PROJECT X AT FERMILAB: PROSPECTS AND PLANS*

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Abstract

As the Fermilab Tevatron Collider program draws to a close, a strategy has emerged of an experimental program built around the high intensity frontier. The centerpiece of this program will be a new 8 GeV superconducting H^- linac that will support world leading programs in long baseline neutrino experimentation and the study of rare processes. Based on technology shared with the International Linear Collider, Project X will provide multi-MW beams at 60-120 GeV from the Main Injector, simultaneous with several hundred kilowatt beams at 8 GeV. Project X will support the possibility of a future energy frontier facility based its utilization as the front end of a muon storage ring based facility.

STRATEGIC CONTEXT

Fermilab currently operates both the highest energy particle collider, the Tevatron, and the highest power accelerator generated neutrino beam in the world. This situation will change in 2009 when the Large Hadron Collider (LHC) at CERN in Geneva, Switzerland will initiate operations at five-seven times the energy of the Tevatron, and the J-PARC facility in Tokai, Japan, will initiate a long baseline neutrino program that will provide strong competition to the Fermilab program. In anticipation of these developments the U.S. elementary particle physics (EPP) community has adopted a strategic plan for the U.S. over the coming decade emphasizing forefront research on three frontiers: the energy frontier, the intensity frontier, and the cosmic frontier [1]. This strategy includes both accelerator and non-accelerator based initiatives on these three frontiers, and initiatives based both in the U.S. and abroad. The strategy recognizes that over the coming decade Fermilab will be the sole site for accelerator-based EPP in the U.S. The Fermilab strategy [2] is fully aligned with the U.S. plan, and features the development of a multi-Megawatt proton source as the centerpiece of the long term U.S. strategy for domestic facilities at the energy and intensity frontiers.

Role of Project X

Project X is the name applied to a multi-MW proton source, to be constructed at Fermilab, based on a superconducting H^- linac and reutilization of portions of the existing proton accelerator complex. Project X is the lynchpin of Fermilab's strategy for future development of the accelerator complex. The strategy retains the possibility for the siting at Fermilab of a future energy frontier facility, including the International Linear Collider (ILC) or a Muon Collider, through aligned technology development.

On the intensity frontier Project X provides a natural evolutionary path sustaining world leading capabilities over the next several decades, starting with the current long baseline neutrino program, extending through the development of a very long baseline (>1000 km) facility, the development of a low energy (<10 GeV) program probing beyond-the-Standard-Model phenomena (such as muon to electron conversion), and retaining the possibility of construction of a muon-storage-ring-based Neutrino Factory on the Fermilab site.

PROJECT X GOALS AND CONFIGURATION

The P5 Report [1] defines the performance requirements for a multi-MW proton facility supporting the U.S. strategy over the coming decade(s):

- A neutrino beam for long baseline neutrino oscillation experiments based on a proton source capable of delivering at least 2 MW of beam power at any energy over the range 60-120 GeV;
- High intensity 8 GeV protons supporting muon and kaon precision experiments, <u>simultaneous with the neutrino program</u>; and
- A path toward a muon source for a possible future Neutrino Factory or Muon Collider. This requires that the initial facility retain the potential for upgrading to 2-4 MW at 8 GeV.

Project X Initial Configuration

Based on the P5 requirements we have established three high level design criteria for Project X:

- 2 MW of beam power available over the range 60-120 GeV;
- Simultaneous operations with at least 150 kW of beam power available at 8 GeV;
- Compatibility with future upgrades to 2-4 MW at 8 GeV.

An initial configuration that meets these requirements is indicated schematically in Figure 1 and the associated high level operational performance parameters in Table 1. This particular parameter set corresponds to Main Injector operation at 120 GeV.

