NEW AND EFFICIENT NEUTRINO FACTORY FRONT-END DESIGN

J.C. Gallardo*, J.S. Berg, R.C. Fernow, H. Kirk, R.B. Palmer, BNL, Upton, NY 11973, USA
D. Neuffer, FNAL, Batavia, IL 60510, USA; K. Paul, Muons, Inc., Batavia, IL 60510, USA

Abstract

The front-end of a neutrino factory (the part of the facility between the target and the first linear accelerator) represented a large fraction, about $40\,\%$, of the total facility costs as discussed in a rather comprehensive feasibility study (FS2) [1]. Several recent developments, briefly summarize in this article, lead to the idea that a new design for the front end may be possible and that it is significantly less expensive than the front end used in FS2.

INTRODUCTION

A new approach to bunching and phase rotation using the concept of adiabatic rf bunching [2] eliminates the very expensive induction linacs used in FS2. The concept of the adiabatic buncher is compared with the system used in FS2 in Fig. 1. Initially, there is a small spread in time, but a very large spread in energy. The target is followed by a drift space in both cases, where a strong correlation develops between time and energy. In FS2 the energy spread in the correlated beam was first flattened using a series of induction linacs, which reduced the final rms energy spread to 4.4%. The beam was then sent through a series of rf cavities for bunching, which increased the energy spread to $\approx 8\%$. In the new scheme, the correlated beam is first adiabatically bunched using a series of rf cavities with decreasing frequencies and increasing gradients. The beam is then phase rotated with a second string of rf cavities with decreasing frequencies and constant gradient. The final rms energy spread in the new design is 10.5%. This spread is acceptable for the new cooling channel. The overall layout of the new front-end design is shown schematically in Fig. 2.

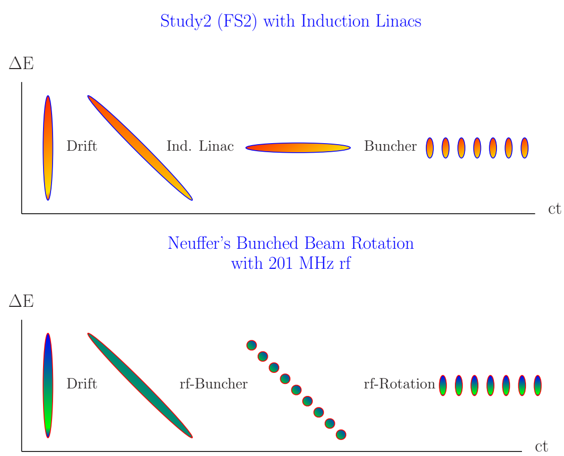

Figure 1: (Color) Comparison of the buncher concept used here (bottom) with the bunching system used in FS2 (top).

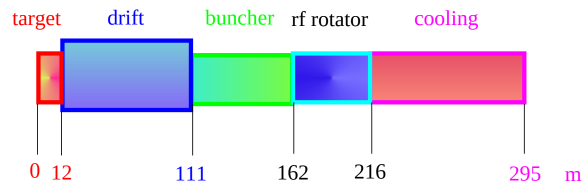

Figure 2: (Color) Overall layout of the front-end.

The article is organized as follows. In the first section we describe the different regions of the front end and in the second we show the Monte Carlo performance of the channel simulated with the code ICOOL [3].

DIFFERENT REGIONS

Target and Decay Region

The first 12 m is used to capture pions produced in the target. The field here drops adiabatically from 20 T over the target to 1.75 T. At the same time, the radius of the beam pipe increases from 7.5 cm at the target up to 25 cm. Next comes a drift of 99 m for the pions to decay into muons and for the energy-time correlation to develop.

