USING PROJECT X AS A PROTON DRIVER FOR MUON COLLIDERS AND NEUTRINO FACTORIES*

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Abstract

The designs of accelerator systems that will be needed to transform Fermilab's Project X [1-3] into a high-power proton driver for a muon collider and/or a neutrino factory are discussed. These applications require several megawatts of beam power delivered in tens or hundreds of short multi-GeV bunches per second, respectively. Project X may require a linac extension to higher energy for this purpose. Other major subsystems that are likely to be needed include storage rings to accumulate and shorten the proton bunches and an external beam combiner to deliver multiple bunches simultaneously to the pion production target.

INTRODUCTION

Fermilab is proposing a major intensity upgrade known as Project X. Various design concepts for Project X have been considered, all based on a multi-GeV superconducting H^- linac with considerable beam power. One initial configuration (IC-1) is based on an 8-GeV pulsed linac; a second concept (IC-2) includes a CW linac of about 3 GeV [1,2].

The designs of muon colliders and neutrino factories are also evolving, but all concepts require about 4 MW of proton beam power delivered to the pion production target in short (a few ns rms) bunches at rates of tens of bunches per second (for a muon collider at the energy frontier) to hundreds (for a neutrino factory or muon collider Higgs or Z' factory). The international scoping study (ISS) [4] for a neutrino factory specifies that the proton kinetic energy should be in the range of 5–15 GeV, and it is believed that the optimum proton energy for a muon collider is likely to fall in the same range [5].

The required time distribution of proton bunches implies "post-processing" downstream of the linac. The most feasible post-processor consists of a pair of rings, one to accumulate the desired number of bunches and the other to shorten the bunches. Fixed energy storage rings have many advantages over synchrotrons for these applications; however, the linac must deliver the full energy that is required by the storage rings. To resolve the different repetition rates between a neutrino factory and a muon collider, an external bunch combiner can be placed between the bunch shortening ring and the pion production target. The combiner would be used to make several bunches arrive at the production target simultaneously, thereby reducing the apparent repetition rate at the target.

The requirements on the proton driver for these purposes are quite daunting, well beyond the currently demonstrated state of the art. Accordingly, the design must incorporate the best features of the existing state-of-the-art designs and also provide considerable flexibility to adapt to differing programmatic requirements and unanticipated operational limitations.

This paper describes a particular three-stage development plan for a proton driver, starting with a 3-GeV, 0.5 mA CW SRF H^- linac (initial stage of Project X) and ending with the proton bunch parameters at the pion production target for a muon collider. Additionally, it describes several new concepts that enhance the feasibility and reduce the cost of such a proton driver. One new concept is the aforementioned external bunch combiner. Other new concepts promise to extend the art of foil stripping technology in order to facilitate charge exchange injection over many turns from a CW linac into a storage ring.

FROM PROJECT X TO A MUON COLLIDER

If muon colliders and neutrino factories are separately designed and optimized, the front ends tend to diverge. The divergence stems from muon colliders needing luminosity and neutrino factories needing flux. Fortunately there is considerable overlap between the proton beam requirements for an energy frontier muon collider and an intensity frontier neutrino factory (based on muon storage rings). Muon colliders tend to be more demanding on their front ends than neutrino factories. A facility that meets the beam requirements of the former is likely to also meet the requirements of the latter. This paper describes a staged approach to using Project X to drive a neutrino factory and ultimately a muon collider.

