THE MUON LINAC FOR THE INTERNATIONAL DESIGN STUDY FOR THE NEUTRINO FACTORY

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Abstract

The first stage of muon acceleration in the Neutrino Factory utilises a superconducting linac to accelerate muons from 244 MeV to 900 MeV. The linac was split into three types of cryomodules with decreasing magnetic fields and increasing amounts of RF voltage but with the design of the superconducting solenoid and RF cavities being the same for all cryomodules.

The current status of the muon linac for the International Design Study for the Neutrino Factory will be presented including a final lattice design of the linac and tracking simulations.

INTRODUCTION

The Neutrino Factory aims to produce an intense neutrino beam from the decays of stored muons with an energy of 25 GeV. The acceleration of the muons is done using a series of machines starting with a single pass linac from 0.244 GeV to 0.9 GeV; two 4.5 pass dogbone recirculating linacs to go from 0.9 GeV to 12.6 GeV; and an FFAG for the final acceleration to 25 GeV.

The first design of the linac for the International Design Study for the Neutrino Factory (IDS-NF) was presented here [1]. Since then a number of improvements have been made to the design. This paper presents the current design including the optics design and tracking simulations.

UPDATED DESIGN

The design presented in [1] and [2] utilised three cryomodules (referred to as short, intermediate and long) to match the change in the relativistic beta as the muons are accelerated. The short module used for low beta has only one RF cavity whereas the other two cryomodules have two RF cavities. The short and intermediate cryomodules have RF cavities with an aperture radius of 23 cm whereas the long cryomodule has an aperture radius of 15 cm, to give a higher gradient. However, the aperture of the long cryomodule is the same as the required acceptance and so it was decided to redesign the lattice of the linac to use only short and intermediate cryomodules to allow a margin for error and minimise the possibility of the beam scraping the superconducting cavity and solenoid. Table 1 summarises the lattice parameters for the old and new design and Figure 1 gives the dimensions of the short and intermediate cryomodules. The length of the linac has therefore decreased from 218 m to 192 m.

Table 1: Lattice Parameters

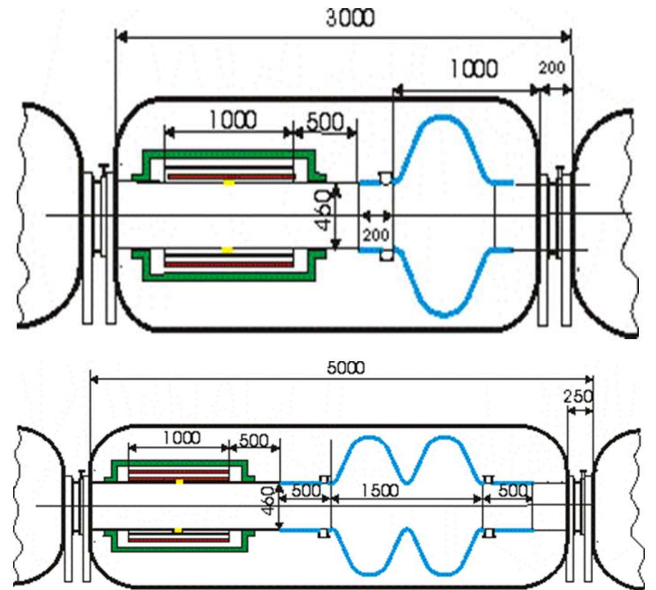|	Linac Section	Cell Length	No. Solenoids	No. RF Cavities
Old Design	Short	3 m	6	6
	Intermediate	5 m	8	16
	Long	8 m	20	44
New Design	Short	3 m	24	24
	Intermediate	5 m	24	48

Figure 1: Engineering sketch of the short(top) cryomodule and the intermediate(bottom) cryomodule.

Lattice calculations were performed using OptiM [4]. Figure 2 shows the matched beta functions (for no acceleration) where the input Twiss parameters are $\beta_{x,y} = 2.58761$ m and $\alpha_{x,y} = -0.249427$. The transit time factor was determined using a field map from an electromagnetic simulation of the cavity. Particles were tracked using G4beamline [5] and the transit time factor was determined for muons from 30 MeV/c to 10 GeV/c. The distribution of transit time factor as a function of momentum was then fit using

$$\text{TF}(P) = e^{\frac{a}{(P-b)^2-c}}, \qquad (1)$$

where a, b and c are constants. This arbitrary analytic expression for the transit time factor was then used to determine the required phasing of the cavities.
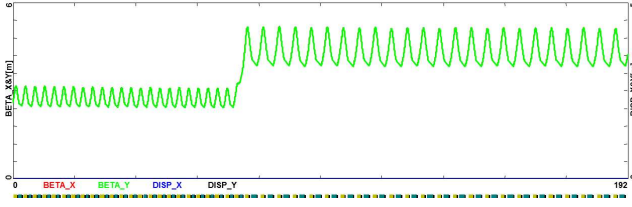
Figure 2: Matched beta functions as calculated by OptiM for the new lattice design.

