SIMULATIONS OF A MUON LINAC FOR A NEUTRINO FACTORY*

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Abstract

The Neutrino Factory baseline design involves a complex chain of accelerators including a single-pass linac, two recirculating linacs and an FFAG. The first linac follows the capture and bunching section and accelerates the muons from about 244 to 900 MeV. It must accept a high emittance beam about 30 cm wide with a 10% energy spread. This linac uses counter wound, shielded superconducting solenoids and 201 MHz superconducting cavities. Simulations have been carried out using several codes including Zgoubi, OptiM, GPT, Elegant and G4beamline, both to determine the optics and to estimate radiation loads on the elements due to beam loss and muon decay.

INTRODUCTION

Any neutrino factory or muon collider must quickly accelerate muons from their production to a high energy before they decay. The Interim Design Study for the neutrino factory (IDS-NF) [1] describes a single-pass 146 m pre-accelerator linac that raises the $\mu^{\pm}$ beam's total energy from 244 MeV to 900 MeV, making the muons sufficiently relativistic to facilitate further acceleration in a pair of recirculating linear accelerators.

The initial phase-space of the beam, as delivered by the front-end, is characterized by significant energy spread; the linac has been designed [2] so that it first confines the muon bunches in the longitudinal phase space, then adiabatically impinges acceleration over the confinement motion and finally boosts the confined bunches to 900 MeV. [3] The peak electric fields in the 201 MHz cavities are 23.09 and 26.17 MV/m, corresponding to an effective 15 and 17 MV/m when the transit time is included. To achieve a manageable beam size in the linac front-end, short focusing cells are used for the first 6 cryo-modules. The beam size is adiabatically damped with acceleration, and that allows the short cryo-modules to be followed by 8 intermediate length cryo-modules, and then with 11 long cryo-modules. Consequently, the linac was split into three sections (upper, middle and lower), each one being built of a particular type of cryo-module as shown in Figs. 1a and b [4].

Each linac section is configured with periodic FOFO cells, matched at the section junctions, as illustrated in Fig 2 [3]. Periodicity within each section is maintained by scaling the solenoid fields in consecutive cryomodules linearly with increasing momentum (Table 1).

A number of programs were used in the design of the lattice; the tracking code GPT [5] and the matrix-based OptiM [6] and Elegant [7]. In order to estimate the effects of the muons and electrons from the muon decay striking various parts of the linac, we are using another program, G4beamline [8], which is based on the Geant4 toolkit [9]. G4beamline uses field maps calculated using Superfish for the solenoids and COMSOL for the RF cavities. [2]

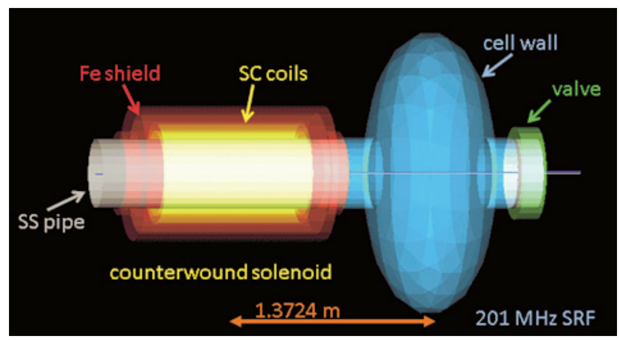

Figure 1b: G4beamline model of upper cryomodule.

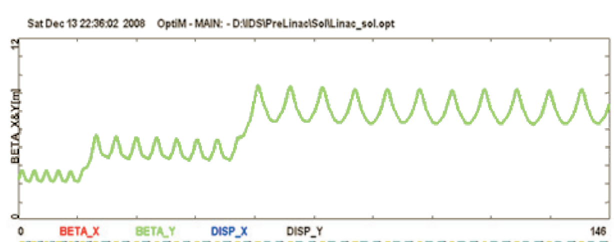

Figure 2: Transverse FOFO optics of the entire linac; the upper, middle, and lower periodic sections uniformly matched at the junctions; done in OptiM.

