Neutrino Factory Parameters from Feasibility Studies 1 and 2

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A μ-storage ring neutrino factory has somewhat different requirements on the muon beams from those of a μ^+-μ^- collider. The ν-source event rate depends primarily on the number of stored muons and not on the quality of the μ-beam; therefore the beam needs only to be cooled sufficiently to be within the acceptance of the accelerator and storage ring, and not to a minimal emittance for high luminosity. Also the μ-beam need not be confined within single bunches, but can be distributed in a string of bunches.

The MC collaboration has produced two detailed Neutrino Factory design studies[1,2]. Both studies have a similar muon collection and cooling system. A schematic layout of the Study 1 scenario is shown in Fig. 1a. Following the target there is a 50 m long drift, a 100 m long induction linac for phase rotation, a mini-cooling stage, a 17 m long buncher and a 140 m long cooling section. The Study 2 scenario layout is shown in Fig. 1b. It has a 18 m drift following the target, a 108 m induction linac, a mini-cooling stage, an additional 200 m of induction linac and drift to complete the phase rotation, a 55 m buncher and a 108 m cooling section, for a total length of 540 m, about 200m longer than Study 1. Most of the following description will concentrate on the more recent Study 2 case, which is an improvement of Study 1.

I. ν-Factory precooler

In the neutrino factory studies a proton bunch on the target produces a π beam, which is then allowed to drift while the π's decay into μ's and the beam develops a position-energy correlation with the lower-energy μ's trailing behind the higher energy μ's. The energy spread of the muons is very large, much larger in fact than the acceptance of the following cooling stage and accelerators. Therefore this drift is followed by an induction linac system that decelerates high-energy μ's and accelerates low energy μ's, reducing the energy spread. The voltage pulse across the gaps in the induction linac cells can be tailored to match the time-energy correlation of the incoming beam bunch. In Study 2 the induction linac is broken up into two sections in order to reduce the distortion in the resulting longitudinal phase space of the muons. The fractional energy spread of the beam after the induction linacs is reduced to 3.7%. However, the rms bunch width grows to 27 m (~100 m full width). The induction linac system includes a 3.5 m long liquid H_2 absorber. This "mini-cooler" stage provides an ~20% reduction in transverse normalized emittance to $\varepsilon_{t,rms} \cong 0.012$ m.

After the induction linacs, the muons are distributed continuously over a bunch length of around 100 m. It is then necessary to form the muons into a train of bunches for cooling and subsequent acceleration, as well as to match the beam transversely into the focusing lattice used for cooling. Thus the beam is transported into a 201 MHz rf buncher section, which forms the beam into about 70 bunches. The transverse and longitudinal functions of this section are performed sequentially for design simplicity. First an 11 m long magnetic lattice section is used to match the beam from the approximately uniform solenoidal field used in the induction linacs to the so-called "super-FOFO", or sFOFO, focussing lattice used in the remainder of the front end. This is followed by the 55 m long rf buncher, which consists of rf cavity sections interspersed with drift regions.

The buncher magnetic lattice is identical to that used in the first cooling section. It contains rf cavities in selected lattice cells and no absorbers. The main rf frequency is chosen to be 201.25 MHz in the front end, so that the beam would fit radially inside the cavity aperture and because power sources and other technical components are available at this frequency. The 201.25 MHz cavities are placed at the high beta regions in this lattice, just as in the cooling section. Maximum bunching efficiency was obtained by breaking the region into three rf stages separated by drift regions. Second harmonic cavities (402.5 MHz) are added at the entrance and exit of the first and second stages to linearize the shape of the rf pulse. The buncher encompasses 20 lattice cells, each 2.75 m long. By the end of the buncher, most, but not all, particles are within the 201.25 MHz buckets. About 25% are outside the bucket and are lost relatively rapidly, and another 25% are lost more slowly as the longitudinal emittance rises from straggling and the negative slope of the energy loss with energy.

