Concept: Low Energy, Low Intensity NF from ProjectX

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Abstract

This note describes the concept of a Low Luminosity Low Energy Neutrino Factory (L^3ENF) using a Project X pulsed, or CW, Linac at 8GeV. By collecting π and μ with energy ~ 1 GeV, and accelerating them to 10 GeV, it is possible to store ~10^{20} μ per year. Most of the concepts suggested here can be tested using the Booster beam, Recycler, Antiproton Target Station, the Main Injector and the Tevatron. Once the VLENF Muon Storage Ring is built, components needed for L^3ENF could be used in experiments before Project X completion.

Introduction

A collection system based on Lithium Lenses and quadrupole triplets in a ring will be used to store multi-MW protons for π/μ production. Accumulation of protons is carried continuously for 100 ms for CW linac, or for 16 ms for a pulsed linac, and then beam is sent onto a Be target using a single turn extraction and accumulation is continued. The beam from the Linac has a 162.5 MHz structure, and the accumulation ring is a multiple of this frequency so that the beam is transferred bunch to bucket in the ring. There will be a gap of ~10 buckets, 61cns long, in the linac beam train to create a beam gap in the ring for extraction. The Li lens is used to collect as many 1 GeV pions as possible, and that bunched pion beam is injected into the linac structure used as a 200 meter long decay/buncher channel. Finally, the 1 GeV muon beam with a bunch structure of 162 MHz is accelerated to 10 GeV using 325 MHz superconducting beta=1 cavities.

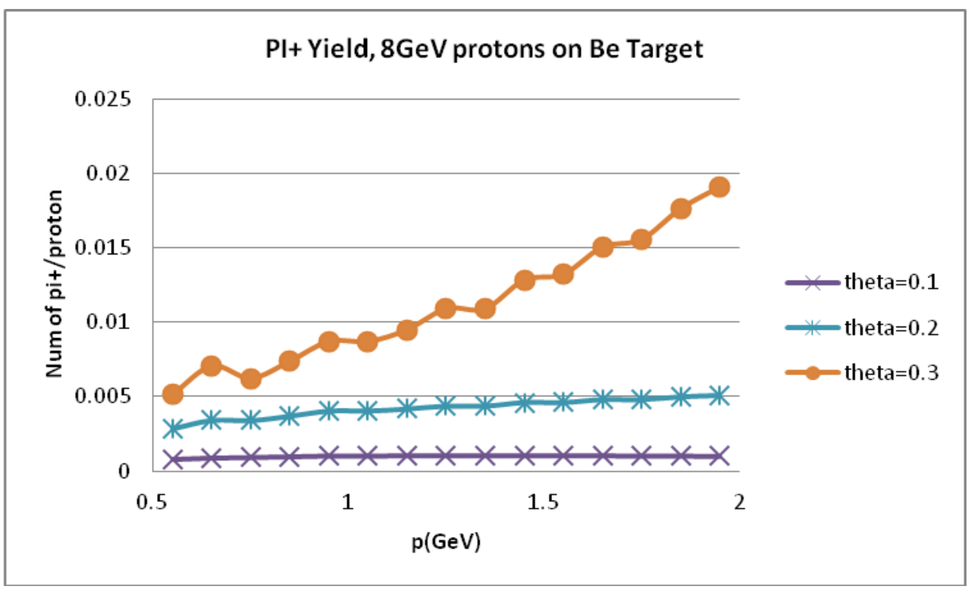


Figure 1. The pion yield curves above are produced using Striganov calculations.

Figure 1 shows number of positive pions produced with 8 GeV protons on a Be target with energy bins of +/-0.1GeV for three different values of forward acceptance angle theta. Table 1 lists conponents and main parameters of each stage of L^3ENF. Figure 2 shows a sketch of the whole complex.