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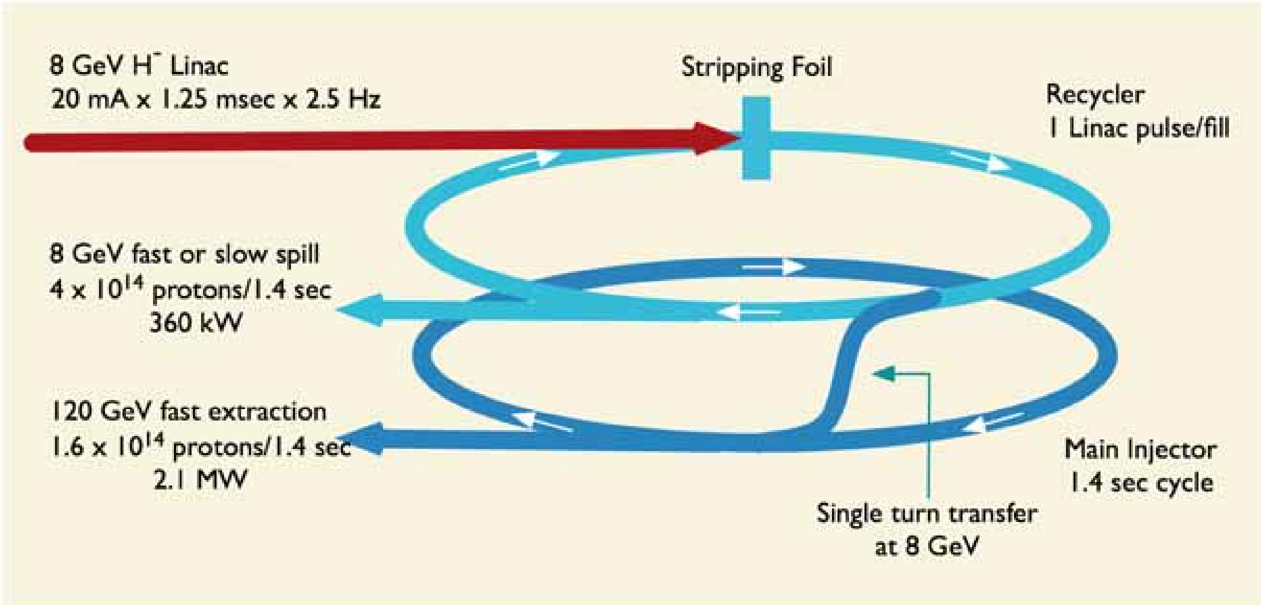

Figure 1: Project X Initial Configuration.

Table 1: Project X Initial Configuration Parameters

Linac		
Particle Type	H^-	
Kinetic Energy	8.0	GeV
Particles per Pulse	1.6×10^{14}	
Pulse Rate	2.5	Hz
Beam Power	500	kW
Recycler		
Particle Type	protons	
Kinetic Energy	8	GeV
Cycle Time	1.4	sec
Particle per Pulse to MI	1.6×10^{14}	
Particles per Pulse to 8 GeV	1.6×10^{14}	
Beam Power to 8 GeV	360	kW
Main Injector		
Kinetic Energy (maximum)	120	GeV
Cycle Time	1.4	sec
Particles per Pulse	1.6×10^{14}	
Beam Power to 120 GeV	2100	kW

The Project X initial configuration [3] is comprised of an 8 GeV superconducting H^- linac, paired with the existing (but modified) Recycler and Main Injector accelerators. The linac operates at 325 MHz up to 420 MeV and at 1.3 GHz beyond, utilizing ILC-like accelerating structures beyond 1.3 GeV. A total of 1.6×10^{14} H^- ions are delivered per pulse at 2.5 Hz, corresponding to a total available beam power at 8 GeV of 0.5 MW. The H^- ions are stripped at injection into the Recycler in a manner that "paints" the beam both transversely and longitudinally to reduce space charge forces. Following the 1.25 ms (~100 turns) injection, the proton beam is moved off the stripping foil and is transferred in a single turn into the Main Injector. These protons are then accelerated to 120 GeV and fast extracted to a neutrino target. The 120 GeV Main Injector cycle is 1.4 seconds, producing 2.1 MW of beam power. Since loading the Main Injector requires only one linac beam pulse, the remaining linac cycles (five for each two 1.4 sec MI cycles) are available for distribution of 8 GeV protons from the Recycler. Total available 8 GeV beam power is 360 kW and can in principle be maintained above 150 kW with Main Injector operations at ~2 MW for energies anywhere within the range 60-120 GeV.

Modifications to the Recycler Ring to support Project X include integration of an H^- injection system, a new RF system, a new extraction system, and measures to mitigate electron cloud effects. The Main Injector will require a new RF system, measures to preserve beam stability through transition, and measures to mitigate electron cloud effects.

The upgrade path to a high intensity beam supporting a possible future Neutrino Factory or a Muon Collider is an increase in the repetition rate: 20 Hz operations at the pulse characteristics shown would result in 4 MW of beam power at 8 GeV. The linac hardware, conventional facilities, cryogenic plant, and utilities will be designed to accommodate these upgrades.