II. sFOFO Cooling System

In the Neutrino Factory the rms transverse emittance of the muon beam emerging from the induction linac must be reduced to ~ 2 mm-rad (normalized) in order to fit into the downstream accelerators, and be contained in the storage rings. Ionization cooling is currently our only feasible option. The cooling channel described below is based on extensive theoretical studies and computer simulations.

Solenoidal fields are used for focusing; however, energy-loss cooling within a constant (or same-sign) field leads to an increasing beam angular momentum through the cooling channel. The solenoidal field must flip sign, while maintaining good focusing throughout the beam transport and low $\beta_\perp$ at the absorbers. One of the simplest solutions is to vary the field sinusoidally; this is the “FOFO” lattice. The cooling system of Study 2 is composed of “sFOFO” or “super-FOFO” lattice cells. (See Fig. 2.) Each of these cells includes an absorber for energy-loss cooling, an rf cavity of beam reacceleration and solenoids for transverse focusing, with the focusing designed to minimize beam size in the absorbers. The sFOFO lattice uses alternating solenoids like the FOFO, but is a bit more complicated. As in the FOFO case, the longitudinal B-field vanishes at the $\beta_{\perp,min}$ position, located at the center of the absorber. This is accomplished by placing two short, strong “focussing” coils about the absorber, running in opposite polarities. The field is decreased and flattened outside the absorber region, due to a “coupling” coil located around the linac.

The Study 2 cooling channel operates at a nominal momentum of 200 MeV/c. There are six sections with steadily decreasing $\beta_{\perp,min}$. In the first three the lattice half period length is 2.75 m, and in the last three sections this half period length is 1.65 m. The matching sections between these sections also consist of cooling cells, which differ from the regular cooling sections only by the currents (except for matching between different cell lengths, where the length is also changed).

Each lattice half-period includes a multicell linac, and to increase the useful gradient of the accelerating cavities, the cell irises are covered with a foil or grid. The baseline design calls for thin, pre-stressed beryllium foils with thicknesses that increase with radius. An accelerating gradient of E = 16 MV/m is required in each linac.

The absorber material is liquid hydrogen (LH_2). The length of these absorbers is 35 cm for the 2.75 m lattices and 21 cm for the 1.65 m lattices, respectively. The LH_2 vessels must also be equipped with thin aluminum windows. Their thickness is 360 μm (220), with a radius of 18 (11) cm, for the 2.75 m and 1.65 m lattices, respectively. The muons therefore lose ~12 MeV per lattice cell for the 2.75 m lattices and ~7 MeV for the 1.65 m lattices.

The complete Study 2 cooling system contains 16 2.75m cells, 36 1.65m cells, and a 4.4 m matching section between them for a total length of ~108 m. Complete descriptions of the system and detailed simulations of its cooling performance are presented in Study 2 [2] and summarized below.

III. Simulation results

An important accomplishment in the collaboration has been the development of the simulation codes ICOOL [3] and DPGeant [4], which include the full complexity of the absorber + rf + solenoid system, including all materials and their properties, magnets defined in terms of coils, currents, and positions (rather than actual focusing fields), rf defined with complete cavity fields, etc. The goal is to establish cooling systems which function when described in full complexity. These simulations confirm that the Study 1 and 2 cooling systems will perform as planned. In this section we describe these simulation results.

The $\beta_{\perp,min}$ function, calculated at the absorber centers using the beam second-order moments calculated in Geant4 simulations, is shown in Fig. 3. This function is reduced with each new section of the cooling lattice. The transverse and longitudinal emittances as calculated through the cooling system are shown in Fig. 4. Emittances are computed using diagonalized covariance matrices. The emittance values are corrected for correlations between the variables, including the strong momentum-transverse amplitude correlation. At the end of the cooling channel a transverse emittance of 2.2 mm rad is reached. The longitudinal emittance shows an initial rise and fall as particles not within the rf bucket increase in amplitude and are later lost, and then an approach to an asymptotic value set by the bucket size. The longitudinal emittance should rise due to straggling and the negative slope of energy loss with energy, but, since the rf bucket is already full, we see a steady loss of particles instead of an emittance growth.

