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High intensity muon beam source for neutrino beam experiments

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ABSTRACT

High intensity muon beams are essential for Muon accelerators like Neutrino Factories and Muon Colliders. In this study we report on a global optimization of the muon beam production and capture based on end-to-end simulations of the Muon Front End. The study includes the pion beam production target geometry, capture field profile, and forming muon beam into microbunches for further acceleration. The interplay between the transverse and longitudinal beam dynamics during the capture and transport of muon beam is evaluated and discussed. The goal of the optimization is to provide a set of design parameters that delivers high intensity muon beam that could be fit within the acceptance of a muon beam accelerator.

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1. Introduction

High intensity muon beams are produced from decays of pions, which are produced as a secondary beam from a primary high power proton beam hitting a pion production target. When protons hit the target material, the nucleon–nucleon interactions are responsible for pions production. The pion production is dominated by the single and double production processes given by (1). Later pions decay into muons and neutrinos.

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. Figs. 1 and 2 show schematic drawings of the target station and the front end [1,2]. 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 ensure 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.

The efficiency of the pion beam production has a strong dependence on the choice of the target material and target geometry. Whereas the efficiency of capturing the secondary pions and the subsequent muons depends on the capture field profile. In this study we report on new target design parameters based on a global optimization of the target geometry and the capture field profile. The key parameters considered in this study include the proton beam and target geometrical parameters, the capture and transport field, the Buncher and Energy Phase Rotator phases, frequencies, and gradients, and finally the broadband match to the ionization cooling channel.

A parallelized evolutionary optimization algorithm was deployed on a CRAY based supercomputer to find the optimal design parameters. The goal of this study is to find the optimal parameters within the feasible limits of operation of high power targets and maximum achievable magnetic fields. In this study the statement of optimization strategy is discussed along with results of the optimization.

$$\begin{array}{ll}
p+n\to p+n+\pi^{+}+\pi^{-} & p+n\to n+n+\pi^{+}+\pi^{0}\\
p+n\to p+p+\pi^{-}+\pi^{0} & p+n\to d+\pi^{+}+\pi^{-}\\
p+p\to p+n+\pi^{+} & p+n\to p+p+\pi^{-}\\
p+n\to n+n+\pi^{+} & p+p\to d+\pi^{+}\\
p+p\to p+p+\pi^{+}+\pi^{-} & p+p\to n+p+\pi^{+}+\pi^{0}\\
p+p\to d+\pi^{+}+\pi^{0} & p+n\to p+n+\pi^{+}+\pi^{-}\\
p+n\to n+n+\pi^{+}+\pi^{0} & p+n\to p+p+\pi^{-}+\pi^{0}\\
p+n\to d+\pi^{+}+\pi^{-} &
\end{array} \quad (1)$$

2. Muon beam production and capture

The target station of the muon beam production is designed to accommodate a target rod made of graphite. The target is surrounded by a set of superconducting coils which provide a

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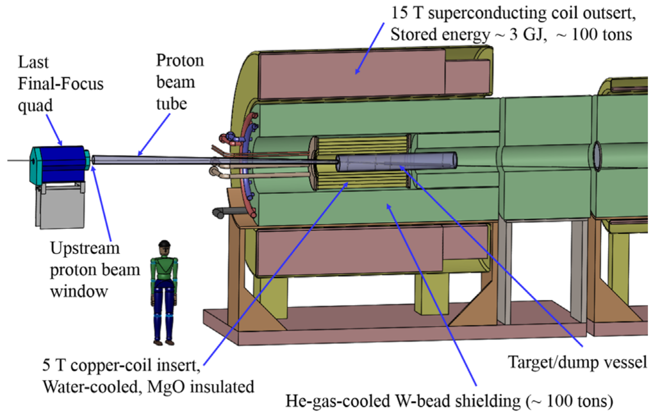

Fig. 1. Schematic of a high power Muon Accelerator Target station.

