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Project X and its Connection to Neutrino Physics

Deborah Harris
Fermi National Accelerator Laboratory
Batavia, USA
E-mail: dharris@fnal.gov

Andreas Jansson
Fermi National Accelerator Laboratory
Batavia, USA
E-mail: jansson@fnal.gov

Project X is a new high intensity proton source that is being planned at Fermilab to usher in a new era of high intensity physics. The high intensity frontier can provide a wealth of new measurements—the most voracious consumer of protons is the long baseline neutrino program, but with the proton source upgrades being planned there are even more protons available than current neutrino targets can withstand. Those protons can provide a rich program on their own of muon physics and neutrino scattering physics that is complimentary to the long baseline program. In this article we discuss the physics motivation for Project X that comes from these short baseline experiments, and also the status of the design of this new source and what it will take to move forward on that design.

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1. Introduction

The recently released P5 report stresses that there are three frontiers that must be explored in particle physics[1]. Measurements at the energy frontier, currently being probed by the Tevatron at Fermilab and soon by the LHC at CERN, will hopefully shed light on the origin of mass. The cosmic frontier, currently being probed by a host of detectors giving ever increasingly precise pictures of our universe, will hopefully shed light on Dark Energy and the makeup of cosmic particles. Measurements at the Intensity frontier, currently shared between the NuMI Beamline at Fermilab and the CNGS beamline at CERN, will bring us a more precise picture of neutrino oscillation physics. The next step in the Intensity Frontier is to build a new proton source that can provide not only >400kWatts of proton power for a $\nu_\mu \rightarrow \nu_e$ oscillation experiment, but also provide beams for experiments probing other rare processes.

Project X has been proposed as a way to bring Fermilab to the next level of intensity by replacing the first stages of proton acceleration. Currently the Fermilab proton source consists of a Linac followed by a booster, which can provide and accelerate $\sim 5\times10^{12}$ protons per pulse at 8 GeV, at a frequency of 15 Hz[a]. The next step in the complex is to stack booster bunches on top of each other and accelerate them to 120GeV in the Main Injector. Currently the Main Injector can send up to $\sim 4\times10^{13}$ protons per pulse to the NuMI target every 2 seconds, which corresponds to approximately 400kW. By replacing the 35 year old Booster with a new proton source and linear accelerator, the plan is to provide up to 2.3 MW of 120GeV protons[2], in addition up to 200 kW of proton power at 8 GeV.

Another new step in the intensity frontier is the JPARC accelerator complex, which is currently under construction[3]. At the time of the NuFact08 Workshop, the J-PARC Main Ring was being commissioned. This complex is designed to provide up to 700kW of power using 40-50 GeV protons. This source will be used by the T2K experiment to search for $\nu_\mu \rightarrow \nu_e$ oscillations, but with the flexibility of this source there will also be kaon and muon experiments at that facility. The physics that lies at the intensity frontier is much broader than any one facility could support, however, and the experiments described here are not among those being undertaken at the JPARC facility.

The added capability of extremely long baseline measurements using either the existing NuMI beamline or a new beamline to the DUSEL makes Fermilab an extremely attractive place to take this next step in intensity.

2. Physics Program at Project X

Given the tantalizing possibility of measuring the mass hierarchy and searching for CP violation in the lepton sector, the primary motivation of this new proton source would

[a] The average linac rate is currently limited to 6Hz due to radiation safety requirements.

be to take these important steps in long baseline oscillation physics. For a recent review of the physics reach of oscillation experiments with Project X compared to current and near future plans see N. Saoulidou's proceedings submitted to this workshop[4].
There can also be a very rich program of muon flavor and neutrino scattering physics measurements at Fermilab given the capabilities of this new accelerator complex. One aspect of this program is the search for muon to electron conversion, and another is detector R&D studies with liquid argon, which will pave the way for the large detectors needed to search for CP violation and the mass hierarchy.

2.1 Muon to Electron Conversion

Because neutrinos can oscillate from muon to electron type in the standard model, it is straightforward to draw a diagram in which a muon converts to an electron in the presence of a photon provided by the electromagnetic field of a nucleus, as shown in figure Figure 1a. However, the standard model rate for this corresponds to a 10^{-54} branching fraction. Figure Figure 1b) shows what can happen if a supersymmetric particle can enter that loop, which would contribute to the branching ratio at a 10^{-15} level, and figure Figure 1c shows a tree-level contribution from a lepto-quark. The importance of these latter two diagrams depend on the coupling constants, and the masses of these as of yet undiscovered particles.