At proton energies lower than 120 GeV the Main Injector cycle times can be shortened to maintain beam power above 2 MW at energies throughout the range 60-120 GeV. Figure 2 displays the operating scenario for 64 GeV operations of the Main Injector in parallel with 8 GeV operations for a planned muon to electron (mu2e) conversion experiment based on a slow spill beam extracted from the existing, but modified, Antiproton Source facility. The base cycle time in this scenario is 0.8 seconds. Over this period one linac pulse is delivered via the Recycler to the Main Injector for acceleration to 64 GeV, while the second pulse is delivered in 67 msec increments to the reconfigured Antiproton Source complex for extraction to a mu2e experiment. For this particular utilization the linac beam intensity on the second pulse is limited to 8.5×10^{13} because of space-charge limitations in the Antiproton Source. While this limitation may or may not persist into the future, it does provide a motivation for designing the Project X linac in a manner that supports variable pulse intensities and variable chopping patterns. At total of 136 kW is available for the 8 GeV mu2e program in parallel with 2120 kW to the neutrino program at 64 GeV in this scenario.

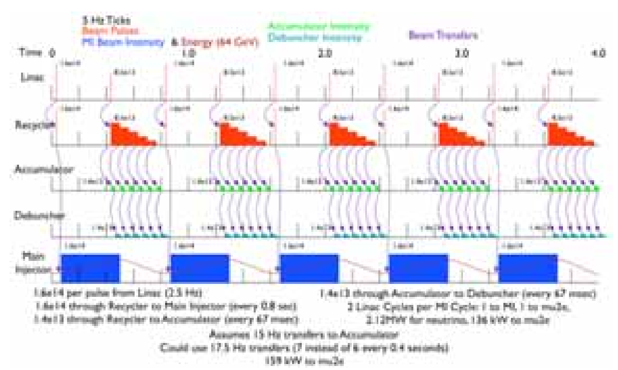

Figure 2: Operating scenario for 64 GeV from the Main Injector.

Site Layout

The provisionally identified layout of Project X on the Fermilab site is shown in Figure 3. The linac has a total length of roughly 700 m and would reside on the Tevatron infield. It is connected to the Recycler via a beam transport line of roughly 1100 m in length. The beam transport line connects to the Recycler at the injection point that will be operable at the time of construction. The long beam transport is required to provide effective momentum collimation while meeting constraints on the magnetic field in bend and focusing elements that assure the H^- is not prematurely stripped.

RESEARCH DESIGN AND DEVELOPMENT PLAN

A Research, Design, and Development (RD&D) Plan has been created [4] to support a fully developed baseline scope, cost estimate, and schedule in 2012. The plan includes both design activities and technical component development and prototyping. The Project X RD&D Plan is also closely coordinated with the ILC, Neutrino Factory, and Muon Collider programs.

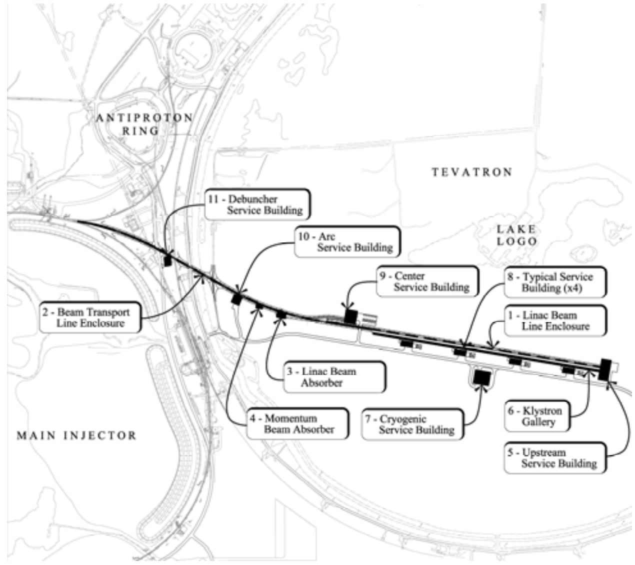

Figure 3: Project X provisional siting.

