid axis.

(c) Muon yield $vs.$ target length. (d) Muon yield $vs.$ target radius.

Figure 2: (a,b) Impact of initial proton beam size and angle on the muon yield. (c,d) impact of the target length and radius on the muon yield.

Table 1: Optimal proton beam and graphite target geometrical parameters.

Target Parameter	Unit	Optimal Working Point
Target Rod Length	m	0.8
Target Radius	cm	1.0
Angle to solenoid axis	degree	2.4
Proton beam size	mm	0.2
Aperture size	cm	12.5

The target capture solenoid field peaks at the target location and should be adiabatically matched to a lower field solenoid channel for transport to the rest of the accelerator. In this study we examined only peak field of 20 T. The optimization run included the end field and the tapering length from peak value to end field value, see Fig. 3 for examples of such fields.

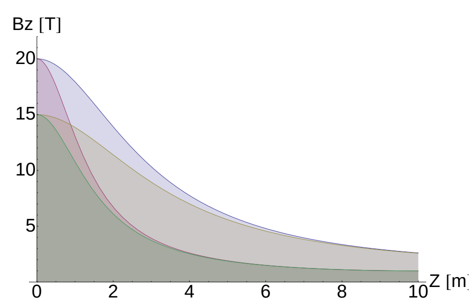


Figure 3: On-axis magnetic field profiles for the Target System.

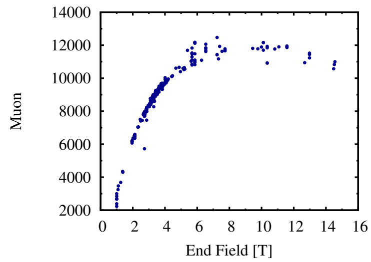
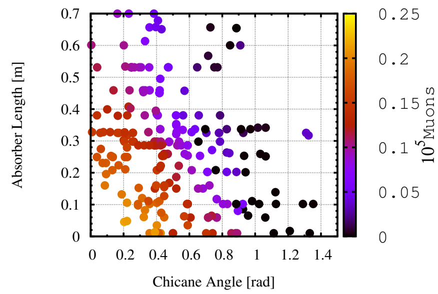
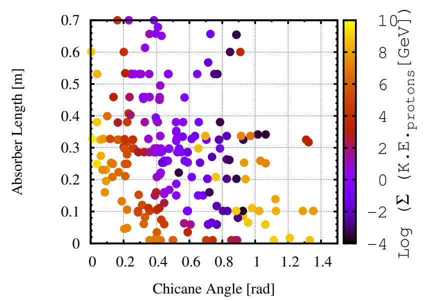


Figure 4: Dependence of the muon yield on the end field. Muons are counted at the end of Decay Channel.



(a) Number of transmitted muons *vs*. Chicane angle and absorber length.



(b) Total transmitted K.E. after absorber *vs*. Chicane angle and absorber length .

Figure 5: Chicane Optimization.

Particle selection section: Chicane and Be absorber

Protons with wide energy spectrum travel through the target and are transported to a downstream Decay Channel. A Chicane followed by a Be absorber were implemented to limit the total transmitted proton beam power [5]. The Chicane bends positive and negative pions/muons and transport them to the the downstream channel while high energy protons are trapped in the shielding absorbers of the Chicane walls. The rest of low energy unwanted particles are removed by a Be absorber downstream of the Chicane. The Chicane impacts the efficiency of muon transport and the optimization of the Chicane parameters (radius of curvature and length) and the Be absorber thickness is crucial to the overall performance of the Front End. Figure 5 shows the optimization of the Chicane and the Be absorber parameters to maximize the muon transport and minimize total transmitted protons kinetic energy downstream of the Be absorber.

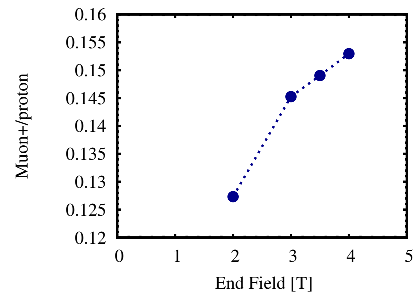


Figure 6: Normalized number of muons within the acceptance of the downstream accelerator as a function of the end field through the rest of the Front End.

GLOBAL OPTIMIZATION OF THE MUON FRONT END

A global optimization of a 20 Front End parameters was launched which includes: the proton beam driver and target geometrical parameters, capture field parameters, phases of the Buncher/Rotator RF cavities, matching coils to Ionization Cooling Channel, and finally the phase of Ionization Cooling Channel RF cavities. The results parameterized in terms of the end field throughout the Front End is shown in Fig. 6.

CONCLUSION

A genetic algorithm with multi-level of parallelism was developed and discussed. A first application of this robust algorithm was adopted for the Muon Front End design effort. A global optimization scheme for a high intensity muon beam Front End was discussed. The dependence of the muon capture efficiency on various systems in the Front End was optimized locally then globally. The final performance of the end field was shown.

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