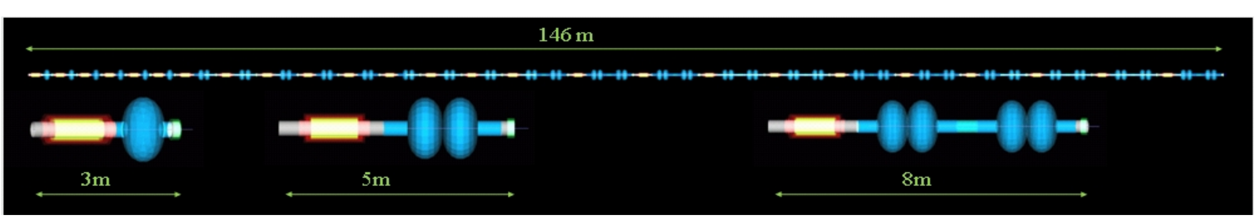

Figure 1a: Whole linac and enlargements of upper, middle, and lower cryomodules.

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DYNAMICS

Longitudinal Dynamics

One of the main goals of a single-pass pre-accelerator linac is to adiabatically compress the longitudinal phase-space volume in the course of acceleration. The initial longitudinal acceptance of the linac (chosen at 2.5 σ) calls for a "full bucket acceleration" with the initial momentum acceptance of $\Delta p/p = \pm 17\%$ and the bunch length of $\Delta\varphi = \pm 102°$ (rf deg.). To perform adiabatic bunching one needs to invoke rather strong synchrotron motion along the linac. The profile of the RF cavities' phases is organized so that the first cavity is shifted by 73° (off crest) at the beginning of the linac and the phase shift is then gradually changed to zero by the linac's end; see Table 1.

Table 1: Parameters of the Linac

short cryo-module	1	2	3	4	5	6
K_E (exit) [MeV]	141.6	145.1	149.0	153.1	157.6	162.4
B [Tesla]	-1.04	1.06	-1.07	1.09	-1.12	0.89
RF phase [deg. off-crest]	-73.3	-71.6	-69.8	-68.1	-66.4	-64.6

medium cryo-module	1	2	3	4	5	6	7	8
K_E (exit) [MeV]	174.3	187.3	201.3	216.5	232.6	249.7	267.7	286.6
B [Tesla]	-0.99	0.98	-1.03	1.08	-1.14	1.21	-1.28	1.03
RF phase [deg. off-crest]	-62.11	-59.13	-56.22	-53.31	-50.4	-47.52	-44.67	-41.85

long cryo-module	1	2	3	4	5	6	7	8	9	10	11
K_E (exit) [MeV]	326.4	368.6	412.6	458.3	505.5	553.7	602.8	652.6	702.8	753.3	803.9
B [Tesla]	-1.13	1.17	-1.29	1.41	-1.54	1.68	-1.81	1.95	-2.09	2.23	-2.37
RF phase [deg. off-crest]	-38.1	-33.8	-29.5	-25.5	-21.5	-17.8	-14.2	-10.8	-7.6	-4.5	-1.7

In the initial part of the linac, when the beam is still not fully relativistic, the far-off-crest acceleration induces rapid synchrotron motion (about one full period), which allows bunch compression in both length and momentum spread.

A GPT simulation showing the longitudinal evolution of the bunch is shown in Fig 3, and a comparison of an OptiM and G4beamline simulation is shown in Fig 4. A G4beamline comparison of the longitudinal phase space of the bunch with and without synchrotron motion is shown in Fig 5.

Initially, G4beamline was run with the RF phasing taken from OptiM (shown in green), which resulted in significant phase error by the end of the linac. Slightly adjusting the RF phases greatly improved the agreement (shown in blue). In general, the longitudinal dynamics shown by GPT, OptiM, and Elegant are in good agreement; if the RF phases are adjusted slightly they are in good agreement with G4beamline too.

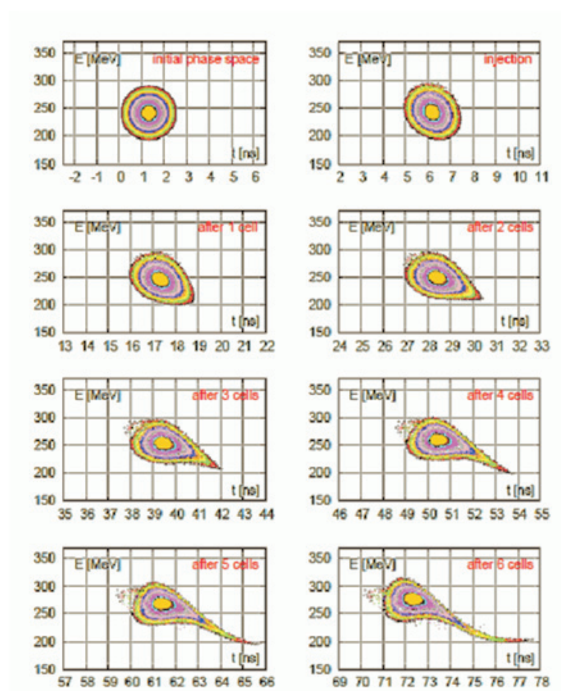

Figure 3: Total E vs. time of the bunch in GPT.