Despite the overall particle loss, the numbers of particles within the accelerator acceptance increases, as seen in Fig. 5. The gain in muons within the accelerator acceptance of 150 mm due to cooling is ~3.1× (or 5× if the Study 1 acceptances were used). If the particle loss from longitudinal emittance growth could be eliminated, as should be the case if emittance exchange were used, then these gains could double.

Table 1 Beam characteristics summary

Location (end of)	σ_X	$\sigma_{X'}$	σ_P	σ_t(per bunch)	<p>
	Cm	mrad	MeV/c	ns	MeV/c
Induction linac	8.6	95	113		260
Matching section	5.8	114	113		260
Buncher	5.3	107	111	0.84	256
2.75 m cooler	3.0	91	70	0.55	226
1.65 m cooler	1.8	102	30	0.51	207

The rms beam characteristics in the buncher and cooler sections are summarized in Table 1. The beam is symmetric in this lattice, so the y properties are similar to those in x. We see that the size steadily decreases as we proceed down the channel. The angular divergence is kept constant for maximum cooling efficiency. The momentum spread of the entire beam is still large after the induction linac, but this includes very low and high energy muons that do not get transmitted through the subsequent sFOFO lattice. The decrease in energy spread is due to particle losses, since there is no longitudinal cooling or emittance exchange in this lattice. These losses could be controlled by adding some longitudinal cooling to the channel.

IV. Alternatives for ν-Factory cooling

We have presented in detail only one example of a cooling scenario for preparing the μ-beams of a ν-factory, the baseline cooling scenario for Feasibility Study 2. Other cooling scenarios could be used and future studies will explore alternative configurations, either by optimizing the present proposal or developing a substantially different but superior system. However any cooling scenario would also require: absorbers for energy-loss, acceleration for longitudinal energy recovery, and a transport lattice with strong focusing of the beam into the absorbers.

The liquid hydrogen absorbers were chosen because hydrogen has the least multiple scattering; however other low-Z material (LiH, Li, Be, …) could also be used and would avoid the mechanical difficulties of handling liquid hydrogen, at the cost of more scattering. It is likely that such denser materials may be necessary for emittance exchange wedges.

The sFOFO focusing system was used here, but other lattices could be used. An attractive alternative is the "double-flip" scenario [5], which has long constant or same-sign field sections with only two changes in sign. This is a simpler lattice, but it requires more field volume for the same focusing effect as the sFOFO. Lattices that incorporate energy cooling could also be preferable (see below).

The ~200 MHz rf system was based on the perception that 200 MHz rf would be available and affordable. A low-frequency system (40-80 MHz) for capture and cooling has been proposed at CERN [6] and has some preferable properties. It would develop fewer μ-bunches per primary p-bunch and would be more adaptable to future μ^+-μ^- collider beams.

References

[1] N. Holtkamp and D. Finley, ed. “A Feasibility Study of a Neutrino Source Based on a Muon Storage Ring”, Fermilab, April 15th, 2000.

[2] S. Ozaki, R. Palmer, and M. Zisman, ed., “BNL ν-Factory Feasibility Study”, April, 2001.

[3] R. Fernow, “ICOOL: a simulation code for ionization cooling of muon beams,” Proc. 1999 Particle Accelerator Conference, New York, p. 3020-2.

[4] The DPGEANT and GEANT4 codes have been developed at FNAL under the direction of P. Lebrun.

[5] V. Balbekov, “Comparison of an alternate solenoid and long solenoid cooling channels”, NuMu note 130, 2000.

[6] A. Lombardi, “a 40-80 MHz system for phase rotation and cooling”, CERN–NUFACT Note 34, 1 August 2000.

