Proton Beam from Project X for a μ-Collider or ν-Factory

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Abstract. For a Muon Collider or Neutrino Factory short intense bunches of ~10 GeV protons at a frequency of ~15 to ~60Hz are required. In its current incarnation, the Fermilab Project X linac would produce 3GeV cw proton beam at 1ma, with varying bunch structures. For Project X the facility would be extended to provide pulsed H^- beam at ~8GeV, with 5ma at a 10% duty factor providing 4MW. To form beam for a collider or a factory, the H- beam would be charge-exchange injected into an accumulator ring and formed into bunches. The bunches are then extracted into a Compressor ring where the bunches are compressed into short lengths suitable for extraction onto a target for π→μ production. Parameters of the system are discussed.

Keywords: Enter Keywords here.
PACS: 14.60.Ef, 41.85.Ar, 41.85.Ct

INTRODUCTION

A Muon Collider (MC) or Neutrino Factory (NF) requires short intense bunches of ~10 GeV protons at a frequency of ~15 to ~60Hz and power of ~4MW. With the baseline proton energy set at 8 GeV, this implies $\sim 2\times10^{14}$ protons at 15Hz or $\sim 5\times10^{13}$ at 60Hz. At extraction onto a target to produce a high-intenity muon pulse, these protons would need to be compressed to ~1m long bunches.

In its current incarnation, the Fermilab Project X linac would produce 3GeV cw proton beam at 1ma, with varying bunch structures.[1] To extend this to a MC or NF source beam, one might begin by adding a linac extension to 8 GeV, and a pulsed 3-8 GeV linac is considered as a project X component to provide beam at ~250kW for the Fermilab Main Injector program. To obtain 4MW at 8 GeV both the cw linac and the pulsed linac must be upgraded to support acceleration of 5ma H^- beam at a ~10% duty cycle. This would provide 4MW but would not provide the desired time structure.

Formation of short intense bunches requires accumulation of beam from the linac in a storage ring and compression of that beam to short bunches. In the present note we develop a particular scenario of that compression to illustrate the method, with some supporting calculations that indicate some of the details and challenges in the method. In the scenario we imagine using two storage rings, the first with beam dynamics to facilitate accumulation of beam from the linac (an Accumulator) with initial bunching and a second where bunches from the accumulator are compressed to very short lengths (a Compressor ring).

ACCUMULATOR/COMPRESSOR SCENARIO

In the present discussion we follow a similar scheme used in the mu2e proposal[2, 3, 4], a scenario for storing and extracting 8 GeV proton beam.

In the scenario the beam is injected by multiturn H^- injection into an 8 GeV storage ring, which is labeled the Accumulator. The ring circumference is initially chosen to be 300m. For a baseline scenario we choose 15Hz as our reference fill frequency and form 4 bunches in the ring. $\sim 2\times10^{14}$ protons must be injected in each cycle. For a 60Hz cycle bunches would be extracted one at a time into the Compressor where the bunches are shortened to ~1m rms length (~3ns), where they are then extracted onto the π→μ production target. In a 15 Hz scenario, the 4 bunches are simultaneously transferred into the Compressor, compressed, extracted, and transported to simultaneous impact on the production target. The simultaneous impact requires separate beam transports for the 4 bunches, with lengths adjusted to obtain the simultaneity. (The separate transport system has been called a "trombone".[6])

We have developed scenarios for accumulation and bunching of the beams based on these parameters. Beam would be injected into accumulator over an extended period (7ms at 5ma) to provide 2×10^{14} protons. In an initial scenario we assume that that initial beam is completely unchopped. After completion of injection an h=4 rf system is turned on, ramping from 0 to 3.0 kV/turn over 35ms. This forms the beam into 4 bunches with rms bunch lengths of ~10m each. These could then be transferred to a compressor (one at a time or all four at once), where ¼ synchrotron oscillation in a 120kV/turn rf system compresses the bunches to ~1m rms bunch lengths. This requires ~1600 turns(~1.6ms). The bunches would be immediately extracted and targeted. Note that the entire process (7ms injection, 35ms Accumulator bunching and 4 1.6ms compressions) fits within ~48ms of the 67ms of a 15 Hz cycle, and could be stretched a bit. Increasing the adiabatic bunching time to 50ms improves the bunching by ~10%; obtaining ~0.9m long final bunch length without increasing momentum spread.