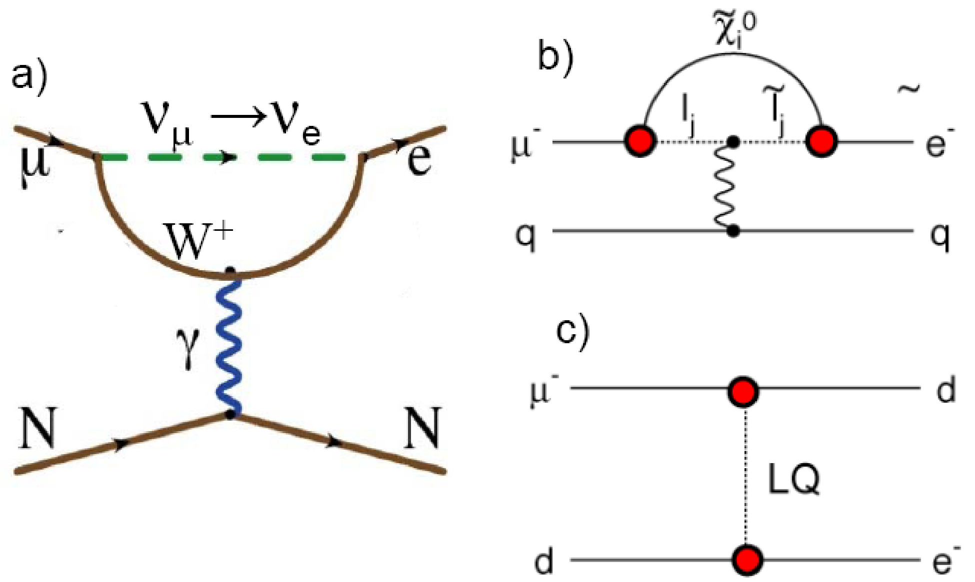

Figure 1a) shows how a muon can convert into an electron, given the electric field of a nucleus and the fact that muon neutrinos can oscillate into electron neutrinos. Figures 1 b)and c) show how both supersymmetryand leptoquarks can contribute to this process, respectively.

The strategy for looking for $\mu \rightarrow e$ conversion proposed by the mu to e collaboration[5] looks, not surprisingly, like the front end of a neutrino factory: 8 GeV protons strike a target, the produced pions are captured where they decay to muons. At this point the muons are transported to a detector, where they stop in thin foils. The stopped muons are captured by the nucleus where they either convert to electrons (signal) or they decay while in orbit (background). The resulting electron then leaves the foil since now it has some 105MeV, and it spirals and is momentum analyzed in the surrounding magnetic spectrometer. The way to reject the decaying muon background is to use both the momentum resolution of the spectrometer and the timing of the beam: the former helps with rejecting decay electrons, and the latter helps with removing the prompt background from the high rate of neutrons that are created by the protons striking the target.

The mu2e conversion proposal that has been submitted to the Fermilab Physics Advisory Committee, expects 0.5 events background and 5 events signal for a 10^{-16} branching ratio. This corresponds to a leptoquark mass of up to 10^4 TeV. This experiment has the sensitivity to probe 10^4 times better than previous experiments due to its improved energy resolution and beamline design, and possibly a factor of 10^6 with Project X with the added intensity that would be available.

2.2 Liquid Argon Detector R&D

One possibility for the far detector for the long baseline neutrino program served by project X is a liquid Argon TPC. This technology has shown much promise during the ICARUS cosmic ray run in Pavia[6]. Unfortunately, however, the ICARUS detector would be extremely expensive to produce at the 100 kton scale, because the levels of purity that were achieved in ICARUS came only through evacuating the entire chamber before filling it with ultra-pure liquid argon. Although industry knows how to make cryogenic vessels capable of holding hundreds of kilotons of liquid argon, these are not vacuum vessels and so the outstanding question is how clean can such a vessel be made. The MicroBooNE experiment proposes to use a 100-200 ton Liquid Argon TPC in the Booster neutrino beamline to do neutrino scattering measurements and investigate the MiniBooNE low energy excess in their $\nu_\mu \rightarrow \nu_e$ oscillation search[7], but it proposes to do so using a detector design that does not require a vacuum vessel. If the apparatus can be made cleanly enough at this size it is expected that scaling up to a higher mass would be not only feasible but affordable. The next step in this stage of detector development might be a 5 kton liquid argon detector in the NuMI beamline (in Soudan, Minnesota).

2.3 Electroweak Measurements with Neutrinos at Project X

There are two ideas for doing electroweak measurements at Project X: both want to use a fine-grained detector technology in an extremely intense neutrino beam to measure neutrino-electron and anti-neutrino electron scattering. By comparing the two cross sections one hopes to measure the weak mixing angle $\sin^2\Theta_W$. Both of these experiments would take advantage of the extra protons afforded by Project X: NuSonG[8] would use 800 GeV protons to make a NuTeV-style high energy beam, and HiResMu[9] proposed running in the NuMI beamline in front of the MINOS near detector.

