DESIGN AND OPTIMIZATION OF A PARTICLE SELECTION SYSTEM FOR MUON BASED ACCELERATORS

Diktys Stratakis, J. Scott Berg, Brookhaven National Laboratory, Upton, NY, 11973-5000, USA*
David Neuffer, Fermilab, Batavia, IL, USA
Pavel Snopok, Illinois Institute of Technology, Chicago, IL, USA

Abstract

In muon accelerators, muons are produced by impacting high energy protons onto a target to produce pions. The pions decay to muons which are eventually accelerated. A significant background of protons and electrons are generated that deposit heat in superconducting materials and activate the machine. In this paper we describe a two-step particle selection scheme: a chicane to remove the high momentum particles from the beam and a beryllium absorber that reduces the momentum of all particles in the beam, resulting in the loss of low momentum protons. We review the design and numerically examine its impact on the performance of the muon front end.

INTRODUCTION

In a muon accelerator, a high power proton beam fires pulses onto a target to produce pions. The pions are captured within a high field solenoid that tapers down to a lower field (2 T in our case), and that field then remains constant downstream as the pions decay to muons. The muons are then bunched and the bunches are phase-energy rotated to form a string of muon bunches that are subsequently cooled, if necessary, and accelerated. This front end system (target, drift, buncher, and rotator) is designed to produce and accept a maximal number of muons.

In addition to the desirable pions which will eventually decay into muons, there are a number of other particles, in particular protons, which will be focused by the downstream solenoid channel. Without collimation, this flux is lost on the front end apertures at kW/m levels, much larger than the approximately 1 W/m desired to ensure “hands-on” maintenance. An absorber can reduce the uncontrolled energy deposition in the downstream channel from these particles, but making an absorber thick enough to eliminate the high energy protons would also significantly reduce the pion and muon flux. Rogers [1] proposed a solenoid chicane to eliminate the high energy protons, leaving the absorber to deal with the remaining low energy protons. The chicane is a bent solenoid system. Lower momentum particles are strongly focused by the solenoid and follow the chicane with little orbit distortion. High-momentum particles are not strongly deflected by the bent solenoid and are lost in or near the chicane, and collimated on shielding walls.

NEW FRONT END DESIGN

The IDS-NF chicane [2] removes particles with momentum larger than about 500 MeV/c. The chicane is followed by a 10 cm beryllium absorber that removes protons and electrons, particularly at low energy, via energy loss and interactions. Muons pass through but with a large energy-dependent energy loss; low-energy muons are stopped. With the chicane/absorber, uncontrolled losses downstream of the chicane were reduced to around 10 W/m. Adding the chicane and absorber to the front end reduced the useful muon flux. After re-tuning the buncher/rotator system, this reduction was around 10%.

The Muon Accelerator Program [3] modified the base RF frequency from the earlier value of 201.25 MHz to 325 MHz. This required a complete redesign of the front end of the IDS-NF. The baseline solenoid field is 2 T (compared to 1.5 T in the IDS-NF), and the system is compressed to obtain a shorter bunch train. The 20 T–2 T transition is reduced to about 6 m (from 15 m in the IDS-NF). The increased chicane field increases the chicane capture momentum; the chicane length is increased to compensate. The absorber was found to stop pions before they decay to muons, and was therefore moved downstream by about 30 m to avoid this.

The absorber reduces the energy of all the muons, with a larger loss for lower momentum paraticles, which increases longitudinal beam emittance. Additional distance is needed after the absorber to extend the beam distribution and obtain the energy-position correlation needed for bunching and phase-energy rotation. The front end system length increases by about 29.7 m from the case without absorber/chicane.

With the higher field chicane the momentum cut-off is now around 700 MeV/c. The newer chicane is less efficient than the IDS-NF in eliminating high-momentum pions and muons. Moving the absorber downstream and rematching the buncher–rotator increased the length of the system, with a small loss in muons captured. The chicane/absorber system still reduces downstream energy deposition by more than an order of magnitude over the front end without it.

