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CONTROL OF BEAM LOSSES IN THE FRONT END FOR THE NEUTRINO FACTORY

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Abstract

In the Neutrino Factory and Muon Collider, muons are produced by firing high energy protons onto a target to produce pions. The pions decay to muons which are then accelerated. This method of pion production results in significant background from protons and electrons, which may result in heat deposition on superconducting materials and activation of the machine preventing manual handling. In this paper we discuss the design of a secondary particle handling system. The system comprises a solenoidal chicane that filters high momentum particles, followed by a proton absorber that reduces the energy of all particles, resulting in the rejection of low energy protons that pass through the solenoid chicane. We detail the design and optimization of the system and its integration with the rest of the muon front end.

HIGH POWER MUON ACCELERATORS

In the proposed Neutrino Factory [1] facility, a multi-megawatt proton beam is fired onto a target to produce pions. The pions are captured in a high field solenoid that tapers to a 1.5 T constant field solenoid. Pions and their decay products, the muons, are allowed to drift longitudinally in this constant field solenoid and subsequently a variable frequency RF system is used to bunch and then phase rotate the muons. Muons are then passed into an alternating focusing ionization cooling system before acceleration to high energy. The Muon Collider facility has a similar capture system, although the proposed ionization cooling system is considerably more extensive in order to reach the very low emittances required for a high luminosity collider.

In this paper, we examine the effect of undesirable secondary particles exiting the target region and passing through the subsequent muon capture systems. Hadronic pollutants in the beam tend to cause activation of accelerator components, preventing hands-on maintenance of the machine. This would lead to additional construction and operation costs and is highly undesirable. Leptonic pollutants in the beam cause less activation of accelerator components but are still undesirable due to the increased heat load that may be placed on superconducting components.

The effect of these contaminants can be seen in Fig. 1. Losses are concentrated around the start of the ionization cooling channel where the magnetic lattice produces large transverse losses and the presence of Lithium Hydride absorbers for ionization cooling takes energy from electrons and protons. Losses are 100 W/m throughout the length of the front end and peak at several kW/m at the start of the cooling channel. Such high losses would certainly prevent hands on maintenance throughout the entire cooling channel, may cause radiation damage to equipment and quenching of superconducting magnets. Further contamination of critical components in the acceleration system is likely such as septa and injection/extraction systems.

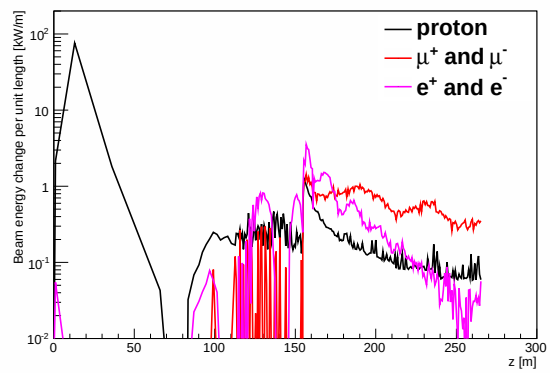

Figure 1: Total energy change of different particle species in the muon front end in the absence of a particle selection system, including gains and losses due to RF.

Two components are foreseen for a particle selection scheme: a chicane to remove high momentum particles from the beam; and a Beryllium plug that reduces momentum of all particles in the beam, resulting in the loss of low momentum protons.

CHICANE DESIGN

The design of a chicane system for the muon front end is not trivial. Other authors have considered combined function chicanes [2]. The beam emittance is such that it is highly challenging to get good transmission over the desired range of momenta using such a chicane. Both the Neutrino Factory and Muon Collider chicanes capture both positive and negative muon species, and any chicane system must do the same. This may be possible with a multipole magnet, but would make any design more difficult.

Owing to these difficulties, a stellarator-type solenoidal chicane is foreseen as an alternative. Solenoidal chicanes induce a vertical dispersion in the beam, resulting in symmetric transmission of both particle charges. Matching from the constant solenoid field of the front end to the bent

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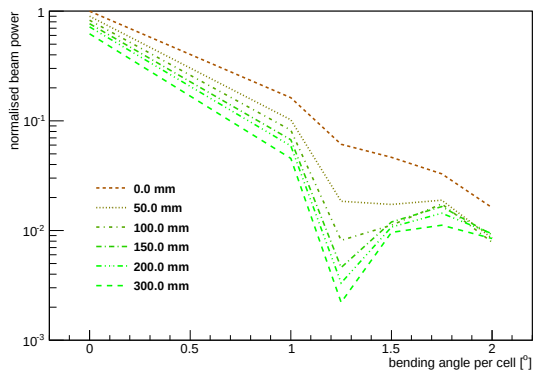

Figure 2: Total beam power of protons passing through the particle selection system, normalised to the case where particle selection system is in place.