3. Accelerator Aspects of Project X

As a response to the 2006 P5 report, which put LHC and ILC at the top of the priority list, the Fermilab director created a long term steering group to develop a roadmap for the lab consistent with these priorities. The committee concluded that if the ILC would be significantly delayed with respect to its "technically limited schedule", Fermilab should embark on an ambitious proton intensity upgrade program called Project X[10].

The current accelerator complex is capable of providing about 400 kW at 120GeV. This number is limited by space charge at injection into the Booster. Both the linac and Booster also have reliability issues due to their age. Project X would replace both of these machines with a new 8GeV linac, thereby significantly increasing the proton intensity that could be supplied to the more modern Main Injector. The Main Injector is expected to be capable of supplying 2.3MW of proton power at 120 GeV, limited by losses at transition crossing early in the acceleration ramp.

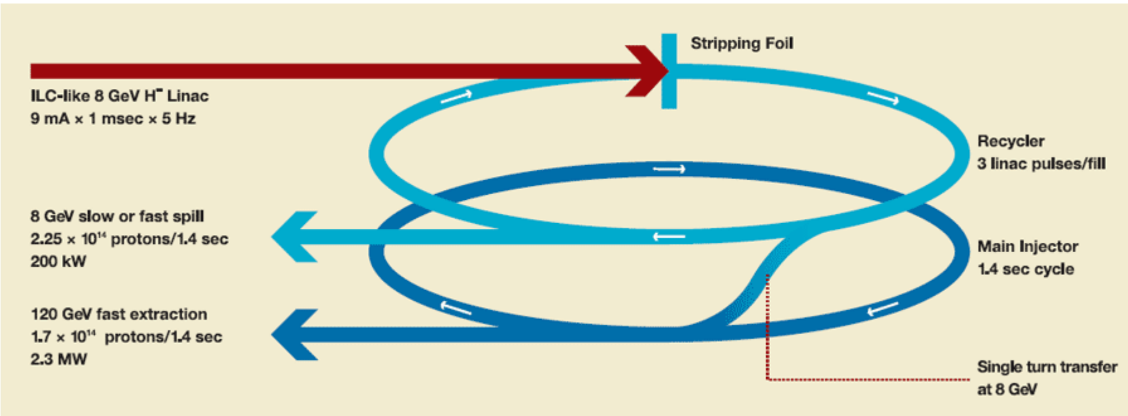

Figure 2 shows the original Project X parameters, where the linac current and pulse length are identical to the ILC. Three linac pulses are needed to fill the Main Injector, and in the meantime the beam is stored in the Recycler.

3.1 The original Project X concept

A central part of the original Project X concept[10] was the idea of maximizing ILC synergy. The high energy part of the linac was therefore conceived as being essentially identical to the ILC, with some modifications in the early part to allow for stronger focusing and longer transit time needed for protons. The design gradient was however set significantly lower than in the ILC, with the idea that Project X could use cryomodules produced while perfecting the ILC cavity production. The low energy part of the linac (below 600MeV) was based on the technology developed within the High Intensity Neutrino Source, an R&D program already established at the lab.

The synergy with the ILC implied using the same linac parameters in terms of current, pulse length, and rep rate, albeit for protons instead of electrons. However, the ILC beam parameters are not sufficient to fill the Main Injector in a single pulse. Therefore, the fixed-energy Recycler would be used as an intermediate 8GeV storage ring.

Accelerating protons in the form of H- and injecting them into the Recycler through a stripping foil allows for an arbitrary phase space density to be created. In this way, collective effects such as space charge can be minimized. Nevertheless, for a few tenths of a second, the intensity in the Recycler would exceed the design value by an order of magnitude. During this time, instabilities would be suppressed with an active damper.

To handle the increased intensity, the main injector would also need to be upgraded. This would include a new dual frequency RF system with lower impedance cavities, a large gamma-transition jump scheme to minimize losses at transition as well as both longitudinal and transverse dampers.

Studies have shown that the NUMI beamline may be upgraded to cope with beam power of up to 2MW[11], although a new beamline would likely be built and directed to DUSEL. Neither the NUMI upgrade nor the DUSEL beamline are formally part of Project X. Instead, they are considered as separate projects, along with the associated detectors.