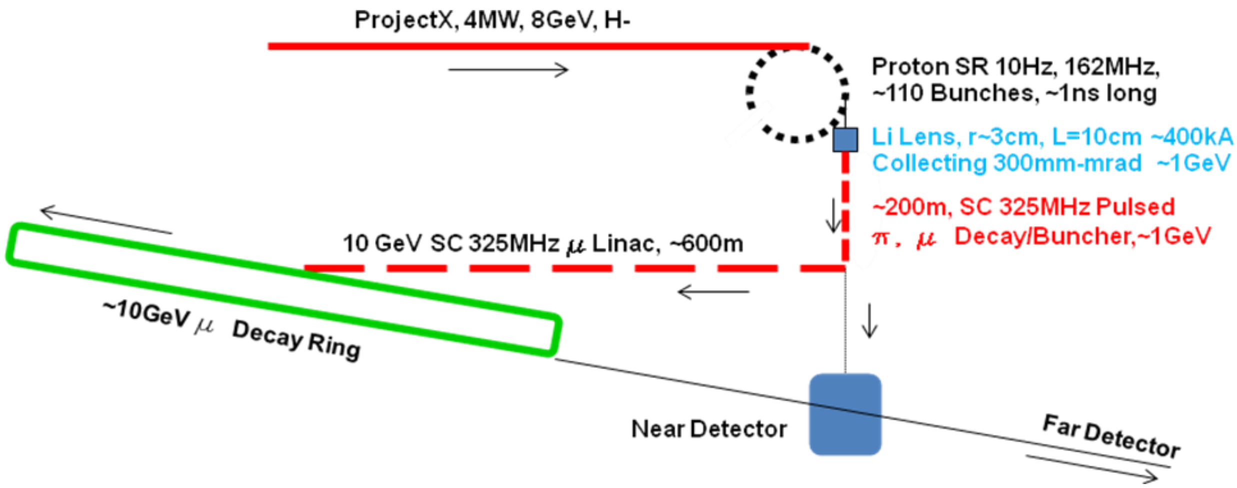


Figure2. Protons are accelerated with ProjectX linac, then accumulated and targeted.

Protons	
Linac, H- Beam, 650MHz SC RF	Beam Power=4MW, CW Average_I=0.5mA ~600ns on, ~60ns off, or 10Hz, 16ms Ekin=8GeV, Bunch Structure=162MHz
Proton Accumulation Ring	RingLength~200m, h=110, of 162MHz, 0.4MW stored per pulse, 100 bunches, ~4*10^{12} protons per bunch, bunch length ~ 1ns, emittance 50mm-mrad, SC tune~0.005 LongLimit ~ 0.1MW per bunch
Pions/Muons	
Target & Collection & Matching, at 1 GeV, energy spread of +/-0.15GeV. Collecting E_un95%=300mm-mrad, L=3.5m, Yield~5x10^{-3} pi+/proton	Target: Be or Hg, Li Lens, 15cm long, 3 cm radius, 10 Hz, Peak Current ~ 600kA, Focal length ~ 20cm. Quad doublet, Q1 g=4.1T/m, l_q1=0.35m, Q2 g=9T/m l_q2=0.7m
Linac/Pi Decay Chanel from 1.0 to 1.2 GeV, SC, pulsed, 325MHz	~20 FODO cells, ~8m, two 3-cell cavities beta=1, ~17MV/m, Cavity bore radius 0.2m L_quad=0.35m, g ~3T/m, Synch Phase~0 degree, Bunching mode
Linac/Mu from 1.2 to 10 GeV, SC, pulsed, 325MHz	~100 FODO cells, ~8m, two 3-cell cavities beta=1 , ~17MV/m, Cavity bore radius 0.2m L_quad=0.35m, g from 3T/m, rumped
Decay Ring, Racetrack	Conventional, with 200m long straits

Table 1.

In the rest of this note detailed descriptions of each stage and its building blocks are given. The assumption is that Project X Linac accelerates H- beam to 8 GeV with a bunch structure of 162.5 MHz and a programmable pulse width.

Accumulation Ring

The ring size is dictated by the space needed for RF, injection and extraction devices. The ring should be based on iron dominated magnets and be able to store an 8 GeV beam. The length of the ring should be multiple of L_rf=1.845m

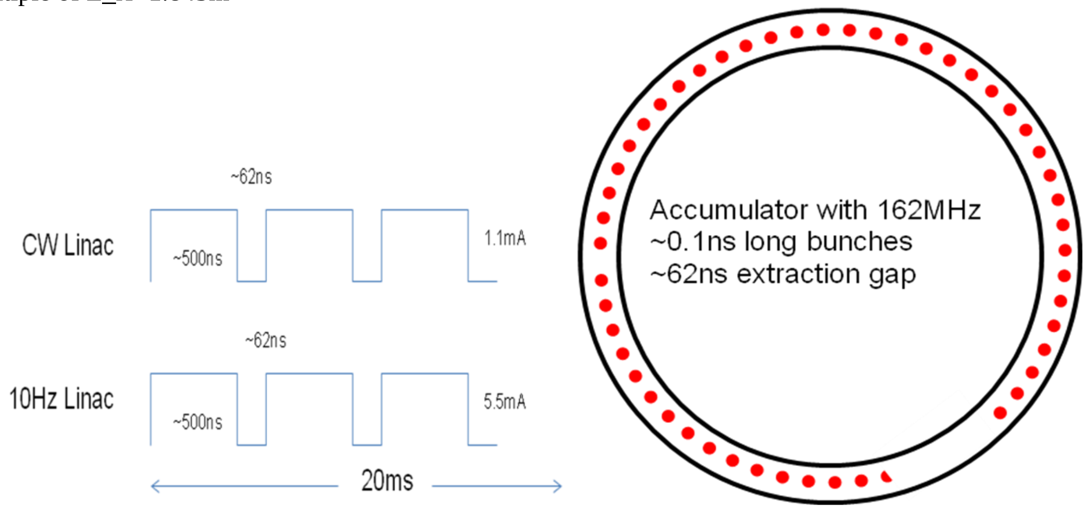


Figure 3 Beam accumulation

The beam from the CW linac has a 95% normalized transverse emittance of ~1 mm-mrad and a total energy spread of ~5 MeV. It is assumed that during injection this beam is painted into a beam with transverse emittances of ~50 mm-mrad with the 162.2MHz beam structure from the Linac preserved.