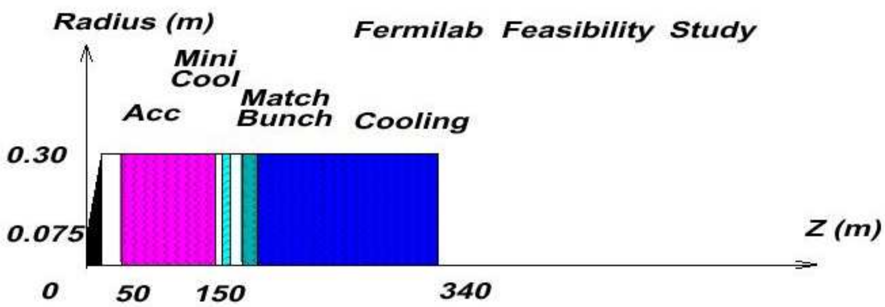

Figure 1a. Study 1 layout of μ-capture and cooling transport.

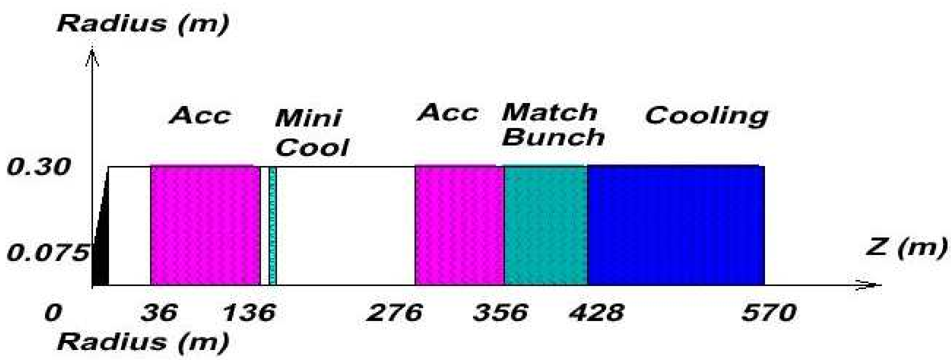

Figure 1b. Study 2 layout of μ-capture and cooling transport

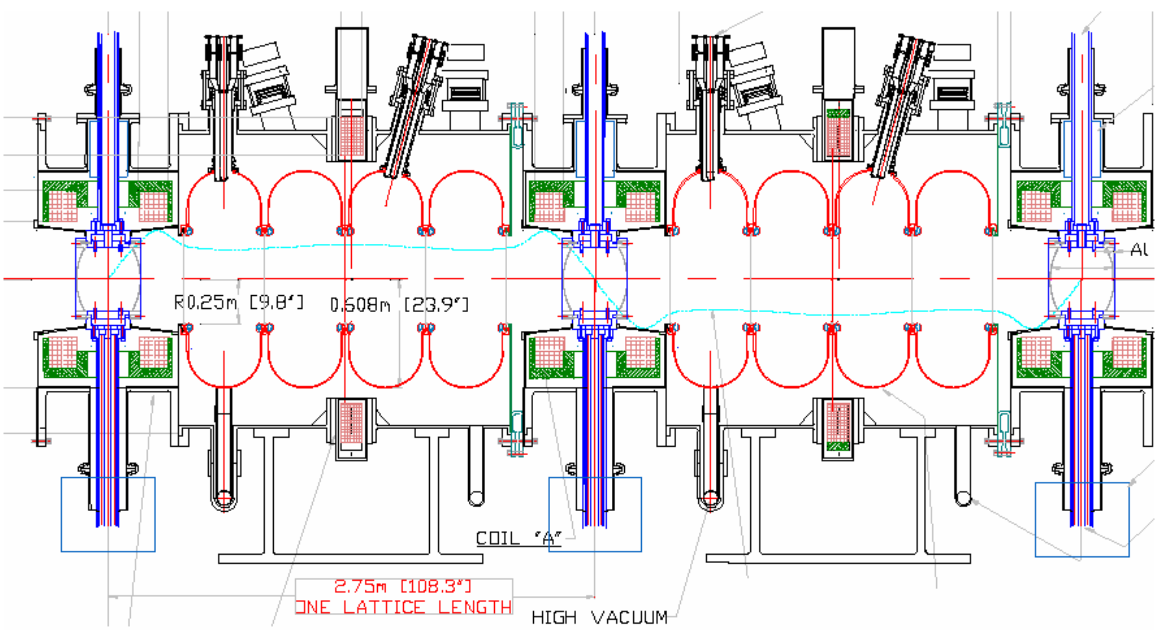

Figure 2. Cross-section of two Study 2 2.75m sFOFO lattice cooling cells, showing two 4-cell rf cavities, 3 Liquid hydrogen absorbers, and magnetic coils for focusing around the absorbers and rf cavities.

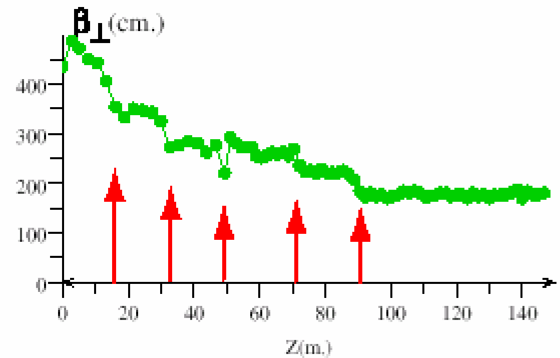

Figure 3. The $\beta_{\perp,min}$ function in mm at cavity centers, as calculated from the second order moments of a beam in GEANT4 simulations, for the entire sFOFO cooling channel. The 5 arrows indicate the beginning of new lattice sections. (In this figure the cooling channel is extended beyond the Study2 reference length of 108 m to 144 m by adding 1.65 m cells.)