A three stage development plan for a proton driver is described below, starting with a 3 GeV, ~0.5 mA CW SRF H^- linac and ending with the proton bunch parameters required at the pion production target for a muon collider. These parameters correspond to 1.5 MW of beam power. The physics goal of the initial activity is to provide a proton beam appropriately packaged to drive a neutrino factory based on muon storage rings. The first stage uses a 3 GeV storage ring to accumulate 3 bunches of protons at a time from the linac, operating on a 70 Hz cycle. The bunches would then be shortened, either in the same ring or a second dedicated ring, for delivery to a pion

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production target to make muons for a neutrino factory based on a muon storage ring. The proton beam power and energy imply that the neutrino flux will be about a factor of three less than what is ultimately desired for a neutrino factory; however, the performance of the ultimate neutrino factory exceeds that of a facility based on a state-of-the-art conventional neutrino superbeam (a neutrino beam resulting from pion decays) by such a large factor [6] that the proposed initial activity would still be capable of enabling interesting neutrino physics competitive with, and complementary to, that from a conventional neutrino superbeam. The beam from the neutrino factory could be directed toward detectors at DUSEL and/or NOvA. (Neutrino beams could be delivered to two locations simultaneously from a triangular muon ring.) Neutrino beams derived from the muon storage ring and from the Main Injector could be distinguished by timing. A magnetized detector would provide an important capability to determine the signs of the lepton charges produced in the interactions of muon and electron neutrinos and antineutrinos from muon decay. The second stage uses the protons from the CW linac extension to 6 GeV with a current of 0.667 mA to provide 4 MW of beam power. The same ring(s) as in the first stage, operating at a correspondingly higher magnetic field, would be used to accumulate and shorten 3 bunches, still at 70 Hz, for a more powerful neutrino factory. The third stage is the conversion of the neutrino factory configuration to a muon collider configuration. Stage three is the augmentation of stage two with an external bunch combiner. The combination of the bunches at the pion production target can be used to drop the repetition rate to 15 Hz, suitable for driving a muon collider. The specific numerical values used above fall within the ranges specified by the proponents of neutrino factories and muon colliders and are choosen to maximize the plausibility that each stage is feasible; in particular, space-charge tune shifts in the rings are tolerable in each case. Somewhat different choices of parameters at each stage may result from detailed optimizations supported by additional R&D. Below we discuss some of the new concepts required to make the aforementioned plan feasible.

Resonant Foil Bypass Injection

It will be challenging to accumulate the required beam current. The challenge comes from preventing degradation/damage of the stripping foil while injecting many turns from a CW linac into an accumulator ring. One new concept to help alleviate target damage is to include a resonant foil bypass injection scheme [7]. The resonant foil bypass uses two or three resonant dipoles to create a "local bump" in the beam orbit. The beam is bumped closer to the foil only when the H^- linac beam is present for injection. This helps to prevent the circulating proton beam from traversing the foil when the incoming beam is not present. This also implies using a pulsed beam in a CW accelerator complex (see summary).

Longitudinal Foil Segmentation

The second idea is to take advantage of the facts that the optimum stripping foil thickness for a multi-GeV beam is about 600 μg/cm^2 and that 200 μg/cm^2 thick stripping foils have proven to be quite durable [8]. Thus the stripping foil can be segmented longitudinally into ~3 foils, so that there are six surfaces to dissipate the heat by radiation instead of two. The use of at least two foils has been advocated in the past to mitigate the effects of any "pinholes" in the foils.

Rotating Stripping Foils

The third idea is to rotate a circular foil rapidly, with an annulus having a radial extent of about 1 cm exposed in one corner of the aperture [8]. That will spread out the energy deposition over an effective area of several square cm. Mechanical concepts for mounting and supporting such a rotating foil are being developed.

External Bunch Combiner

A neutrino factory and a muon collider call for widely varying numbers of bunches per second delivered to the pion production target. Accordingly, an important design goal is to develop a bunching strategy that allows considerable flexibility. For a muon collider, very intense proton beams are required; such beams can be accompanied by significant space charge tune shifts. The external combiner can help mitigate the space charge effects. Instead of requiring a single very intense and very short proton bunch, one can run with multiple less intense bunches and combine them at the pion production target. The configuration described as stage three achieves such flexibility by using an external bunch combination scheme. The combiner is a set of transfer lines and kickers downstream of the bunch rotation ring that can allow for more than one bunch to arrive simultaneously at the production target [6,9]. The first major subsystem of the external bunch combiner, the "trombone", sends bunches on paths of different lengths. The second subsystem, the "funnel", arranges the bunches on the circumference of a circle which is incident on the pion production target.