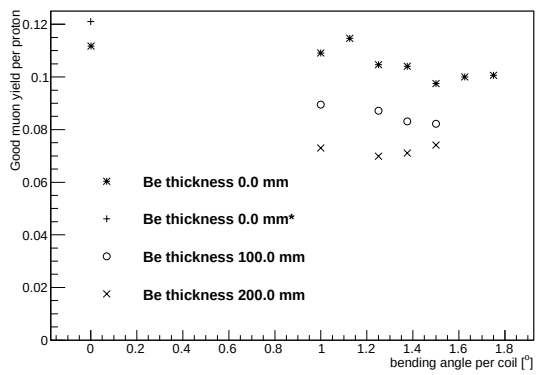

Figure 3: Number of good muons reaching the end of the muon front end cooling channel for various chicane angles and Be plug thicknesses. Note that for the 0 thickness, 0 angle case, two muon yields are listed; the '$+$' point is for an idealized lattice simulation, while the '$*$' point and all other points are for a more realistic coil geometry.

solenoid field is relatively easy. The main problem with this sort of lattice is that it is not possible to make an open midplane solenoid. Either very high radius superconducting coils with significant shielding or normal conducting coils exposed to beam power in the hundred kW range are required. Clearly these components would become active and it is expected that they would be treated as part of the remote handling facility in the target area.

The addition of a Beryllium proton absorber after the chicane serves to lower the overall energy of particles in the system. This has a more significant effect on the protons that pass the chicane, stopping almost all of them, while leaving most muons in the beam. In Fig. 2 and 3 the proton beam power passing the proton absorber and good muon yield for the entire front end system is shown for various chicane and proton absorber parameters, as simulated in G4Beamline [3]. Increasing thickness and increasing angle reduce the good muon yield slightly, while producing a dramatic reduction in the proton beam power escaping the system. Based on these simulations a 12.5° chicane angle (1.25° per coil) and 100 mm proton absorber thickness was chosen.

RF CAPTURE RE-OPTIMIZATION

When the chicane and absorber are added to the front end, the RF matching conditions for the buncher and phase-energy are shifted from the baseline conditions. In the chicane, the time-energy relationship is changed, requiring an increase in the drift by ∼1 m. The major change is imposed by the absorber, where the energy distribution is shifted to lower energies requiring a re-optimisation of the longitudinal capture system, performed by tracking the energy change in reference particles.

Two reference particles are set at the production target. The first is at 270 MeV/c and the second at 185 MeV/c. The time difference between these particles is tracked through the drift into the buncher and rotator to set the frequencies of the rf cavities. At $z = 29$ m the beam and the reference particles pass through 10 cm Be absorbers, with the reference particle momenta reduced to 237 and 144 MeV/c, respectively. The drift to the buncher and rotator increases the distance between the particles $(\Delta c\tau)$ and the RF frequencies in the buncher are set by requiring that distance is 10 RF wavelengths ($\lambda_{rf} = \Delta c\tau/10$). The RF frequency decreases from ∼320 to ∼235 MHz over the buncher over the 33 m length, as $\Delta c\tau$ increases. Following the buncher the beam and reference particles pass through the rotator where the RF wavelength difference is increased to 10.04, and the second reference particle accelerates while the first remains nearly stationary, while RF frequencies decrease from 232 for 202 MHz over the 42 m length. The beam is then matched to ∼230 MeV/c bunches at 201.25 MHz.

After rematching the drift section of the front end is increased by ∼5 m. The net number of muons that propagate through the system and arrive in the acceptance for accelerated muons is reduced by ∼10%. The background of beam propagating down the channel that is unmatched is reduced by much larger factors. As shown in Fig. 4 the chicane removes high energy muons, which would continue down the cooling channel but not be properly phased for cooling. They would arrive at the end as a pre-flash of unmatched beam that would not be phased for acceleration and capture.

