

# Muon RLA - design status and simulations

K B Beard<sup>1</sup>, S A Bogacz<sup>2</sup>, V S Morozov<sup>2</sup>, Y R Roblin<sup>2</sup>

<sup>1</sup>Muons, Inc., Batavia, IL, USA

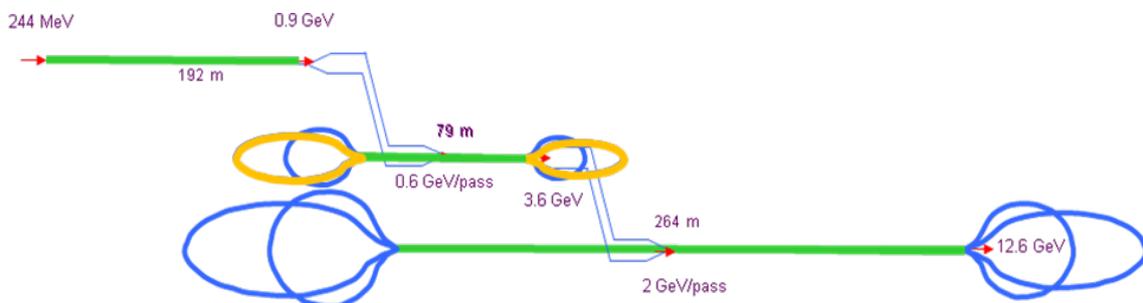
<sup>2</sup>Jefferson Lab, Newport News, VA, USA

Email: beard@muonsinc.com

**Abstract.** The Neutrino Factory baseline design involves a complex chain of accelerators beginning with a linac. This first pre-linac follows the capture and bunching section and accelerates the muons from about 244 to 900 MeV and must accept a high emittance beam about 30 cm wide with a 10% energy spread. It uses counterwound, shielded superconducting solenoids and 201 MHz superconducting cavities, and currently consists of 24 3 m and 24 5 m long cryomodules. The next stage is a 1<sup>st</sup> dogbone-shaped RLA that takes the total energy from 900 MeV to 3.6 GeV in 4.5 passes, followed by a 2<sup>nd</sup> RLA that takes the energy from 3.6 to 12.6 GeV in 4.5 passes. Simulations are in progress to optimize the optics and determine the radiation loads from beam loss and muon decay.

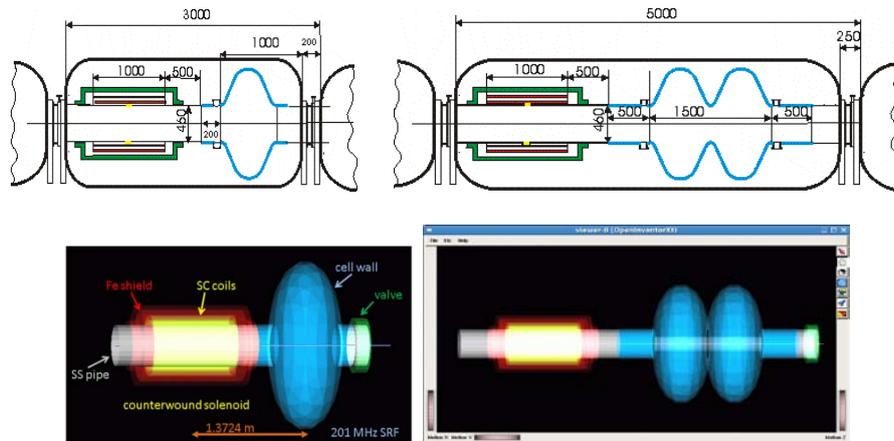
## 1. Overview

The baseline Neutrino Factory (NF) acceleration scheme has been evolving for some time. It begins with a pre-linac that takes the muons from about 244 MeV total energy to around 900 MeV; from there, it is injected into the middle of a 4.5 pass dogbone shaped Recirculating Linear Accelerator (RLA) that accelerates the beam to 3.6 GeV; next it is injected into the middle of second dogbone shaped RLA which takes the beam to 12.6 GeV in 4.5 passes (Fig 1.). Muons of opposite sign travel in alternating buckets in the same direction down the linacs and around the arcs in opposite directions.