The main injector ramp to 120GeV and back takes 1.4s. Only three of the seven linac pulses available during this time would be required to fill the Main Injector. The remainder could be used for a 8GeV Physics program, supplying up to 200kW. This could be either slow-spilled directly from the Recycler, or transferred to e.g. a modified Debuncher, as is foreseen for the mu2e experiment.
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3.2 Evolution of Project X

With any decision on the ILC now officially being contingent on the first LHC results, the ILC synergy in the Project X design has become less important. In the meantime, several review committees have pointed out that a too close ILC alignment in the linac design may limit the future upgrade potential. Also, as mentioned above, the most recent P5 report stressed the importance of the intensity frontier, alongside the energy frontier. Therefore, the Project X requirements are now being reconsidered, with a particular focus on the upgrade potential that may be required for a neutrino factory or Muon Collider. An Initial Configuration Document is being prepared[12] based on a 1MW linac with an further upgrade potential of a factor 4-5. In this scenario, the Recycler is still used as a stripping ring, but the Main Injector can be filled with a single linac pulse (see Fig. 3). The proton power at 120GeV would still be limited to 2.3MW, but more beam would be available for an 8GeV physics program. This document will be used in the process of getting an initial funding decision (DOE “critical decision” CD-0). While the focus will remain on delivering high intensity, the details of Project X may well evolve further before a final decision is made.

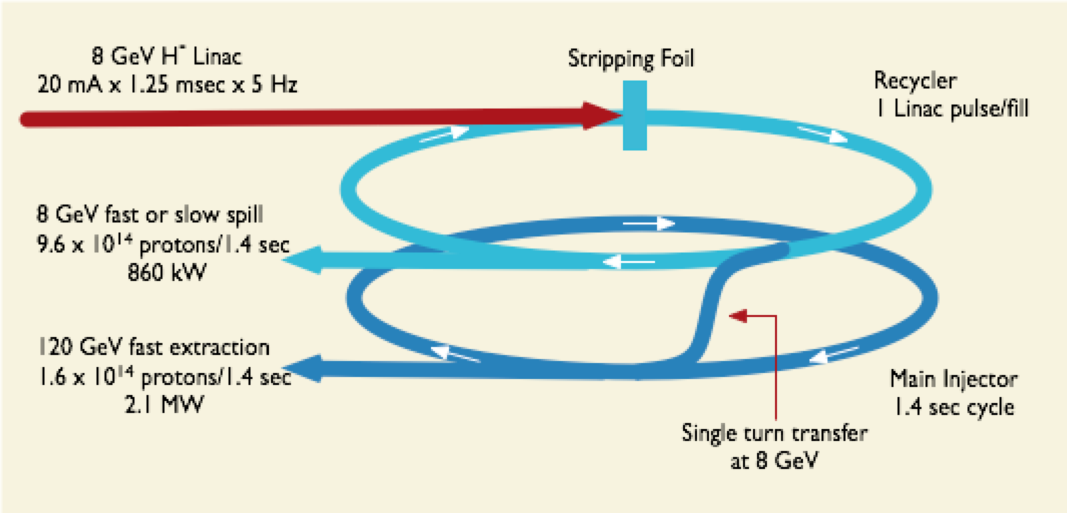

Figure 3 shows the current baseline Project X parameters, where the linac current and pulse length have been increased from the ILC values. This allows the Main Injector to be filled in a single shot, and provides more beam power at 8GeV, while the 120GeV beam power is still limited by transition crossing in the Main Injector.

4. Conclusions

Fermilab is preparing for project X on many fronts: first and foremost, by doing the machine design studies and costing exercises required in order to prepare for an initial funding decision (CD-0). An aggressive schedule has also been put in place with the aim of getting final project approval within a few years.

But one cannot only build the proton source without preparing the downstream experimental program.

The most challenging experiments to come with project X are associated with the long baseline neutrino oscillation program with a detector at the Deep Underground Science and Engineering Lab, DUSEL[13] Part of getting ready to stage an experiment in DUSEL involves understanding the costs: Fermilab has started a Water Cerenkov Costing Study to understand what it would take to build a 150kton mass detector for long baseline oscillations. This study is to be submitted for CD-0 documentation by the end of 2008. As described earlier, the MicroBooNE experiment is the next step in a staged Liquid Argon development program. There are intense beamline design studies underway as well: as the NuFact community knows well, designing a neutrino beamline that can withstand 2.3MW of protons is far from trivial and under study at Fermilab. Beamline designs to get the extinction rate needed for the muon to electron conversion experiment are also underway.

The most immediate work that Fermilab is doing to set the stage for long distance neutrino oscillation experiments is the work on the SciBooNE experiment[14] whose run will be completed in the fall of 2008, and the MINERvA experiment[15], which will be taking data starting at the end of 2009 and will run concurrently with the MINOS and

NOvA experiments. Only by understanding the detectors and the neutrinos that will interact in them can we make full use of the enormous leap in statistics that Project X can provide.

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