IRRADIATION IN THE CHICANE

The chicane as simulated in MARS [4] starts at the end of the target/capture region, 30 meters downstream from the target. Field maps for MARS simulations are generated by G4beamline. Coils have inner radius of 43 cm, outer radius of 53 cm, length of 18 cm, with on-axis field of 1.5 T throughout the channel. Either copper or a standard

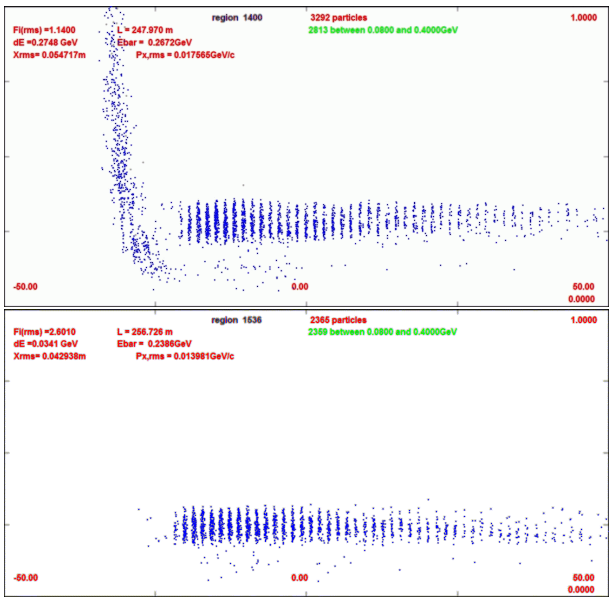

Figure 4: Phase–momenta distributions of simulated μ beam at the end of the cooling channel. Vertical scale 0 to 1000 MeV/c; horizontal is $c\tau$ (-50 to 50 m); (top) without chicane/absorber; (bottom) with chicane/absorber.

MARS material SCON consisting of 90% superconductor (60% Cu and 40% NbTi) and 10% Kapton ($C_{22}H_{10}N_2O_5$) are used for simulations. The proton absorber is a 10 cm Be disk of outer radius of 42.9 cm.

The case of a straight drift channel with no chicane and no absorber is used as a reference. In this case the peak total deposited power density (DPD) in the coils is 0.148 mW/g (a common 0.15 mW/g limit for superconducting coils is not exceeded). In terms of peak linear power density for the geometry described above that corresponds to 399 W/m for Cu coils, see Fig. 5, or 312 W/m for SCON coils. That is significantly larger than the typical 1 W/m limit for hands-on operation; however, the average linear power density is much less, 34.1 W/m for Cu coils and 26.6 W/m for SCON coils.

When a chicane and absorber is included the basic radiation limit of 0.15 mW/g is exceeded in coils #18 through #89; however, it could be reasonably reduced by providing extra shielding in coils #40 and up, so only coils #18–39 need to be replaced by normal conducting ones. DPD peaks at coil #26 at 15.8 mW/g with a significantly longer right tail in the DPD distribution due to the contribution from protons of lower energies. That translates into 42.6 kW/m for Cu coils, see Fig. 5, or 33.3 kW/m for SCON coils. Proton absorber DPD is 292 mW/g or 312 kW/m.

Proton, μ^+ and μ^- beam power ratios (compared to the initial distribution at 30 m downstream of the target) are summarized in Table 1 for various chicane angles.

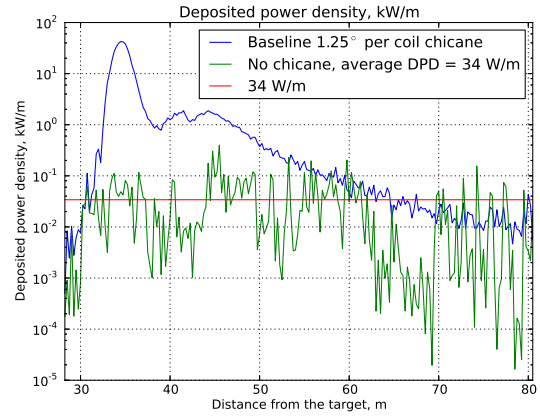

Figure 5: Deposited power density, kW/m, drift channel only, no subsequent cooling section, with and without chicane.

Table 1: Beam power fraction for protons and muons after the chicane/absorber for various chicane cell angles. Beam power before the chicane is used as a reference (100%). Only the muons in the range of interest $p \in [100, 400]$ MeV/c are taken into account. No momentum cut is imposed on protons.

Chicane cell angle [deg]	protons [%] (no mom. cut)	μ^+ [%] ($p \in [100, 400]$ MeV/c)	μ^- [%]
0.75	33.3/9.4	112.9/96.7	113.8/95.6
1.00	22.7/2.7	113.1/95.2	110.4/91.6
1.25	18.5/1.0	112.7/92.9	108.2/87.1
1.50	15.1/0.3	104.6/84.3	103.5/80.9
1.75	12.7/0.2	96.9/74.1	96.7/72.9

CONCLUSIONS

A particle selection system has been designed for the Neutrino Factory and Muon Collider that reject secondary particle contaminants that would otherwise irradiate large parts of any subsequent acceleration system. The particle selection system has been shown to reject up to 99.9% of proton contaminants as well as creating a better conditioned muon beam at the expense of a slight reduction in muon yield.

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