The beam distributions used in the simulations were generated using MARS [4]. The distribution was calculated for a 24 GeV proton beam interacting with a Hg jet [5]. The jet was incident at an angle of 100 mrad to the solenoid axis, whereas the beam was incident at an angle of 67 mrad to the solenoid axis. This geometry gives near-peak acceptance for the produced pions. An examination of the distribution of particles that were propagated to the end of the front-end channel showed that they have a peak $p_{\parallel}^{initial} \approx 300$ MeV/c with a long high-energy tail, and a peak $p_{\perp}^{initial} \approx 180$ MeV/c. In addition, we used an improved axial field profile in the capture region that increased the final number of muons per proton in the accelerator acceptance by ≈10%.

The actual coil configuration in the collection region is shown in the contribution to the multi-divisional APS study, *Joint Study on the Future of Neutrino Physics* [6]. A MARS calculation of the absorbed radiation dose in the collection region has been carried out. The peak energy deposition dose in the superconducting coils, is $\approx 0.5 \times 10^{-8}$GeV/g per proton on target. This dose is about $\approx$ 1 MGy/yr for a 1 MW beam running for a *Snowmass year* of 1×10^7 s. Assuming a lifetime dose for the insulation of 100 MGy, there should be no problem with radiation

* Correspondent: gallardo@bnl.gov

damage in the coils.

Bunching and Phase Rotation Region

The buncher is ≈ 50 m long; two cells of the buncher lattice are shown schematically in Fig. 3. Most of the 75 cm cell length is occupied by the 50 cm long rf cavity. The cavity iris is covered with a Be window. The limiting radial aperture in the cell is determined by the 25 cm radius of the window. The 50 cm long solenoid was placed outside the rf cavity in order to decrease the magnetic field ripple on the axis and minimize beam losses from momentum stop bands. The buncher section contains 27 cavities with 13 discrete frequencies and gradients varying from 5–10 MV/m.

The frequencies decrease from 333 to 234 MHz in the buncher region. The cavities are not equally spaced. Fewer cavities are used at the beginning where the required gradients are small.

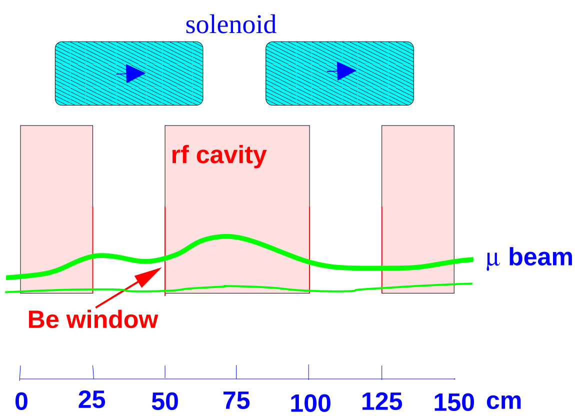

Figure 3: (Color) Schematic of two cells of the buncher or phase rotator section.

The rotator cell is very similar to the buncher cell. The major difference is the use of tapered Be windows on the cavities because of the higher rf gradient. There are 72 cavities in the rotator region, with 15 different frequencies. The frequencies decrease from 232 to 201 MHz in this part of the front end. All cavities have a gradient of 12.5 MV/m.

Cooling Region

The cooling channel was designed with a solenoidal FOFO lattice giving a transverse beta function that is relatively constant with position and has a magnitude of about 80 cm. One cell of the channel is shown in Fig. 4. Most of the 150 cm magnetic cell length is taken up by the 50 cm long rf cavities. The cavities have a frequency of 201.25 MHz and a gradient of 15.25 MV/m. A novel aspect of this design comes from using the windows on the rf cavity as the cooling absorbers. This is possible because the near constant β function does not significantly increase the emittance heating at the window location. The window consists of a 1 cm thickness of LiH with a 75 μm thick layer

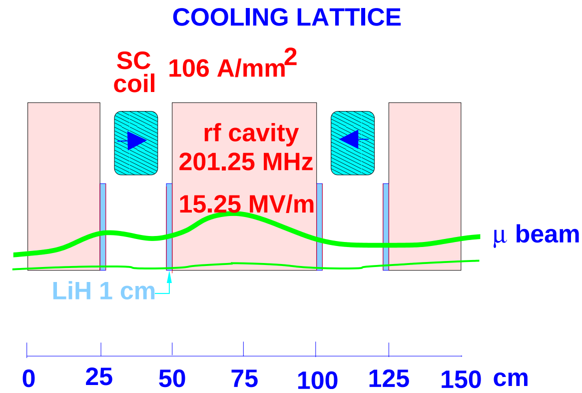

Figure 4: (Color) Schematic of one cell of the cooling section.