SIMULATION CODE DISCREPANCIES

Earlier simulations based on the 201.25 MHz RF lattice showed that there was a significant (on the order of 15%) discrepancy in muon beam transmission between G4beamline [4] and ICOOL [5]. The discrepancy could be due to the different models the two codes use for the chicane field. G4beamline uses a field map generated by a set of coils, while ICOOL uses a toroidal field model (described below). Simulation results dismissed that hypothesis. Fig-

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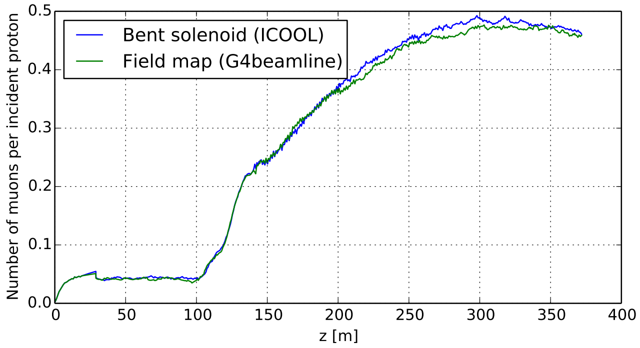

Figure 1: Comparison of muon transmission as simulated by G4beamline (field map generated by a set of coils) and ICOOL (continuous bent solenoid field), number of useful muons per incident proton (within the $100 < P_{total} < 300$ MeV/c momentum range and the consistent transverse and longitudinal amplitude cuts).

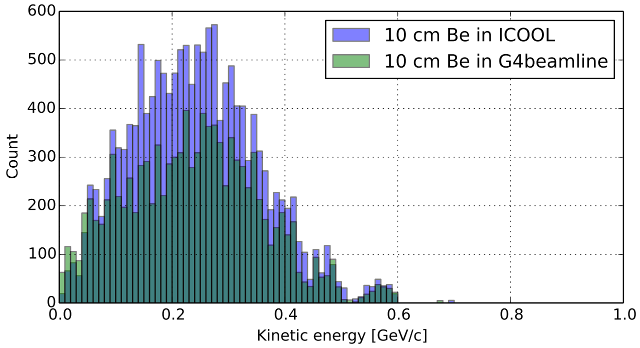

Figure 2: Comparison of pion transmission through 10 cm of beryllium as simulated by G4beamline and ICOOL.

ure 1 shows muon transmission through the chicane down to the beginning of the buncher in both codes. The discrepancy is less than 0.5%.

Another possible source of the discrepancy is the nuclear interaction of pions in the beryllium absorber. ICOOL does not include a model for nuclear interactions of pions, whereas G4beamline does. Figure 2 shows pion transmission in G4beamline and ICOOL for 10 cm of beryllium. A significant number of pions are stopped in the material when simulating in G4beamline, while that does not happen in ICOOL. These pions would have eventually decayed into muons. G4beamline must therefore be used in regions with material where there are significant numbers of pions. Furthermore, this indicates that there could be a benefit in moving the absorber further downstream, where more of the pions have decayed, and therefore fewer will be lost in the absorber.

PARAMETRIC CHICANE STUDY

We study the design of the particle selection system by first scanning the geometric parameters of the chicane and looking for solutions with the best transmission that remove

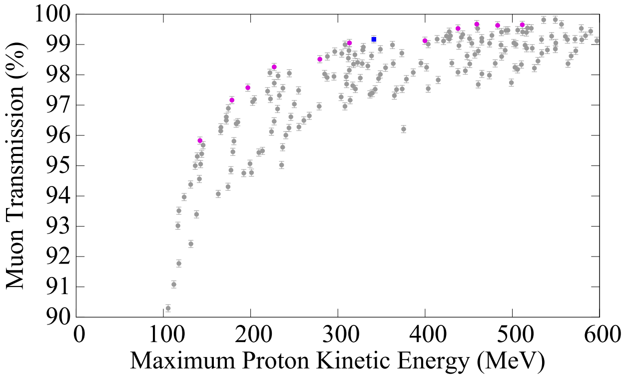

Figure 3: Muon and pion transmission (as defined in text) and K for the chicane parameters we scanned. Magenta points were used to fit the chicane geometry parameters as a function of the K. The square blue point was also originally selected, but was removed from the fit.

almost all the protons above a given energy (the "maximum proton kinetic energy", which we will henceforth denote with K). We use this to express the parameters of the chicane geometry in terms of K. We choose several of these optimal geometries and add a beryllium absorber downstream of the chicane, put it at two different positions, vary its thickness, and examine the muon transmission and the effectiveness of the system at removing protons.

We begin with a particle distribution arising from an 8 GeV proton beam incident on a tilted mercury target in a 20 T solenoid field, as simulated by MARS [6]. We then propagate those particles using ICOOL [5] through a solenoid field that tapers down to 2 T in over a distance of 14.75 m (a truncated version of the taper from [7]), then continues at 2 T for another 6.5 m. Downstream from there, we have a chicane which bends by an angle θ over an arc length of L, then bends in the opposite direction over the same angle and length. The magnetic field in each chicane section is modeled with a purely longitudinal field of $B_{s0}(1+\theta x/L)$, where x is the horizontal coordinate, positive away from the center of curvature (θ is always positive), and B_{s0} is 2 T. There is a 2 T solenoid field downstream from that point.