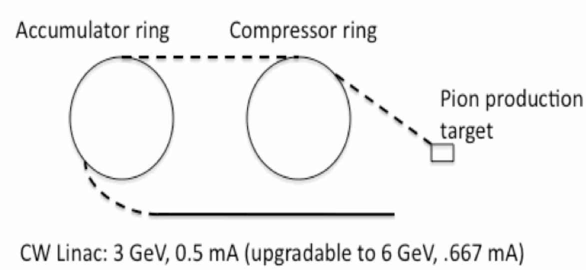

Figure 1: Schematic layout of how to use the Project X linac as a proton driver for a neutrino factory/muon collider.

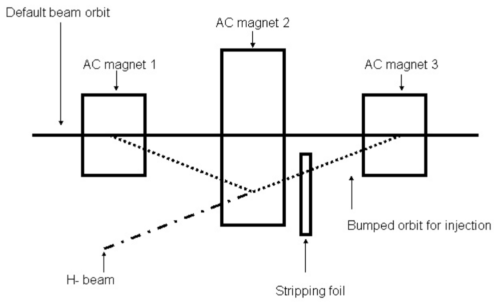

Figure 2: "Resonant foil bypass" uses two or three resonant dipoles to create a "local bump" in the beam orbit. The beam is bumped closer to the foil only when the H^- beam is present for injection. This helps to prevent the circulating proton beam from traversing the foil when the incoming beam is "off".

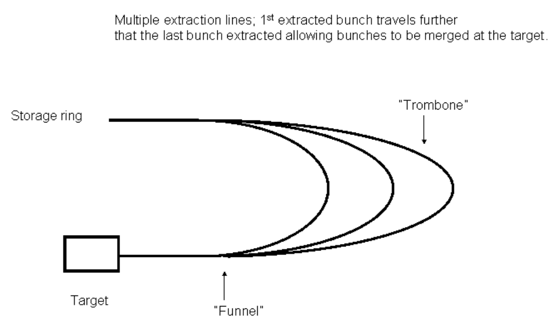

Figure 3: Schematic of trombone and funnel concept. This allows the merging of bunches at the target. This makes it possible to move from a single very intense bunch scenario to a multi-bunch scenario, thus easing the difficulties of handling the space change issues associated with a neutrino factory or muon collider.

SUMMARY

The most promising design approach for a muon collider/neutrino factory proton driver consists of a full-energy H^- linac, a pair of storage rings, and an external bunch combiner. The two storage rings are high-acceptance accumulator and buncher rings. The external bunch combiner allows several bunches to arrive at the same time at the pion production target. The linac could be either CW or pulsed, provided that it is capable of delivering at least 4 MW of beam power. We have presented several new ideas that facilitate the use of a CW linac.

An important conclusion is that a kinetic energy of 6 GeV is high enough to support the 4 MW proton driver required for neutrino factory and muon collider applications.

If the initial Project X linac is significantly less than 6 GeV, it should be extended, using the same technology as the high-energy end of the initial linac, in order to provide the necessary kinetic energy and beam power. Regarding the important question of whether the linac should be CW or pulsed, our answer is a yes. That is, it should be hybrid: the RF power should be CW, but the beam current should be pulsed at a high frequency. That makes a "resonant foil bypass" possible in the accumulator ring. That, together with the other innovations described in this report, will facilitate the injection of a very large number of turns through a stripping foil into a ring from a linac whose average current is low. The new ideas presented underpin the three-step program to go from Project X to a muon collider.

If the need arises for more than 4 MW of beam power, either to enhance the operation of a neutrino factory or a muon collider or to allow simultaneous delivery of beam for other high power applications, then the linac beam current can be upgraded by adding or upgrading power supplies.

ACKNOWLEDGMENTS

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