The main limitations on beam parameters arise from longitudinal instabilities at injection. The maximum allowable beam power per bunch is:

$$P_{MAXperBuch} \leq f_{rep} m_o c^2(\gamma - 1) \frac{\beta^2 \gamma^3 \left(\frac{\sigma_p}{p_0}\right)^2 L_b \eta_{lattice}}{p_r \ln\left(\frac{a_{pipe}}{1.5\sigma_{beam}}\right)}$$

For our choice of parameters, the longitudinal limits require less then ~100 kW per bunch.

Another limit related to the accumulation and bunching of a very large number of protons is set by the space charge tune shift. To produce very short proton bunches we need to have an accumulation ring of small circumference in conjunction with large transverse beam emittances.

$$B_{fact} = \frac{\sigma_s}{2\pi R_{aver}} , \qquad \Delta\nu_{sc} = -N_{ppB} \frac{p_r}{4\pi B_{fact} \beta \gamma^2 \varepsilon_{Nrms}}$$

With the parameters listed in Table 2, we conclude that direct space charge tune shift is ~ 0.02 and is therefore not an issue.

The accumulation ring is made with a banding field limited to ~1.8T. Dipole magnets are combined function magnets. The distance between magnets is minimized to ~0.2 m. There are 32 magnets grouped in eight cells with six 8-meter straights and two 21-meter straights for injection and extraction.

Table 2 below presents the main lattice parameters.

total length = 191.0363m	Qx = 2.599514	Qy = 2.266236
delta(s) = 0.000000 mm	Qx' = -3.904487	Qy' = 0.345342
alfa = 0.130479	betax(max) = 24.774721	betay(max) = 69.408119
gamma(tr) = 2.768406	Dx(max) = 5.111147	Dy(max) = 0.000000
Dx(r.m.s.) = 4.310250	Dy(r.m.s.) = 0.000000	

Table 2. Lattice parameters (obtained from a MAD run).

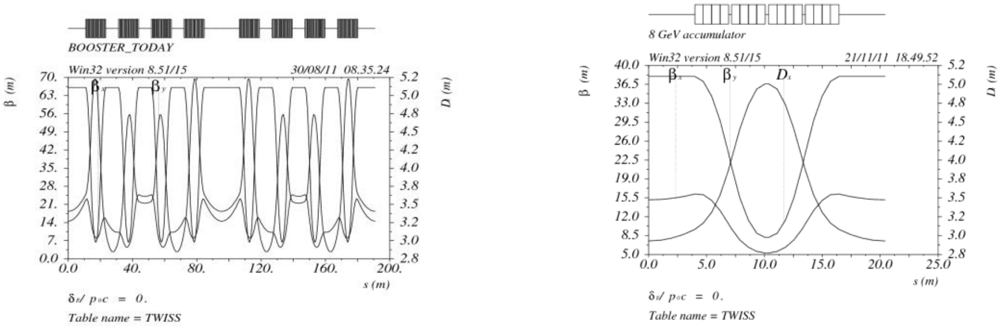


Figure 4. Left, MAD output, for half of the ring. The graph on the right shows the basic magnet group and lattice functions.

The lattice can be improved in the event that the long injection and extraction strait sections, and the six 8-meter long straights, can be shortened. If the injection and extraction will need less space, the lattice can be improved by shortening the strait sections.

Injection

The beam is injected in one of two 21-meter long straights

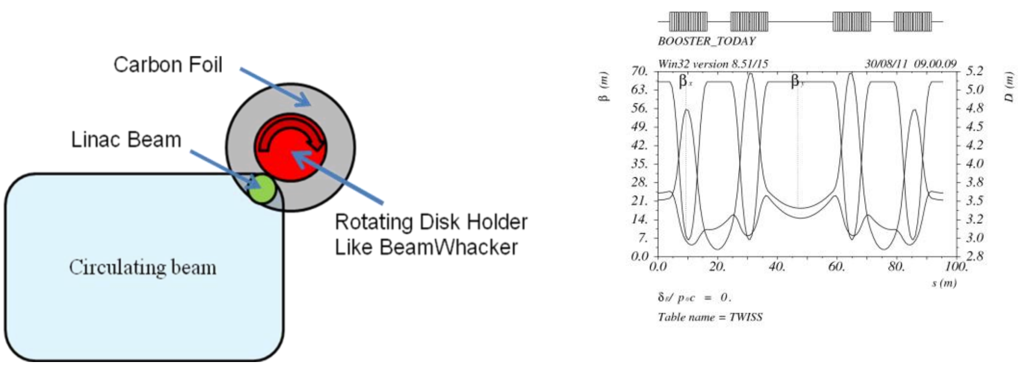


Figure 5. Sketch of the stripping foil and part of lattice around long strait that will be used for injection

To achieve full flexibility for painting, the central orbit is moved independently in each plane. Because the beam will be larger after painting, the central orbit has to be moved approximately ~10 cm in both planes.

