# CONCEPT: LOW ENERGY, LOW INTENSITY NF FROM PROJECT X*

Milorad Popovic#, FERMILAB, Batavia, IL 60510, USA

*Abstract*

This paper describes the concept of a Low Luminosity Low Energy Neutrino Factory ($L^3$ENF) using a Project X pulsed, or CW, Linac at 8GeV. By collecting $\pi$ and $\mu$ with energy ~ 1 GeV, and accelerating them to 10 GeV, it is possible to store ~$10^{20}$ $\mu$ 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 $L^3$ENF could be used in experiments before Project X completion.

## INTRODUCTION

The beam from the Project-X Linac [1] 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, 61ns long, in the linac beam train to create a beam gap in the ring for extraction. 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 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.

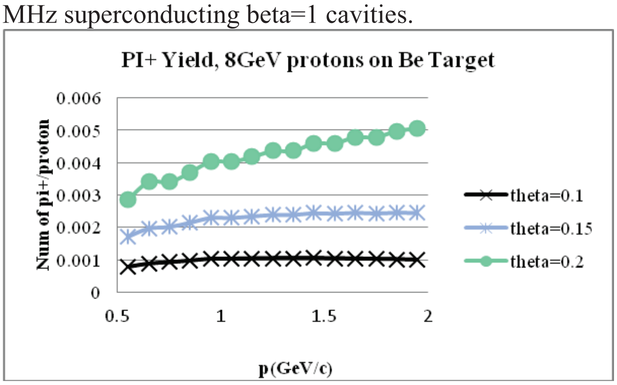


Figure 1: The pion yield curves above are produced using Striganov calculations.

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

*Work supported by Fermi Research Alliance, LLC, under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy.

#popovic@fnal.gov

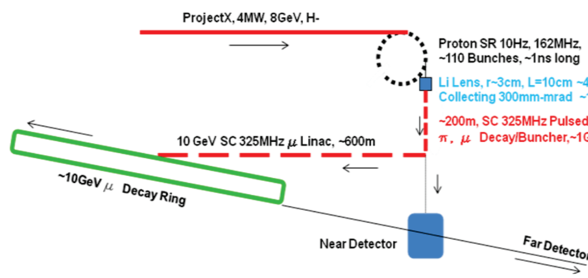


Figure 2: Protons are accelerated with ProjectX linac, then accumulated and targeted.

Table 1: Basic Beam Parameters

| Protons | Parameters |
|---|---|
| Linac, H- Beam, 650MHz SC RF | BeamPower=4MW, CW 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 shift ~0.005 LongLimit ~ 0.1MW per bunch |
| **Pions/Muons** | **Parameters** |
| Target & Collection & Matching, at 1 GeV, energy spread of +/- 0.15GeV. Collecting E_un95%=300mm-mrad, L=3.5m, Yield~5x$10^{-3}$ 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 |

In the rest of this note detailed descriptions of each stage and its building blocks are given. The assumption is that the 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 a multiple of $\lambda_{rf}$=1.845m.



ISBN 978-3-95450-122-9

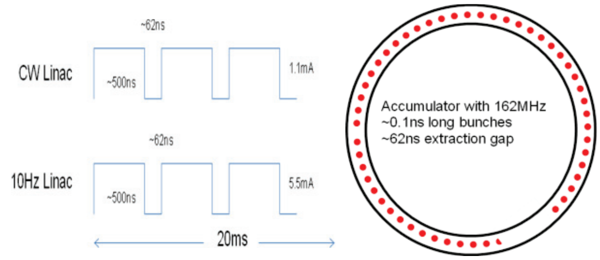


Figure 3: Beam accumulation.

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 162.5MHz 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 than ~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.

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

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 bending field limited to ~1.8 T. 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: Lattice parameters (obtained from a MAD run)

| | | | | | |
|---|---|---|---|---|---|
| total length = | 191.0m | Qx = | 2.59 | Qy = | 2.26 |
| delta(s) = | 0.0 mm | Qx' = | -3.90 | Qy' = | 0.34 |
| alfa = | 0.1304 | betax(max) = | 24.77 | betay(max) = | 69.40 |
| gamma(tr) = | 2.76840 | Dx(max) = | 5.11 | Dy(max) = | 0.0 |
| Dx(r.m.s.) = | 4.310250 | Dy(r.m.s.) = | 0.0 | | |

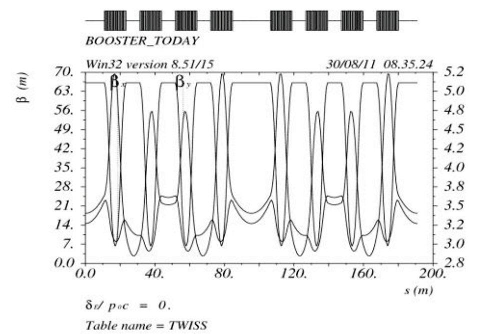


Figure 4: MAD output, for half of the ring.

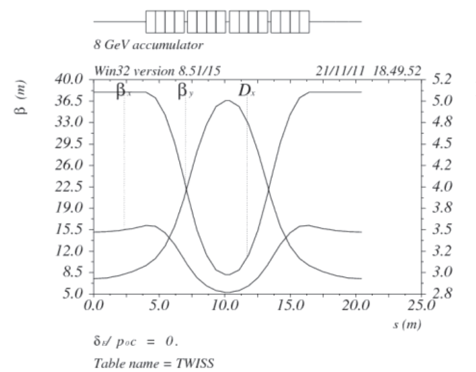


Figure 5: MAD output, the basic magnet group and lattice functions.

The lattice can be improved in the event that the long injection and extraction straight 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 straight sections.