Technology Requirements

Project X requires the application of advanced technologies throughout the linac, the Recycler and the Main Injector. These technologies share many requirements with other high power proton and heavy ion sources, and with the ILC. A "technology map" of the Project X linac is given in Figure 4. Among the more significant requirements on the technologies are:

325 MHz Linac

- Peak/average current 32/20 mA, 1.25 msec pulse width, 2.5 Hz repetition rate
- High speed chopping at 325 MHz
- Variable chopping patterns
- Loss control and mitigation
- RF control of multiple accelerating structures

1.3 GHz Linac

- Peak/average current 32/20 mA, 1.25 msec pulse width, 2.5 Hz repetition rate
- 25 MV/m accelerating gradient
- 500 kW coupler capability
- Loss control and mitigation
- RF control of multiple accelerating structures

Beam Transfer Line and Injection

- Beam transport without stripping (requiring a cryogenically cooled vacuum chamber)
- Loss control and mitigation
- Foil lifetime
- Injection painting

Recycler/Main Injector

- Space-charge effects
- E-cloud effects
- Beam instabilities
- Loss control and mitigation

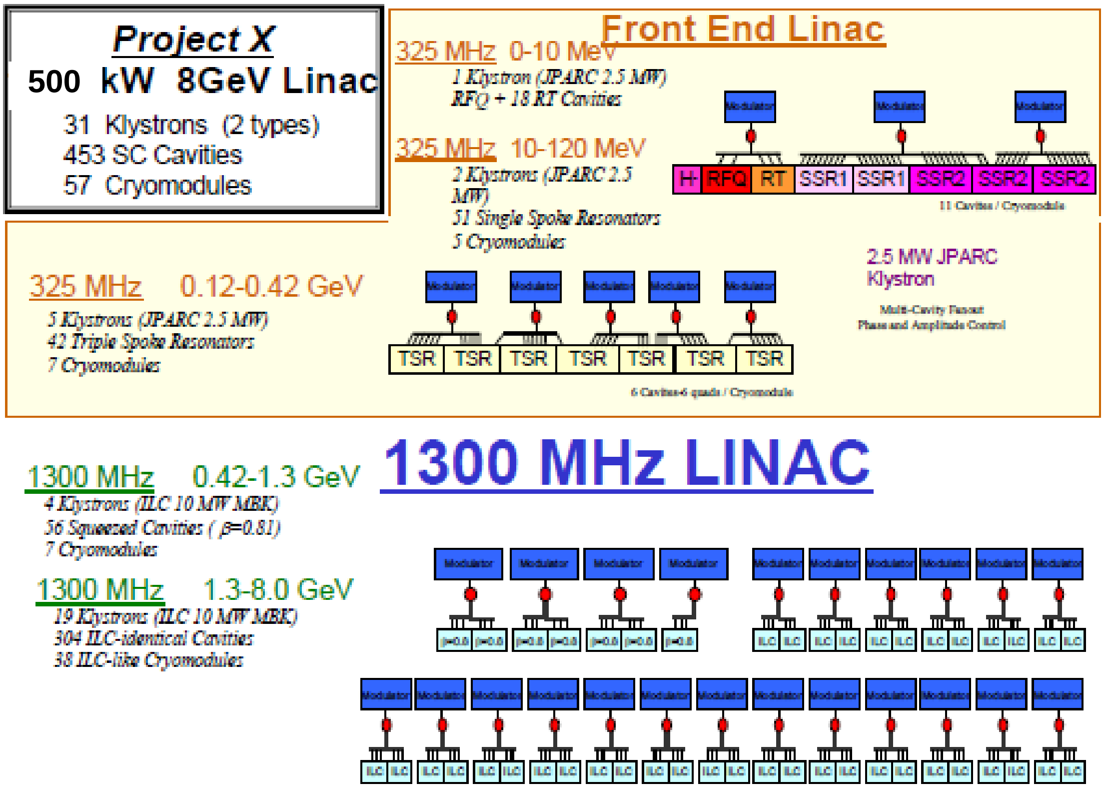

Figure 4: Technology deployment through the Project X linac.

Current Status

The Initial Configuration Document and RD&D Plan are both living documents, with the currently active versions available on the Project X website [5]. A preliminary cost estimate has been completed based on the ICD v1.1, and was subject to a review in March 2009. The multi-institutional collaboration to conduct the RD&D phase is in the process of being formed and work has been initiated on several fronts.