The required longitudinal acceptance (at 95%) is

$$\epsilon_l = \frac{\sigma_{\Delta P} \sigma_z}{m_\mu c} = 24mm, \quad (2)$$

where $\frac{\sigma_{\Delta P}}{P} = 0.84$ and $\sigma_z = 137\,\text{mm}$. Matching the required acceptance with the bucket size of the 201MHz cavities gives an initial phase of $72°$ off-crest, see Figure 3. The beam is then brought linearly to on-crest by the end of
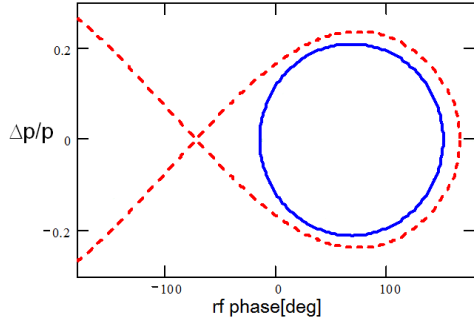

Figure 3: Longitudinal phase space showing the required acceptance at 95% (blue circle) and the bucket separatrix (red curve) for the 201MHz cavity.

the linac. Figure 4 shows the beta functions with this phasing scheme and Figure 5 shows the corresponding increase in beam energy and change in synchrotron phase along the length of the linac.
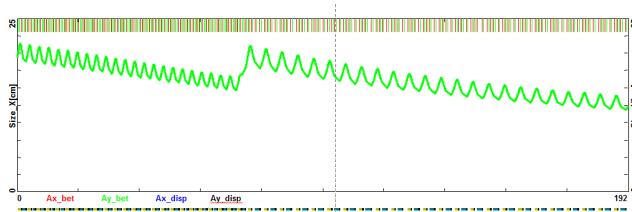

Figure 4: Beta functions calculated by OptiM including RF cavity phasing. The beam starts off at $72°$ off-crest and ends up being on-crest.

Figure 7 shows the initial position, in $P_z - t$ phase space, of muons that do not make it to the end (in red) and muons that are in the main body, tail and extreme tail (in green, blue and mauve respectively) of the bunch at the end of the
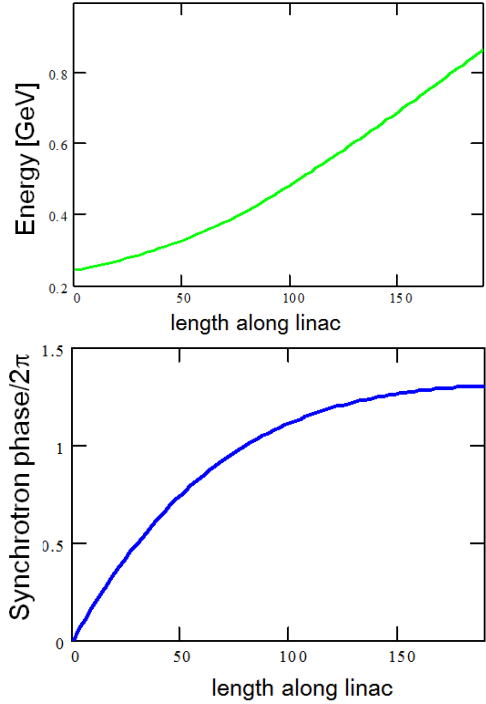

Figure 5: Variation of the beam energy (top) and synchrotron phase (bottom) as a function of length along the linac.

linac. The cavity phasing is currently being optimised to reduce longitudinal phase space filamentation and to increase the transmission efficiency of the linac.

SUMMARY

A new design of the muon linac for the Neutrino Factory has been completed resulting in a linac shorter than the previous design. Lattice calculations have been done and preliminary tracking simulations show signs of longitudinal phase space filamentation. Further tracking studies are underway to optimise the phasing of the cavities to improve the transmission efficiency of the linac and to use a more realistic input beam from the output of the preceding ionization cooling channel.

A cost estimate for the Neutrino Factory needs to be presented in the Reference Design Report which will be completed in 2013. Work on costing the linac has started with defining the breakdown structure of its components, which needs to include all items from the cryomodules to heating and ventilation services for the linac tunnel.