Fig. 1 shows a 1-D simulation of longitudinal phase space within this process. Note that the Accumulator is relatively nonisochronous (γ_t = 4), which enables relatively fast adiabatic bunching, while the Compressor is relatively isochronous (γ_t = 11.3), which enables an extended ¼ synchrotron oscillation to a short bunch. These follow similar properties of the Accumulator and Debuncher that were used in the mu2e scenario. (The Compressor is chosen with $\gamma<\gamma_t$ to improve beam stability; similar bunching could be obtained with γ_t=8, where γ is above transition.)

In this initial example, only h=4 rf is used and the beam was injected completely unchopped. Adiabatic bunching in the Accumulator formed the beam into 4 separated bunches without a need for prechopping, but at a cost of ~30ms time for bunch formation. Higher harmonic rf could also have been added to compress the beam to shorter lengths.

The beam could be injected prechopped. A factor of 2 prechopping is planned in present scenarios. A barrier bucket rf system would then be needed in the accumulator to maintain the chopping through the injection time (~7μs). A chopped beam would be more easily bunched in the accumulator and compressed in the compressor.

In figure 2 we show some simulation of bunching and compression of 50% chopped beam and obtain some potential improvement over the unchopped case. After injection, an h=4 rf system with rf voltage increasing from 2 to 4kV over 15ms compresses the bunch to less than ~8m. Transfer to the Compressor enables compression to <1m (actually <2ns with 120 kV of h=4 rf. The bunching and compression is significantly easier with chopped initial beam.

CONSTRAINTS AND PARAMETERS-ACCUMULATOR AND COMPRESSOR

There are several instabilities and limitations that may be of significance in developing the parameters of the accumulator/compressor system. The desired intensities (2×10^{14}/ cycle, 5×10^{13}/bunch) are larger than in previous systems and compression to short bunch lengths may also generate instability concerns.

Longitudinal motion above transition is intrinsically unstable and requires Landau damping and bunching to maintain stability. Below transition, space charge oscillations are intrinsically stable, but additional impedance components can drive the beam into instability.

Longitudinal instability constraints can be estimated using the coasting beam instability threshold expression:

$$eI_0\left|\frac{Z}{n}\right| \leq F\ 2\pi cP\beta|\eta|\left(\frac{\sigma_p}{P}\right)^2,$$

where F is evaluated in the Landau integral and is ~1 above transition but is ~10 for space charge dominated motion below transition, with Gaussian-like energy distributions. *Z/n* is the impedance expression. For space charge it is:

$$\frac{Z}{n} \cong i\,\frac{Z_o}{\beta\gamma^2}\ln(\frac{a}{1.5\sigma})$$

For resistive wall it is:

$$\frac{Z}{n} \cong (1-i)\frac{Z_o}{a\sqrt{2\mu\omega\sigma_W}}$$

with a as the beam pipe radius and σ_W is the conductivity. At F=1, and I_0 = 32A, the formula would require σ_p > ~2.5MeV/c in our Accumulator simulations. This is a bit larger than what we used in our initial unchopped simulations, but similar to that used in our chopped initial distributions. Thus an initially unchopped beam may develop some longitudinal blowup, particularly if injected with < ~2MeV/c momentum spread, but the chopped scenario would be adaptable to meet requirements.

In the Compressor, the more isochronous motion is more susceptible to longitudinal instability, although σ_p is increased by bunching before insertion in the compressor and bunches are only in the ring for ~1600 turns. Therefore it probably more prudent to design the ring such that $\gamma < \gamma^t$.

Another potential constraint is space charge, where the space charge tune shift is given by :

$$\delta\nu \cong \frac{r_pN}{4\pi\beta\gamma^2 B_F\varepsilon_{N,rms}},$$

where B_F is the bunching factor and $\varepsilon_{N.rms}$ is the rms emittance, and we have assumed a round beam with no size increase (and δν reduction) due to momentum spread.