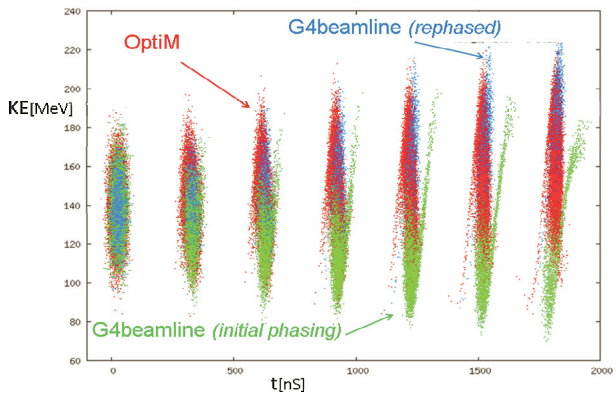

Figure 4a: Comparison of OptiM and G4beamline simulations of the longitudinal bunch phase space; the bunches were shifted in energy and time for clarity.

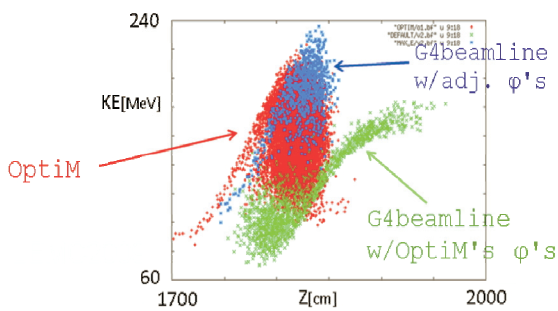

Figure 4b: Enlargement of the last bunch in Fig. 4a.

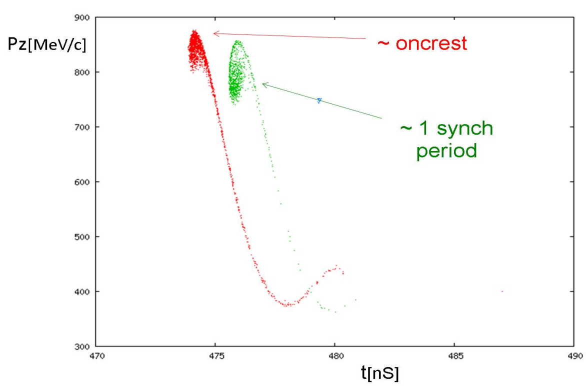

Figure 5: A G4beamline bunch at the end of the linac with and without synchrotron motion.

Transverse Dynamics

While the transverse dynamics are not anticipated to be a serious problem, tracking simulations show that some work needs to be done to reduce losses between sections. Fig. 6 shows tracks and losses of particles in GPT and G4beamline simulations.

CONCLUSIONS

Generally, the GPT, OptiM, Elegant, and G4beamline (with some phase adjustment) simulations are in good agreement. Work is ongoing to greatly improve G4beamline's RF phasing ability, and when that is complete, the transverse matching between the sections will be addressed. After that, extensive simulations will be run to calculate the heat and radiation loads on all the components of the linac. While some collective effects have already been addressed [10], G4beamline has recently added a space charge calculation. [11]

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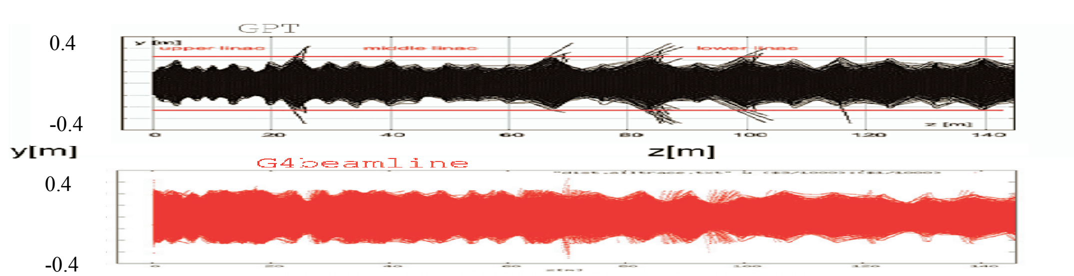

Figure 6: μ^+ tracks in GPT and G4beamline.