**Figure 1.** Baseline Neutrino Factory acceleration 0.2-12.6 GeV.

This scheme is evolving as the simulations progress and become more detailed. The very large size of the bunch,  $\epsilon_x/\epsilon_y = 4.8$  mm rad and  $\epsilon_l = \sigma_{\Delta p} \sigma_z/m_\mu c = 24$  mm, is an important consideration.



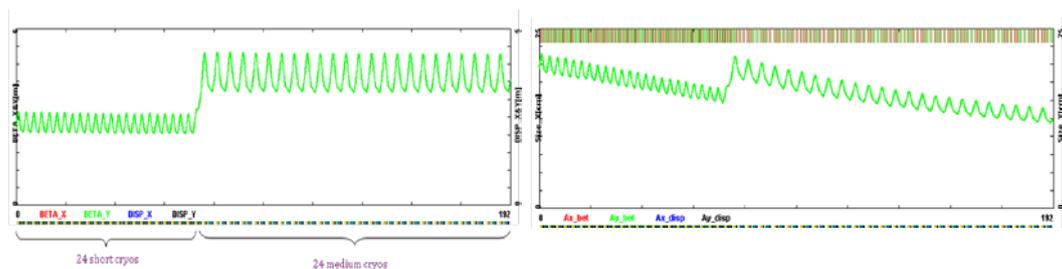
**Figure 2.** Schematic and G4beamline simulation of the 3m and 5m NF cryomodules.

## 2. Recent Changes to the Pre-Linac

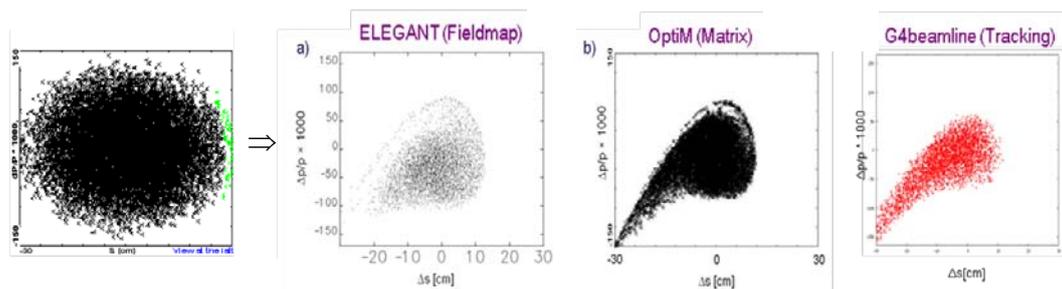
For some time, the pre-linac consisted of 3 types of cryomodules: a 3 m, a 5 m, and an 8 m.<sup>1</sup> All 3 contained a counterwound and magnetically shielded superconducting solenoid and superconducting 201.25 MHz RF. The 3 m contained one single cell RF cavity, the 5 m one double-cell cavity, and the 8 m two double-cell cavities. G4beamline uses field maps calculated using Superfish for the solenoids and COMSOL for the RF cavities.<sup>4</sup> The beam was estimated to be about 30 cm wide with a 10% energy spread. Simulations revealed that the transverse focusing was insufficient and significant beam losses would occur. It also became clear that the longitudinal beam dynamics was more of a challenge than originally anticipated, so the first cavities are run far off-crest.

To address this<sup>2</sup>, the pre-linac now uses 24 3 m and 24 5 m cryomodules (Fig. 2)<sup>3,4</sup>, allowing for more rapid acceleration and greater focusing. An improved pillbox routine in G4beamline was used to better tune the cavities and estimate the Transit Factor effect<sup>5</sup>.

The transverse optics is very straight forward, with the tune taken from OptiM (Fig. 3).