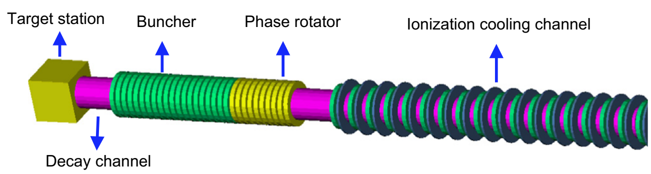

Fig. 2. Schematic of the Front end of the Muon Accelerator.

peak field of 15 T in addition to a normal conducting resistive magnet providing a 5 T field [3,4]. Initial design of the Neutrino Factory target station proposed a Hg jet target. In this work we explore a staged approach that first uses graphite target for 1–2 MW and later uses mercury for higher beam power 3–4 MW. The proton driver is providing 10^{15} protons per second with bunch frequency of 60 Hz.

The advantage of solenoid capture over horn based collection is that they capture both positively and negatively charged pions at the same time. Target solenoid captures charged particles with a broad momentum range and its capture efficiency is only limited by the transverse momentum of captured pions. Target solenoids will capture any charged particle with transverse momentum $\sigma_{P_T} < eBa/2c$, where a is the aperture size at the target location. Most of the secondary pions are produced with $P_z \approx 100$ MeV/c and $P_T \approx 260$ MeV/c, which requires strong capture field in the range of 20 T. Fig. 3 shows the transverse phase space distribution of secondary pions at the end of the target material.

After the particles leave the tapered target solenoid they are transported in the Decay Channel, Buncher, and Energy Phase Rotator in a constant solenoid field. A high frequency Buncher and Energy Phase Rotator were first realized for muon beams on [5] and later adapted in [6].

At the end of the Decay Channel, most pions have decayed into muons and the muon bunch length is about 15 m long. The beam is then bunched into a sequence of microbunches using a set of RF cavities that capture muons with kinetic energy ranging from 50 to 400 MeV. The bunching cavities of RF voltage increase adiabatically along the channel where their frequencies decrease. The RF frequencies and gradients are used as free parameters in the optimization process. Following the RF Buncher an Energy Phase Rotation Channel is used, where 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.

The ionization cooling channel consists of 70 cells. Each cell contains four 325 MHz RF cavities for acceleration and LiH blocks

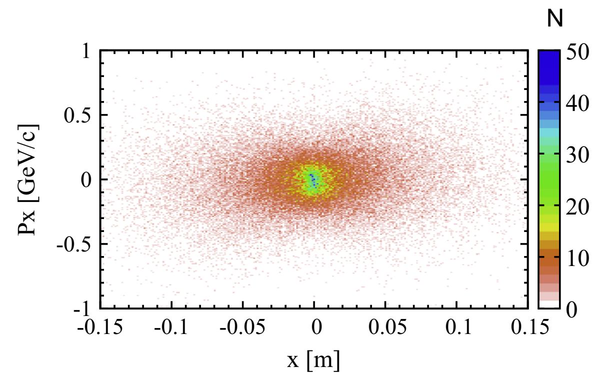

Fig. 3. Transverse phase space of secondary beam at the end of the target.

for ionization cooling. A series of focusing coils providing ± 2.8 T sinusoidal field. The cooling channel provides a transverse emittance reduction by a factor of 2.5 of the bunched muon beam.

3. Optimization algorithm with multi-level of parallelism

A multi-objective global deferential evolution algorithm [7] 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 order to be able to perform such tracking the average evaluation of one run may take up to few hours. We utilized a parallel MPI [8–10] tracking code which reduces the running time of each run to 2 min. The heuristic 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 optimization algorithm runs in parallel mode and each function evolution is evaluated using MPI – parallel Monte-Carlo tracking code.

In previous efforts [10] we were able to implement an integrated MPI-code where the control of parallel cores was managed by the MPI-optimization algorithm and the tracking code was called 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 [11,12] or GEANT4 [13] 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 optimization 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 optimization 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.

The optimization process that we will adopt in the study consist of two parts, the local system optimization followed by a global optimization of the whole front end.

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