To minimize space charge the beam would be injected with an enlarged transverse emittance (25mm-mr), at which the space charge $\delta\nu$ is < ~0.3, even with bunches compressed to σ=1m.

We next need to develop specific lattices for the rings. The parameters can be similar to those for the existing Fermilab Accumulator and Debuncher ring modified for ~300m circumference, with the larger apertures needed for larger emittance.

A critical problem not yet addressed is the charge-exchange injection of $\sim 2\times 10^{14}$ protons into the accumulator ring (in ~6ms). Conventional foil stripping may be difficult.

Table I: Parameters of the accumulator-compressor system.

Parameter	Accumulator	Compressor
Circumference	300m	300m
Transition γ_t	4.0	11.3
Slip factor $\eta=1/\gamma_t^2-1/\gamma^2$	0.051	-0.0032
rf voltage V_{rf}	4.0kV	120kV

SUMMARY

We have introduced an accumulator/compressor scenario for obtaining short bunches from the long-pulse 8-GeV Project X linac. An h=4 scenario with modest rf requirements is capable of obtaining appropriate bunches within the 15 Hz scenarios. Variants with different lattices and harmonics (h=6 or 8) could also be developed as the design continues.

REFERENCES

1. Project X-Reference Design Report V1.0, November 1, 2010, Project X document 776, http://projectx.fnal.gov/.
2. Mu2e Collaboration, "Proposal to search for $\mu^- N\rightarrow e^- N$ with a Single Event Sensitivity Below 10^{-16}," FERMILAB proposal, October, 2008.
3. D. Neuffer, Fermilab Beams-D c-2782, May 2007.
4. D. Neuffer,"Proton Beam Formation at Fermilab for mu2e (and NF/MCC)", Proc. NufACT09, AIP Conf. Proc. 1222, p.279 (2010).
5. V. Lebedev and S. Nagaitsev, "Project X ICD-2 and its Upgrades for Neutrino Factory and Muon Collider", Proc. NufACT09, AIP Conf. Proc. 1222, p.274 (2010).
6. C. Ankenbrandt, unpublished (20XX).