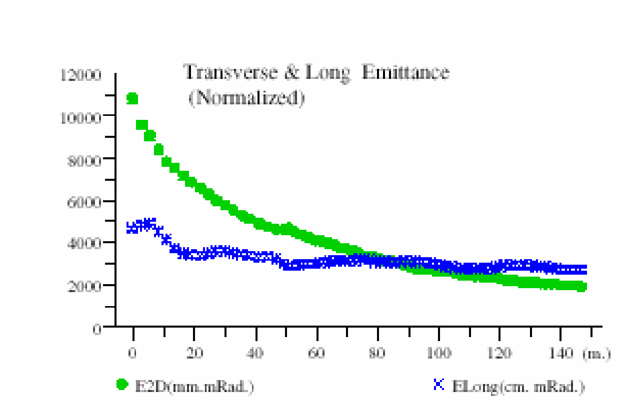

Figure 4. The transverse and longitudinal normalized emittances along the cooling channel.

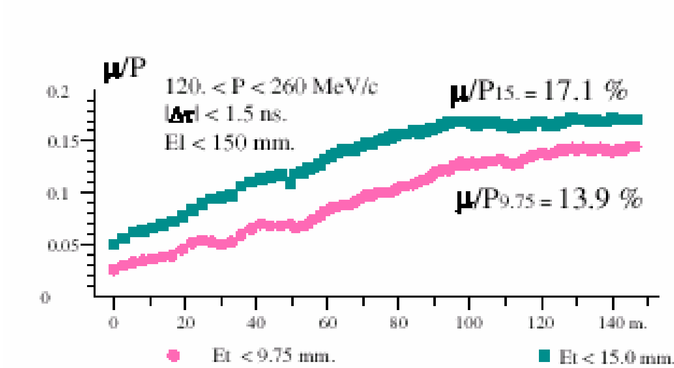

Figure 5. The muon to proton yield ratio for the two emittance cuts, showing that the particle density in the center of the phase space increases as the beam is cooled in the channel. The two curves give the number of particles within the baseline longitudinal and transverse acceptances. The upper line represents the values for the accelerator parameters in this Study. The lower line, given for comparison, gives the values for the acceptances used in Feasibility Study 1.