Horizontal plane

To move up the closed orbit in the horizontal plane by 10 cm, and to do it fast (in 100 ms) and locally, a four-bump magnet system is used: one magnet in the 8-meter straight before the 22-meter long (straight??) , and one magnet at the beginning and at the end of the long straight and one magnet in the straight section located downstream of the injection straight. These magnets provide ~0.3 degree bends;

they are similar to the Orbump magnets recently installed in the Booster, but longer. An 8 GeV storage ring would need 1.5 meter long magnets.

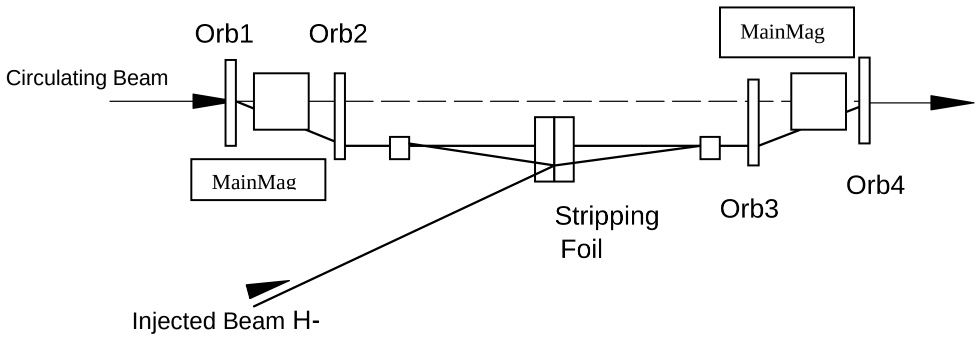


Figure 6. Injection, figure shows vertical plane painting as foil injection concept

and at the end of the long and one magnet in the straight section located downstream of the injection straight. These magnets provide ~0.3 degree bends; they are similar to the Orbump magnets recently installed in the Booster, but longer. An 8 GeV storage ring would need 1.5 meter long magnets.

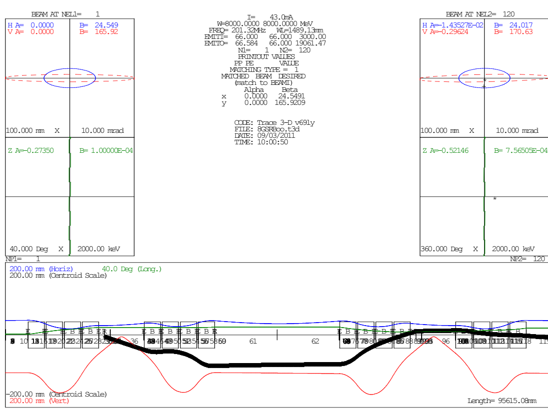


Figure 7a. Horizontal bump for painting

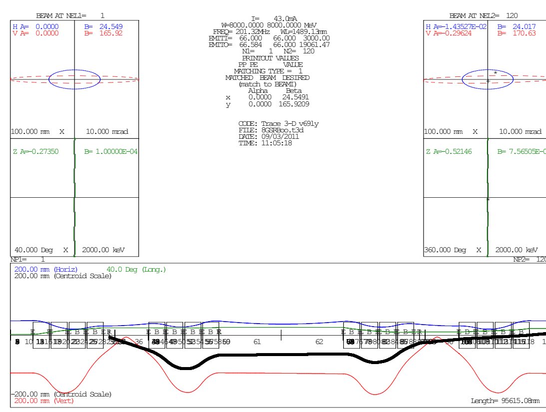


Figure 7b. Vertical bump for painting

Blue trace: horizontal beam envelope, red trace: vertical beam envelope; black traces: central orbit displacements at the start of injection.

Extraction

The beam is extracted horizontally in the long straight opposite to the injection straight. Extraction is accomplished using kickers located in the straights upstream of the extraction region as well as within the extraction region. There are 8 meters available for kickers in the "short straight" and 21 meters in the long straight. Trace3D simulations show that a total kick of 0.1 degree in the short straight combined with a 0.3 degree kick in the long straight moves the beam closed orbit by ~100 mm horizontally 2.5 meter upstream of the main magnet in the long straight section. At this location, there is a DC septum which bends the beam by an additional 1.5 degrees. The bending angles can be achieved using Booster-style kickers. These kickers are one meter long and bend a 8GeV beam by 5.27 μrad/(kV-meter) at 8 GeV. The typical voltage across the kicker plates is 50-60kV with a rise time of 40ns. The DC septum magnet can be two meters long with a field of ~0.4 Tesla. None of these magnets appears too demanding.