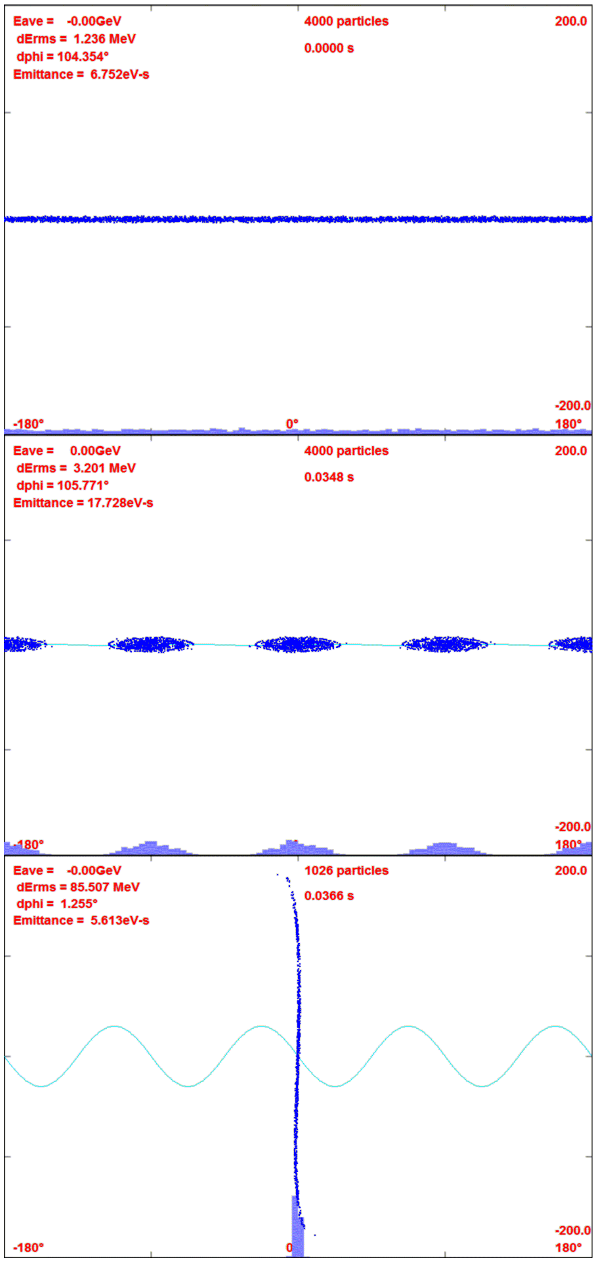

Figure 1. h=4 Simulation of longitudinal motion. In this simulation protons are adiabatically bunched into 4 bunches in the Accumulator. A single bunch is transferred into the Compressor where it is rotated to a short bunch (σ=~3ns). In each of these graphs the x-coordinate is phase around the ring(-180° to +180°), and the y coordinate is the energy offset δE (-200 to +200 MeV).

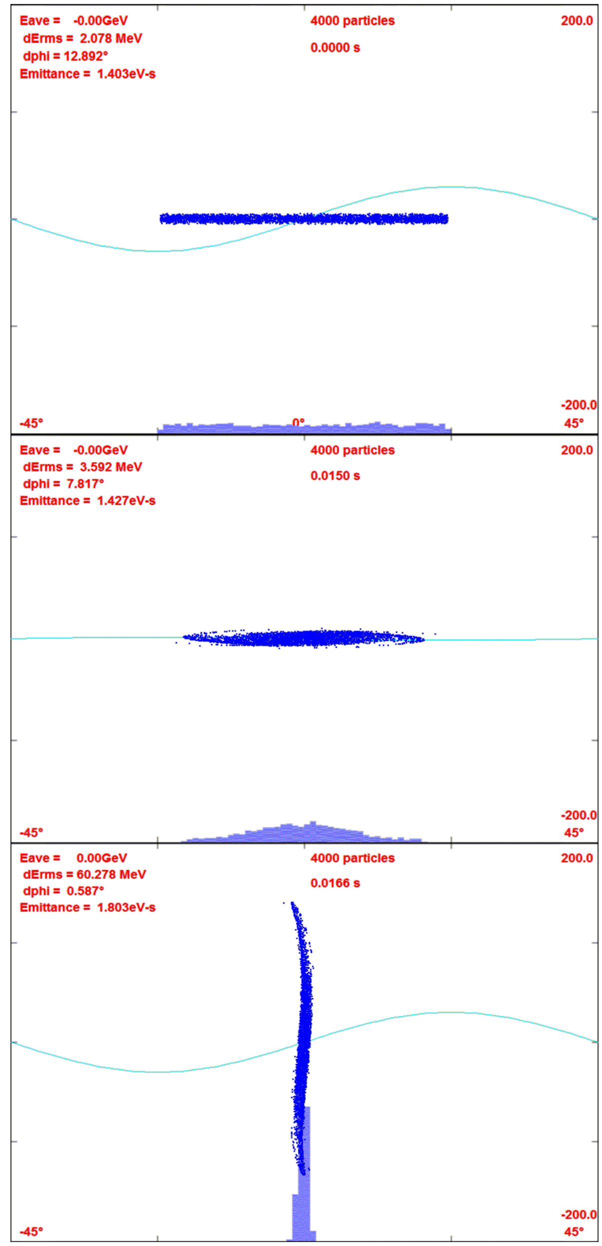

Figure 2. Simulation of longitudinal motion in a bunching scenario with beam chopped at 50%. Bunching at h=4 reduces rms bunch length to ~6.5m rms within 15ms. Compression in the compressor reduces bunch length to ~1.7ns rms with energy spread ~60MeV rms(~±150MeV full width) In the simulations bunching and compression is some what easier than the unchopped case. In each of these graphs the x-coordinate is phase around the ring (-45° to +45°, covering only one period of the h=4 system), and the y coordinate is the energy offset δE (-200 to +200 MeV)