## 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 Litium lens is 15 cm long, with a radius of 3 cm, a peak current of 600 kA and a focal length of ~0.2 m.

## 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 unnormalized 95% transverse emittances of 300mm-mrad




ISBN 978-3-95450-122-9

and energy spread of +/- 200 MeV. The bunch is 30 degrees (of 325MHz) long. Figure 6 shows PARMILA simulation of X, Y and Z planes.

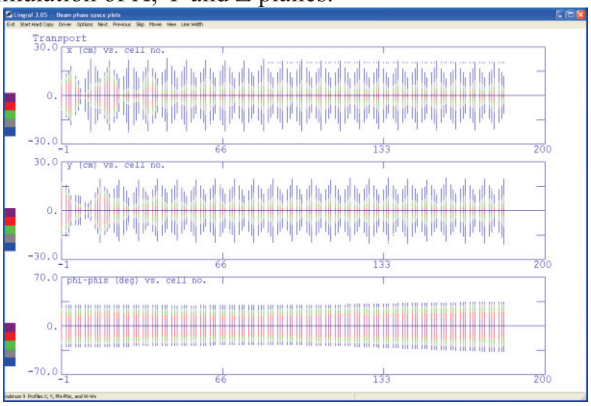


Figure 6: PARMILA run with 10000 particles and synchronous phase of ~2 degrees. FODO cell is around 8 meters long, G=3.1T/m

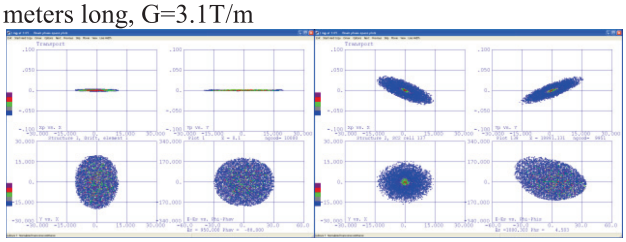

Figure 7: The pion beam phase space at the start and the end of the channel.

There are 28 FODO cells in the channel; G4beamline simulations start at the target and end at a virtual detector after the FODO channel.

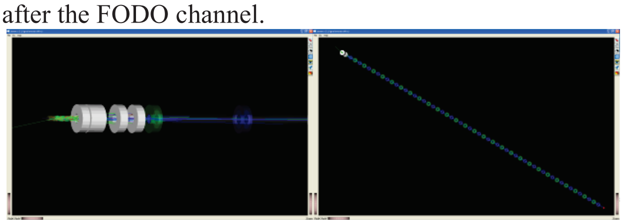

Figure 8: Target, Li lens, matching quads, G4Beamline model of the decay channel.

Starting with $10^5$ protons on the target, G4beamline shows ~300 muons with energy spread and longitudinal spread as shown on graphs in Figure 9.

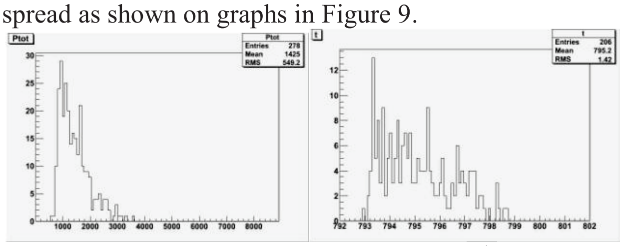

Figure 9: These graphs are with cuts; $\mu^+$ only, with $P_{tot}$=[900:2000]MeV/c.

Figure 9 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 10. Figure 11 shows results of SuperFish calculation and dimensions of basic FODO cell.

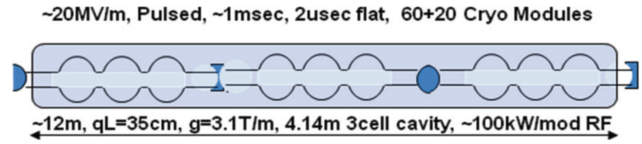


Figure 10: Cryostat has three cavities and two quads to reduce the number of warm-cold transitions.

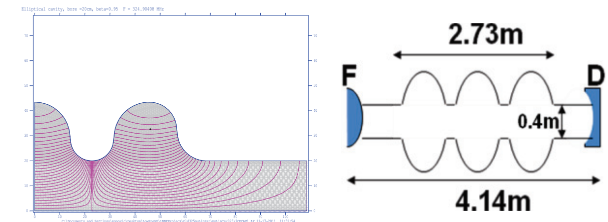


Figure 11: SuperFish result of 3-cell cavity

To design the Linac, the PARMILA code was used, Figure 12. The FODO lattice starts with 3.1T/m quad 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 unnormalized 95% transvers emittances 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.

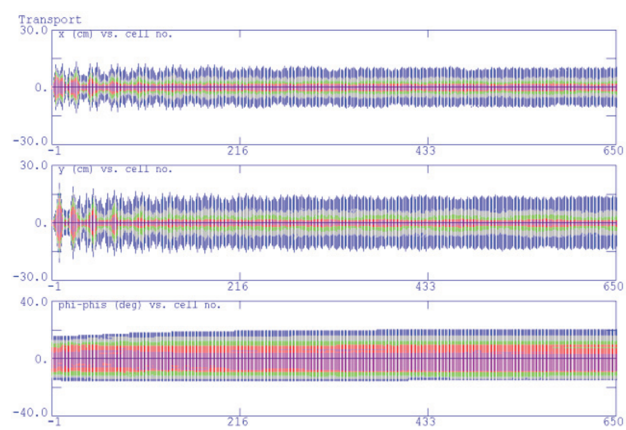


Figure 12: PARMILA outputs.

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.

## REFERENCES

[1] S. Holmes et al., “Project X Reference Design Report,” Project X Document 776-v1 (2010), http://projectx-docdb.fnal.gov