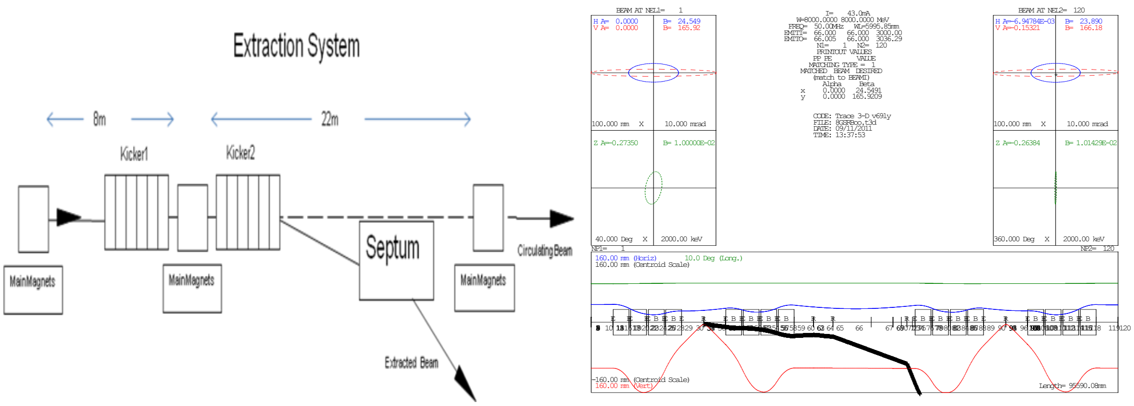


Figure 8. Extraction

Target and Pion Collection

The proton beam is extracted every 100 ms and targeted on a Mercury jet target or Be target. The beam power of each pulse is 0.4 MW and the beam train is ~600 ns long with a bunch structure of 162 MHz and bunch length of ~1 ns.

Right after the target there will be a lithium lens and set of collection quadrupoles. In this note we assume that we collect pions and muons from a 1 mm spot with kinetic energy of 1 GeV and within 0.3 radians in forward direction. The lithium lens is 15 cm long, with a radius of 3cm, a peak current of 600kA and a focal length of ~0.2 m.

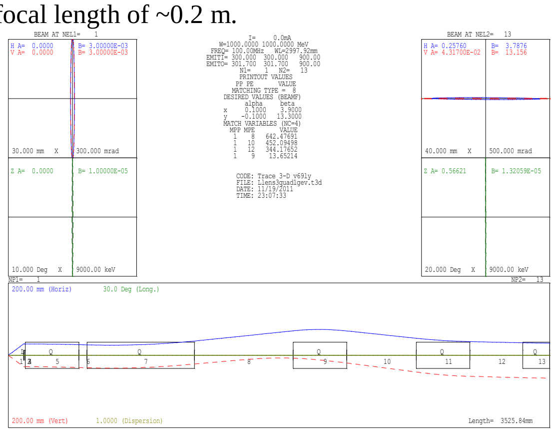


Figure 9a.Target, Li Lens, matching

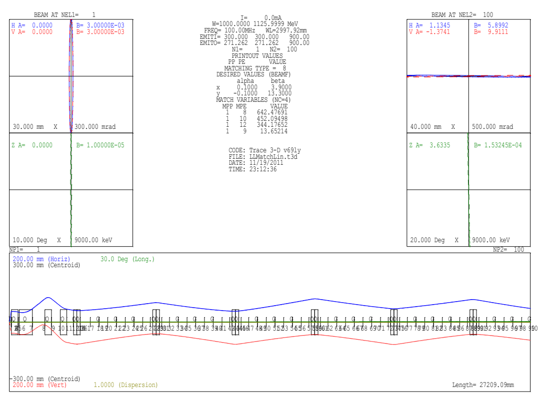


Figure 9b. Target matched with Linac/Buncher

Figures 9a and 9b show beam from the target, Li Lens, two collection quads and three quads that are used to match the beam to the linac, and Pion Decay Chanel. The total length of the collection plus matching line is ~ 3.5 meters.

Pion Decay Channel

This section is identical to the Acceleration Linac. It is about 200 meters long with the RF phase close to zero so that the Linac is effectively a long decay channel with bunching cavities. The particles from the target are captured in the RF buckets, preserving the bunching structure and reducing the momentum spread off the target. The beam collected off the target is 1 GeV, with an unnormalized 95% transversal emittance of 300mm-mrad and energy spread of +/- 200 MeV. The bunch is 30 degrees (of 325MHz) long. Figure 4 shows PARMILA simulation of, X, Y and Z plain.