**Figure 3.** NF pre-linac beta functions (left) and bunch size (right) in OptiM.



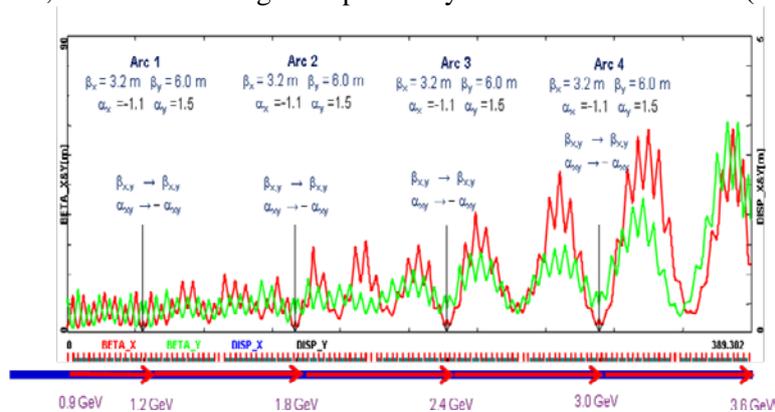
**Figure 4.** Initial and final bunches' longitudinal space as calculated by Elegant, OptiM, and G4beamline.

However, the longitudinal optics is less simple. To capture the bunch with such a large longitudinal size, the first cells are run  $72^\circ$  off crest and linearly varied with position to reach on-crest by the end of the linac. Simulations in OptiM, Elegant, and G4beamline agree well, but work is ongoing to improve the transport (Fig. 4).

### 3. Recent Changes to the RLA

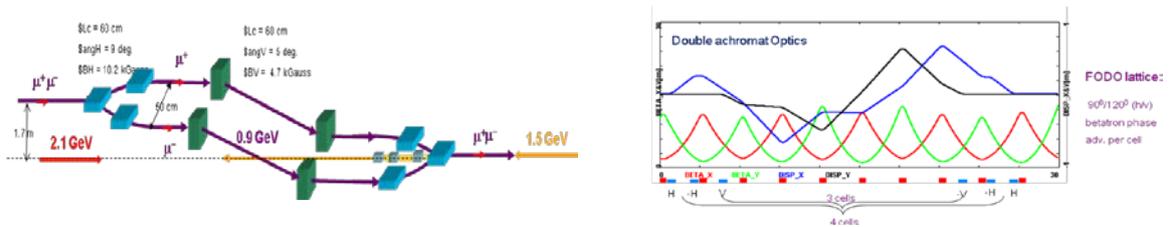
#### 3.1. Linac

Upon each pass through the RLA's linac, the focusing gets weaker. The beta-beating technique has the linac's quads strengths symmetrically increasing with distance from the center of the linac, allowing more passes through the linac with acceptable beta functions. While originally a linear dependence was used, a nonlinear strength vs. position yields even better results (Fig. 5).

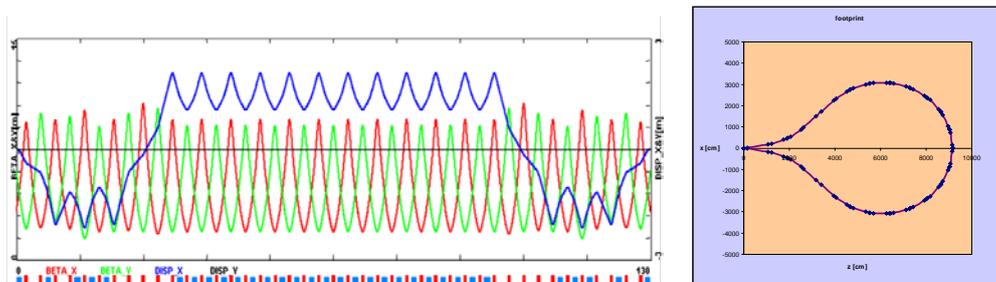


**Figure 5.** Beta functions in the 1<sup>st</sup> RLA linac's 4.5 passes; the arcs are not shown.

To use this technique, the beam must be injected into the center of, and extracted from one end of, the linac. It has 4  $90^\circ$  advance cells horizontally and 3  $120^\circ$  advance cells vertically. A small chicane corrects the higher energy passes.