of Be on the side facing the rf cavity field and a 25 μm thick layer of Be on the opposite side (The Be will, in turn, have a thin coating of TiN to prevent multipactoring.) The alternating 2.8 T solenoidal field is produced with one solenoid per half cell, located between the rf cavities.

The beam at the end of the cooling section consists of a train of bunches with a varying population of muons in each one; this is shown in Fig. 5 for one sign and Fig. 6 shows the longitudinal phase space.

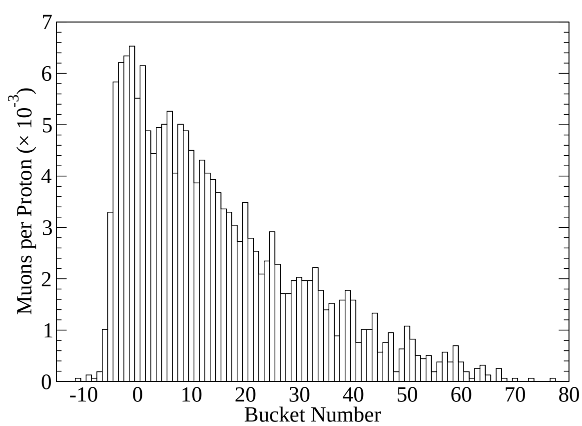

Figure 5: Bunch structure of the beam delivered to the accelerator normalized transverse acceptance of $A_T = 30$ mm rad and normalized longitudinal acceptance of $A_L = 150$ mm for a momentum cut $0.1 \leq p \leq 0.3$ GeV/c.

Heating of Absorber Windows

There are unresolved issues with the absorber windows, in particular, due to the energy deposited by the intense muon beam on the LiH and the rf heating on the Be layer deposited or bonded on the LiH. Under ideal assumptions we have

- Muon beam energy deposition $\approx$ 58 W on LiH. Steady state T_{max} $\approx$ 270°C is well below

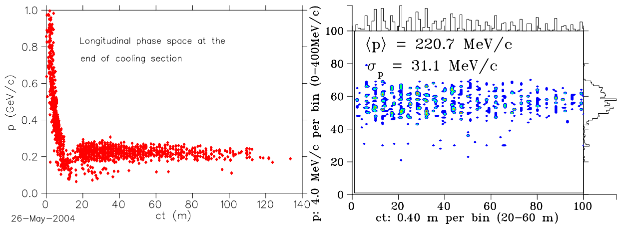

Figure 6: Longitudinal phase space at the end of the channel.

$T_{\text{melting}} = 690°\text{C}$

- Total rf power $\approx 220\ W$ on Be. Steady state $T_{\text{max}} \approx 700°\text{C}$ is well below $T_{\text{melting}} = 1275°\text{C}$

Of course, accurate finite element thermal studies are needed to assess the viability of the composite LiH-Be system.

SIMULATION RESULTS

The channel produces a final value of $\epsilon_{\perp}^{N} = 7.1$ mm rad, which is more than a factor of two reduction from the initial value. The equilibrium value for a LiH absorber with an 80 cm β function is about $\epsilon_{\perp}^{\text{equil.}} \approx 5.5$ mm rad. The change of $\epsilon_{\perp}^{N}$ and ϵ_{L}^{N} along the front end is displayed in Fig. 7. Figure 8 shows the muons per incident proton on target that fit into the accelerator transverse normalized acceptance of $A_T = 30$ mm rad and normalized longitudinal acceptance of $A_L = 150$ mm. The 80-m-long cooling channel raises this quantity by about a factor of 1.7. The current best value is 0.170 ± 0.006 muons per incident proton. This is the same value obtained in FS2. Thus, we have achieved the identical performance at the entrance to the accelerator as FS2, but with a significantly simpler, shorter, and presumably less expensive channel design. In addition, unlike FS2, this channel transmits both signs of muons produced at the target. With appropriate modifications to the storage ring, this design could deliver both (time tagged) neutrinos and antineutrinos to the detector. A summary of the results is seen in Table 1.