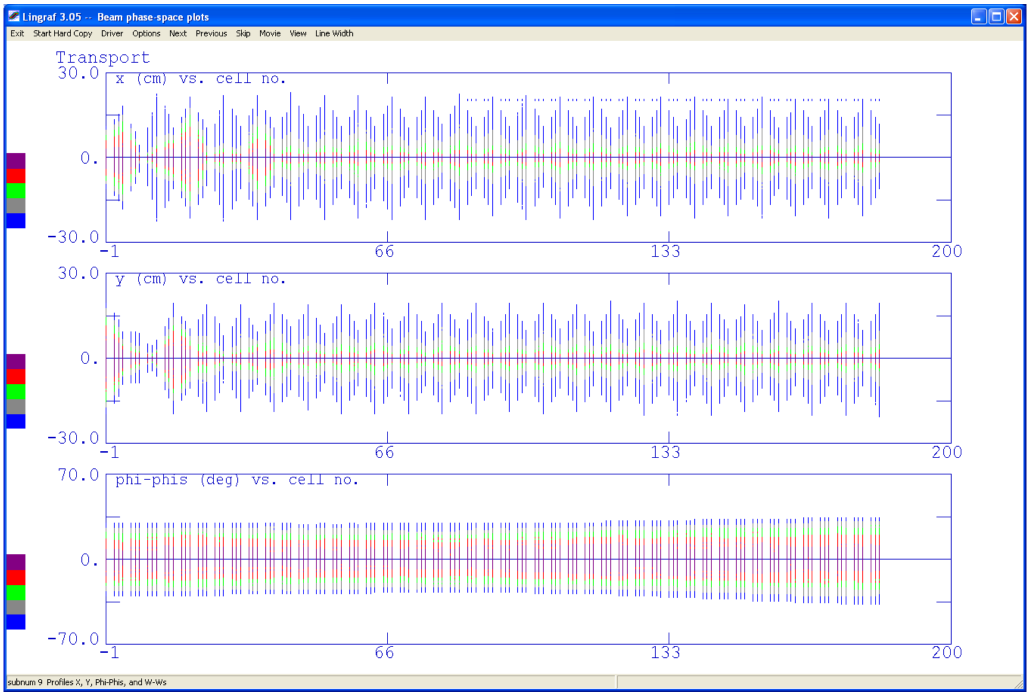


Figure 10. PARMILA run with 10000 particles and synchronous phase of ~2 degrees. FODO cell is around 8 meters long, G=3.1T/m

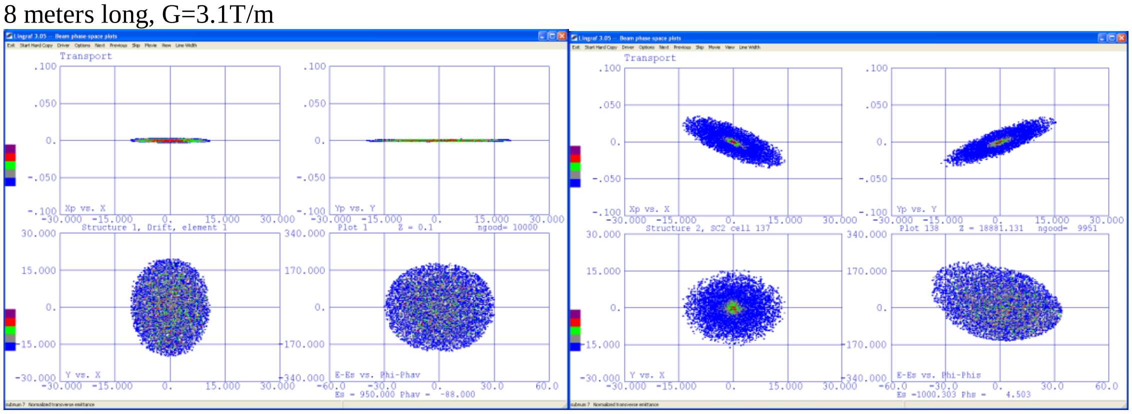
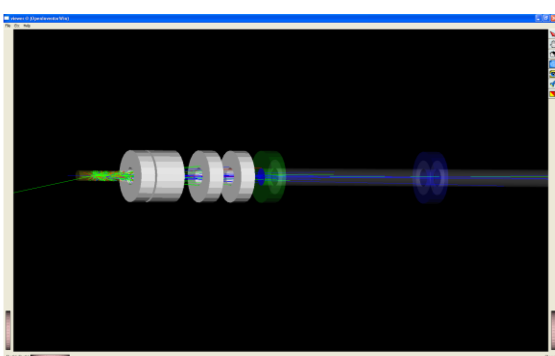


Figure 11. The pion beam phase space at the start and the end of the channel.

There are 28 FODO cells in the channel, G4beamline simulation start at target and end at detector after FODO channel.



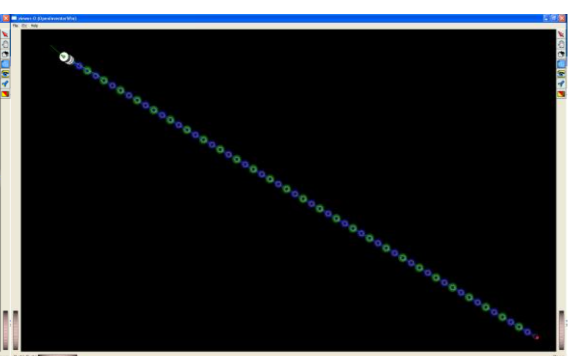


Figure 12a. Target, Li lens, matching quads. Figure 12b. G4Beamline mode of the channel.

Starting with 1E+5 protons on the target G4beamline shows~300 muons with energy spread and longitudinal spread as shown on graphs in Figure 13.