An initial beam was generated using a Gaussian distribution (truncated at 6σ in P and z) for $\epsilon_{x,y} = 4.8\,\text{mm rad}$ and $\epsilon_l = 24\,\text{mm}$. This distribution was then tracked using OptiM, ELEGANT [3] and G4beamline, see Figure 6. The tracking simulations performed with ELEGANT and G4beamline used field maps from electromagnetic simulations of the solenoid and RF cavity. All codes produced similar results and show, to varying extent, filamentation of the longitudinal phase space.
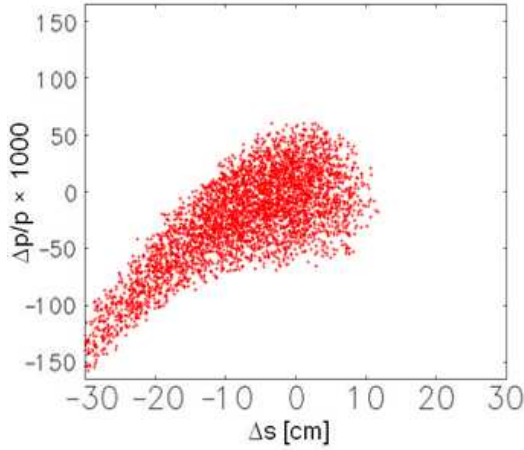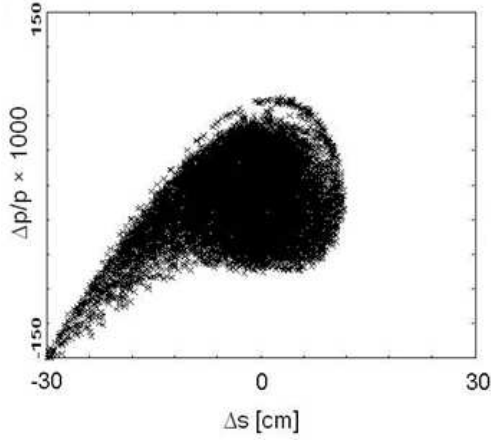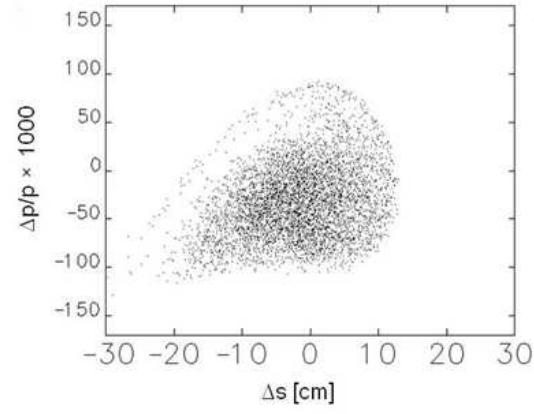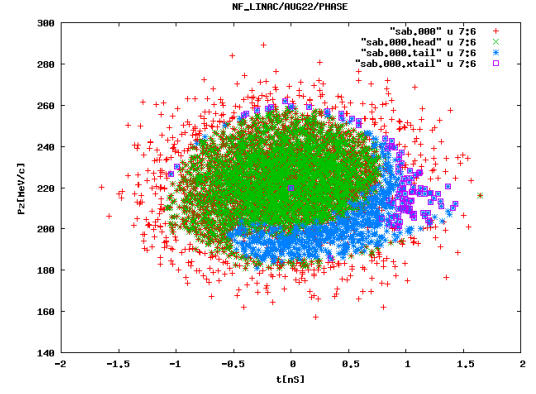
Figure 7: Initial position, in $P_z - t$ phase space, of muons that do not make it to the end (in red) and muons that are in the main body, tail and extreme tail (in green, blue and mauve respectively) of the bunch at the end of the linac.

REFERENCES

[1] C. Bontoiu, M. Aslaninejad, J. Pozimski, A. Bogacz, "Beam Dynamics Studies For The First Muon Linac Of The Neutrino Factory", IPAC'10, Kyoto (2010), p. 4590.

[2] M. Aslaninejad, C. Bontoiu, J. Pozimski, A. Bogacz, "Solenoid Fringe Field Effects For The Neutrino Factory Linac - Mad-X Investigation.", IPAC'10, Kyoto (2010), p. 3963.

[3] M. Borland, "Elegant.", http://www.aps.anl.gov/Accelerator_Systems_Division/Operations_Analysis/oagPackages.shtml.

[4] V. Lebedev, "Optim.", http://www-bdnew.fnal.gov/pbar/organizationalchart/lebedev/optim/optim.htm.

[5] T.J. Roberts et al., "The G4beamline Home Page", http://g4beamline.muonsinc.com/.

Figure 6: Longitudinal phase space at the end of the linac using 10^4 particles tracked with ELEGANT (top), OptiM (middle) and G4beamline (bottom).