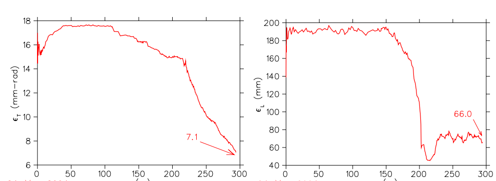

Figure 7: Normalized transverse emittance (left) and longitudinal emittance (right) along the front-end for a momentum cut $0.1 \leq p \leq 0.3$ GeV/c.

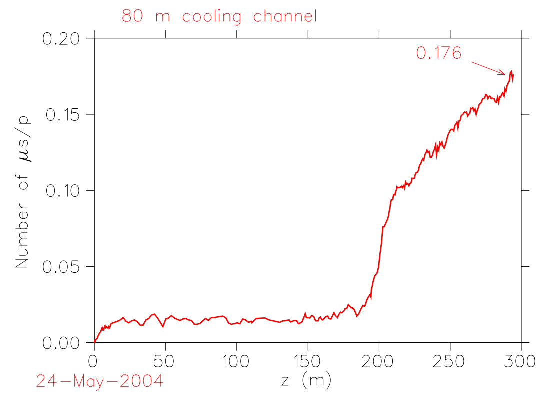

Figure 8: No. μ/p in $A_{\perp}$ and A_L.

Table 1: Summary of Results.

$< p_z >$ Mean Momentum (MeV/c)	220
rms Energy Spread (MeV)	31
$\epsilon_{\perp}^{N}$(mm-rad)	7.1
$\epsilon_{\perp}^{equil.}$(mm-rad)	5.5
ϵ_{L}^{N}(mm)	66
$A_{\perp}$ (mm-rad)	30
A_L (mm)	150
No. μ/p in $A_{\perp}$ and A_L	0.170

ACKNOWLEDGMENTS

We would like to thank the members of the Neutrino Factory and Muon Collider Collaboration (MC) and acknowledge their contribution. This research was supported by the U.S. Department of Energy under Contracts No. DE-AC02-98CH10886, No. DE-AC02-76CH03000, and No. DE-AC03-76SF00098.

REFERENCES

[1] S. Ozaki, R. Palmer, M. Zisman, and J. Gallardo, eds. Feasibility Study-II of a Muon-Based Neutrino Source. Technical report, BNL-52623, 2001. http://www.cap.bnl.gov/mumu/studyii/FS2-report.html.

[2] D. Neuffer. Exploration of the high-frequency buncher concept. MUC-NOTE-269. All MUC-NOTE papers are available from http://www-mucool.fnal.gov/notes/noteSelMin.html, 2003.

[3] R. Fernow. ICOOL: a simulation code for ionization cooling of muon beams. In A. Luccio and W. MacKay, editor, *Proceedings of the 1999 Particle Accelerator Conference*, page 3020, 1999. Latest version is available at http://pubweb.bnl.gov/people/fernow/icool/readme.html.

[4] N. Mokhov. Particle Production and Radiation Environment at a Neutrino Factory Target Station. In *Proceedings of the 2001 Particle Accelerator Conference*, page 745, 2001.

[5] K. McDonald. The Primary Target Facility for a Neutrino Factory Based on Muon Beams. In *Proceedings of the 2001 Particle Accelerator Conference*, page 1583, 2001.

[6] APS Multi-Divisional Study of the Physics of Neutrinos. http://www.interactions.org/neutrinostudy/, sponsored by the American Physical Society Divisions of: Nuclear Physics, Particles and Fields, Astrophysics, Physics of Beams, 2004.