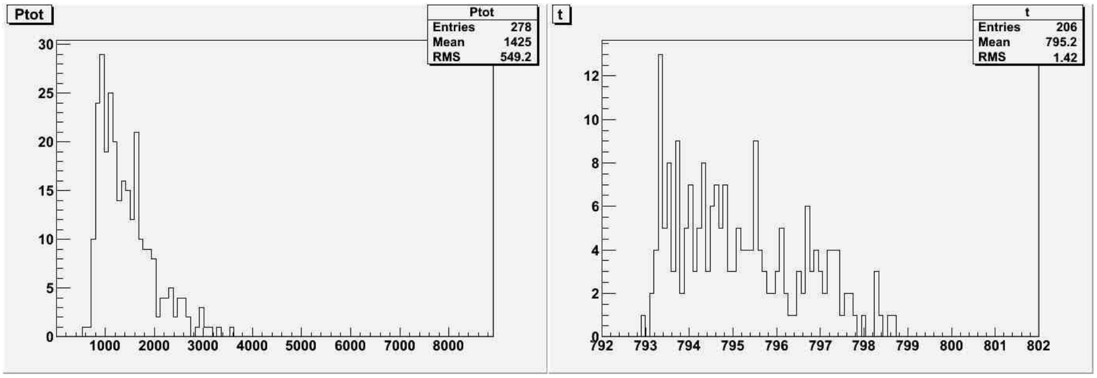


Figure 13. These are graphs are with cuts; μ+ only, with P_{tot}=[900:2000]MeV/c.

Figure 13 shows distributions of μ on the detector at the end of the channel. The whole channel consists of the target, Li lens, matching quads and 28 FODO Cells. In the simulation the space is provided for RF but RF is off.

Muon Acceleration

Pion/muon acceleration starts right after the Bunching Linac. The linac is based on 325MHz SC 3-cell cavities with FODO focusing. Figure 15 shows results of SuperFish calculation and dimensions of basic FODO cell.

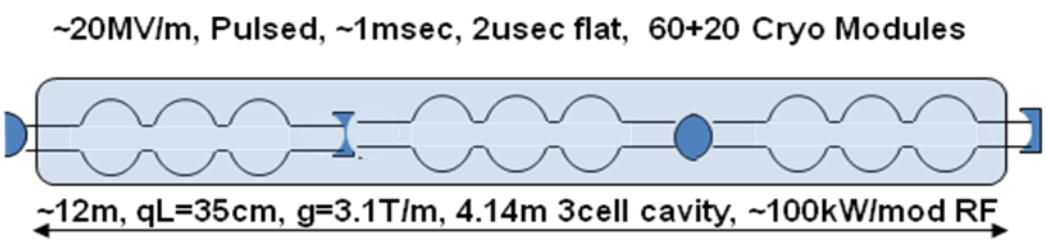


Figure 14. Cryostat has three cavities and two quads to reduce number of warm, cold transition.

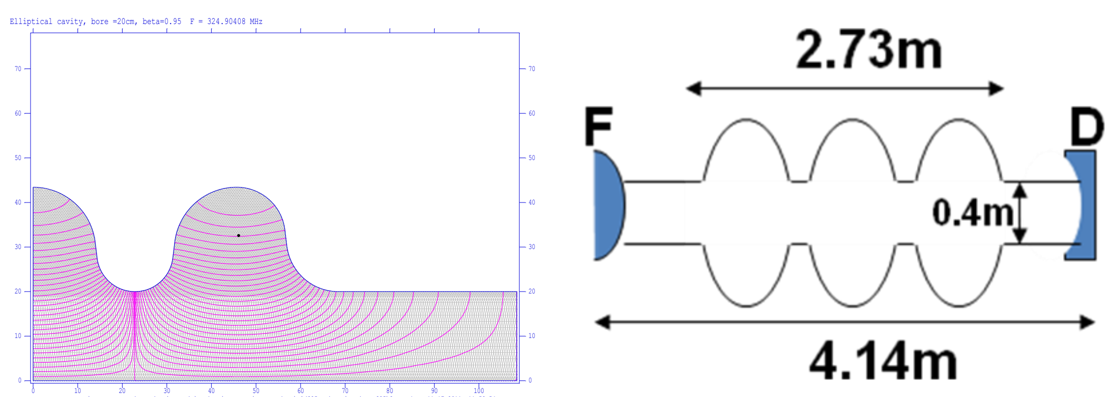


Figure 15.

To design the Linac, PARMILA code was used. FODO lattice starts with 3.1T/m quads gradients and ramps to 6T/m. The distance between quads is 4.14 m and it is constant along whole Linac. Acceleration is done using SC 3cell Beta=1 cavity with resonant frequency of 325MHz. The design requires constant energy gain per cavity to be 42MeV. The linac has a -20 degree synchronous phase which is ramped to -5 degrees in the first 3GeV. Injected beam has an unnormalized 95% transversal emittance of 300 mm-mrad and an energy spread of +/-150MeV. The particles in the bunch are spread +/-15 degree (of 162.5MHz) around the synchronous particle.