We scan θ in 20 mrad steps and L in 0.5 m steps. Our performance criteria are K and the muon transmission, without an absorber, at a position 44.1 m downstream from the start of the chicane. K is computed by finding the lowest proton energy such that the sum of the kinetic energies of all protons with that energy and higher is less than 2 W per MW of proton power hitting the target. The muon transmission is the number of the muons with kinetic energies between 80 and 260 MeV and pions with kinetic energies between 80 and 320 MeV, divided by the same quantity without a chicane. Figures 3 and 4 show the results of that parameter scan. Chicanes with very different parameters can have similar K but different transmissions. We chose some parameters which were on the high transmission edge of the points in Fig. 3. Those points are colored in the figure, and their θ and L are plotted in Fig. 4. We then fit those points to the

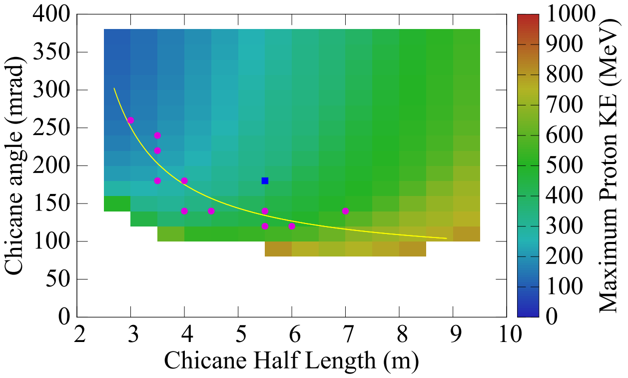

Figure 4: K downstream of the chicane as a function of L and θ. Points correspond to the colored points in Fig. 3. The curve shows the geometric parameters from Eq. 1.

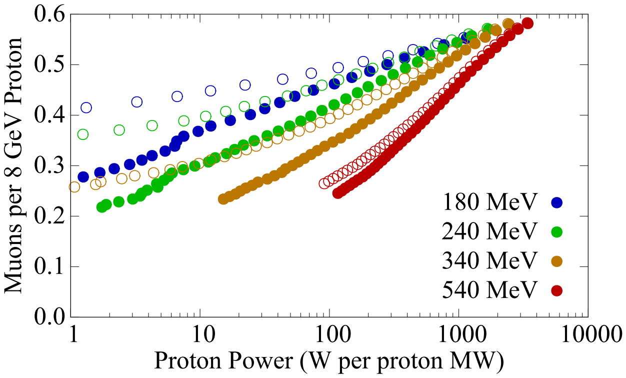

Figure 5: Each point shows, for a given chicane geometry and absorber position and thickness, the muons with kinetic energies in the range of 20 to 390 MeV and the proton power at a position 31 m from the beginning of the chicane. Each color is for a different chicane geometry, as defined by K (shown in the figure key) and Eq. 1. The absorber is positioned at the end of the chicane for filled circles, and with its upstream face 30 m from the beginning of the chicane for open circles. For each symbol, points for different absorber thicknesses in 1 cm, starting at 1 cm in the top right.

functional form

$$L = L_0 + L_1 K \qquad \theta = \theta_0 + \theta_1 / K. \qquad (1)$$

The blue point on Figs. 3 and 4 appears to be an outlier, so we drop it from the fit. The resulting parameters are $L_0 = 1.6$ m, $L_1 = 9.1$ m/GeV, $\theta_0 = 69$ mrad, and $\theta_1 = 28$ mrad GeV; we use these parameters whenever we evaluate Eq. 1.

We next take parameters from Eq. 1 for four values of K and create distributions at the end of the chicane. We then propagate the distributions downstream in G4beamline [4], passing the beam through a beryllium absorber. We vary the thickness of the beryllium absorber and try two locations for the absorber, one at the end of the chicane, the second with the front face of the absorber 30 m from the start of the chicane. 31 m downstream from the start of the chicane, we count the number of muons with kinetic energies between 20 and 390 MeV, and the energy of the protons. Figure 5 shows the results. We find better muon transmission for a given proton power downstream with chicane designs that have a lower K, and for the chicane positioned further downstream. For a given K and absorber position, increased absorber thickness reduces proton power and muon transmission. The power allowed downstream will determine the optimal parameters. The relative merits of different solutions may differ once buncher and phase rotation designs are optimized for each particle selection solution.

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