**Figure 6.** Injection chicane for the first RLA.

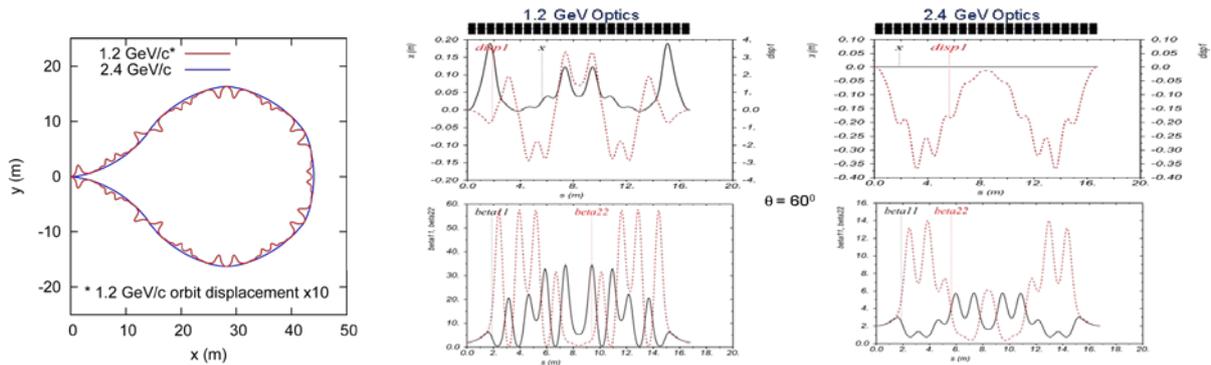


**Figure 7.** Teardrop arc beta functions and shape.

### 3.2. Arcs

The teardrop shaped arcs use 4 outward bending cells, two 2 cell transition regions, and 10 identical but inward bending cells. The current baseline is for one arc/pass. A vertical bypass based on 4  $90^\circ$  cells has been designed.

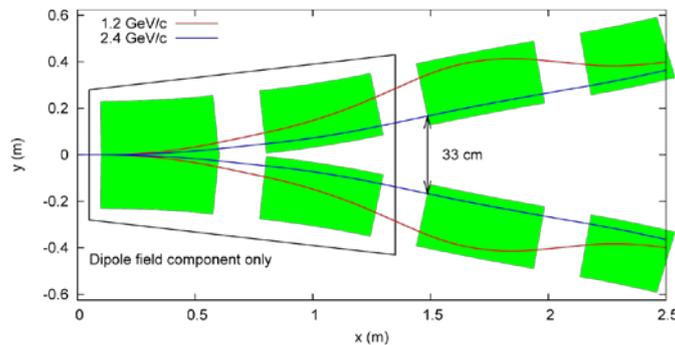
We are investigating a new concept, the multi-pass arc, in which two or more beams with greatly differing momenta travel through the same magnets (Fig. 8). This has the promise of greatly simplifying the RLA and reducing costs.



**Figure 8.** Optics for a 2:1 momentum ratio multi-pass arc.

### 3.3. Splitter

If a multi-pass arc is used, the  $\mu^+$  and  $\mu^-$  beams of two differing momenta must be directed to the same place. This can be done by removing the quadrupole components in the first magnets (Fig. 9).



**Figure 10.** Splitter for a multi-pass arc with trajectories shown to scale.

## 4. Summary

The evolution of the design of the pre-linac and both RLAs for a NF is continuing. The pre-linac's optics are being optimized and a detailed design of the injection and vertical bypass chicanes has been done. An alternative multi-pass arc scheme is being examined.

## References

- [1] Beard K B *et al.* 2011 *2011 Particle Accelerator Conference - Proceedings (New York)* p 181
- [2] Bogacz S A, Berg J S and Beard K B private communication.
- [3] IDS-NF Collaboration 2011 Interim Design Report **IDS-NF 020** (<http://www.ids-nf.org>)
- [4] Bontoiu C *et al.* 2010 *International Particle Accelerator Conference (Kyoto)* p 4590-4592.
- [5] Beard K B *et al.* Neutrino Factory Linac RF Cavity Transit Factor **MAP-doc-4308** (<http://map-docdb.fnal.gov/cgi-bin/ShowDocument?docid=4308>)