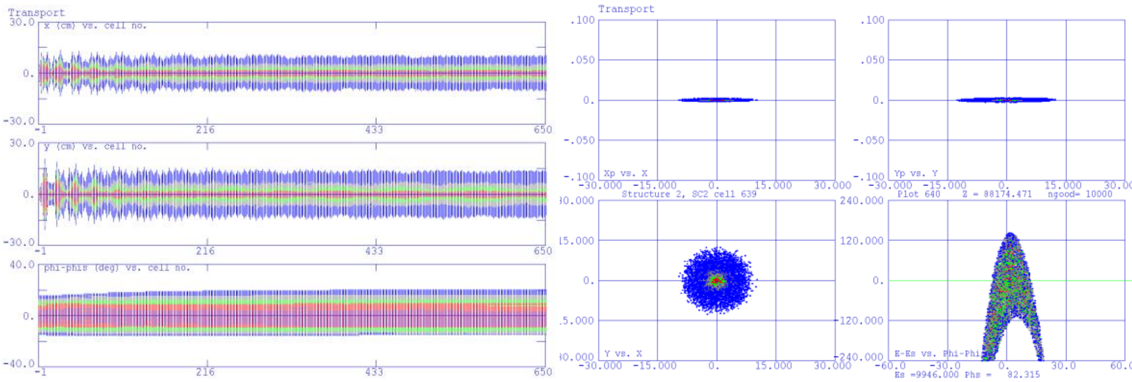


Figure 16. PARMILA outputs,

The entire Linac is ~900 meters long. A muon beam at 10 GeV has more than +/-150MeV spread. If needed the energy spread can be made smaller using coupled RF cavities with a higher synchronous phase. The linac is pulsed with 10 Hz repetition rate and pulse length of few microseconds plus needed fill time.

Decay Ring

The Decay Ring is similar to that in the existing NF studies design. It is a racetrack shape with minimal arc length. The muon pulse is only ~600ns long, which is short compared to the length of the 10 GeV decay ring. This design makes injection kickers less demanding.

Booster Beam

Most of the concepts and components that the Low Energy Low Intensity Neutrino Factory is based on can be tested and used for the VLENF and the Small Muon Storage Ring, and experiments associated with them. For the case of an 8 GeV Project X beam, beam from the Booster can be stored in the Recycler. This beam can be debunched and then adiabatically bunched using one or more 162.5MHz cryo modules that will be installed in the Recycler. This whole process can be done in less than 66 ms. The bunched beam will then be extracted using a single turn extraction and sent on to the P-bar target. To preserve bunch structure, the very same cryo module can be installed in the strait section of the racetrack storage ring. The racetrack will be an integer multiple of 162.5MHz. At the end of the pion decay process, the beam can be additionally accelerated using the same modules if we arrange the phase of the incoming beam to be non-zero.

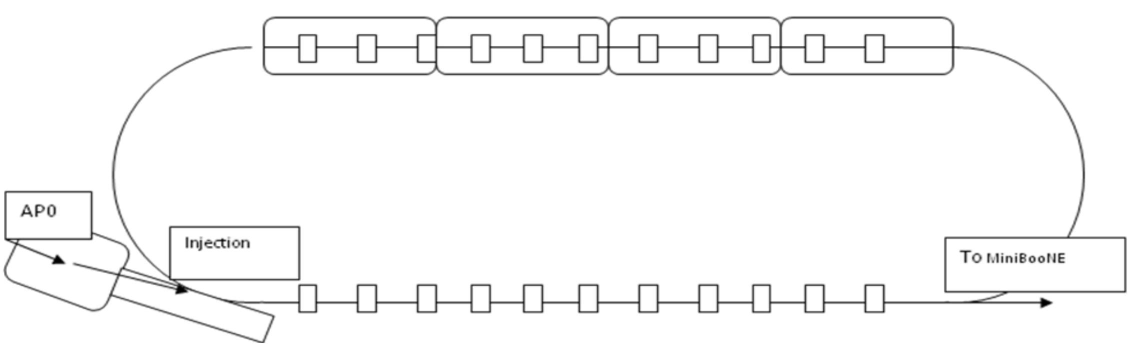


Figure 17.

MI Beam

The 120 GeV beam from Main Injector can be use in a similar way. In this case, the Tevatron can be used as a storage ring. The 162.5 MHz beam structure will be formed in the Tevatron and sent to the P Bar target station. The beam from the target will be sent to the Small Storage Ring as in the case of the Booster beam.

Conclusion

This version of the NF delivers ~10^{20} μ/year at 10 GeV, and is based on previously coasted, existing technologies. None of systems have parameters that are extreme or hard to achieve. With exception of the lithium lens with a 3 cm radius, all other elements have been built in one form or other. Choices of parameters for all subsystems are far from optimum. At this point the simplest version is presented. Possible performance improvements and cost savings are possible almost at every stage. For example, the Decay/Buncher Channel can be replaced with ring similar to VLENF one. The accelerating strait linac can be replaced with recirculating linac or combined with Decay Channel linac. All these and other options should be studied assuming that ~10^{20} μ/year is of interest for future experiments.