Alternative Design Concepts

Consideration of alternative designs for the Project X facility is required by the DOE Project Management Order. Initial thinking has begun and the primary alternative currently under consideration is a 2 GeV linac, upgradable to 4 GeV, and an 8 GeV rapid cycling synchrotron, upgradable to 21 GeV. The linac would be identical to the first 2 GeV of the linac described in the ICD. Other variations could include a CW front end linac or a more traditional utilization of room temperature technology through the first ~100 MeV of the linac. Alternative configurations will be documented via an Alternative Configuration Document (ACD) and an associated preliminary cost estimate. The ACD and associated cost estimate(s) will be prepared using the same methodologies and design team as the ICD.

TECHNOLOGY DEVELOPMENT AND RELATIONSHIP TO OTHER PROGRAMS

Project X shares significant technology overlap with both the ILC [6] and with muon-storage-ring-based facilities. As indicated in Figure 4 a total of 38 ILC-like cryomodules are required for Project X. However, in detail these cryomodules will not be identical to ILC: The total charge per pulse is three times that of ILC while the repetition rate is half; the increased beam current will require a higher power coupler and an "rf unit" will consist of two, rather than three, cryomodules; because the beam is not completely relativistic a focusing element is required in each cryomodule; and a gradient of 25 MV/m is called for in the Project X initial configuration. The strategy for development of the Project X 1.3 GHz cryomodules is closely coordinated with the ILC/GDE during the development phase. The notion of "plug compatibility", developed by the ILC/GDE as a strategy for coordination of the worldwide ILC development program, has been adopted by Project X—all interface dimensions within the Project X cryomodules adhere to

ILC standards. This approach allows a joint ILC/Project X development program utilizing shared facilities for component assembly and testing, and a common beam testing facility at the ILC Test Accelerator (ILCTA) at Fermilab.

Project X also shares many features in common with the proton driver required for a Neutrino Factory or Muon Collider [7]. These facilities require approximately 4 MW of beam power delivered onto a production target at an energy between 5-15 GeV. Project X will be designed with such an upgrade in mind. Current thinking is that the most straightforward path would be an increase of the repetition rate to 20 Hz. Such a path retains all peak power levels in the linac rf systems, but requires higher average power capabilities. The goal of the Project X design will be to support such an upgrade path without having to replace the cryomodules or associated infrastructure within the linac enclosure. Both the Neutrino Factory and the Muon Collider require a bunch structure on target that varies significantly from what is delivered from the Project X linac. In general the requirement is to consolidate all beam in a small number of short bunches. It is inevitable that this requirement will only be met through the construction of an additional ring, or rings, to perform the bunch consolidation and compression functions. Such a ring, or rings, is not anticipated to be part of the Project X construction phase, however consideration of such requirements will be reflected in the Project X siting.

SUMMARY

Project X is central to Fermilab's strategy for future development of the accelerator complex. Project X will support a world leading program in neutrinos and other rare processes over the coming decades, and will be constructed in a manner that could provide a stepping stone to muon-based facilities – either a Neutrino Factory or a Muon Collider. The technology development of the high energy linac is aligned with technology development for the ILC, preserving the opportunity for either construction of the ILC at Fermilab, or strong participation if the ILC were built elsewhere.

An initial Project X configuration has been established that meets the requirements as contained in the U.S. strategic plan for elementary particle physics, most notably >2 MW of available beam power at any energy over the range 60-120 GeV, simultaneous with >150 kW of beam power available at 8 GeV. The facility could be constructed over a five year period starting in ~2014, given the requisite approvals and funding. The Project X R&D effort integrates effort on ILC and Muon Facilities, and the initial configuration can be upgrade to 2-4 MW operation at 8 GeV. A collaboration is being formed to undertake the development of Project X.

REFERENCES

[1] Particle Physics Project Prioritization Panel, "U.S. Particle Physics: Scientific Opportunities, A Strategic Plan for the Next Ten Years", May 2008, http://www.science.doe.gov/hep/files/pdfs/P5_Report%2006022008.pdf

[2] Fermilab Steering Group Report, September 2007, http://www.fnal.gov/pub/directorate/steering/index.shtml

[3] Project X Initial Configuration Document, March 2009, http://projectx-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=83&extension=pdf

[4] Project X Research, Design, and Development Plan, March, 2009, http://projectx-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=149&extension=pdf

[5] Project X website, http://projectx.fnal.gov/

[6] International Linear Collider Reference Design Report, August, 2007, http://www.linearcollider.org/cms/?pid=1000437

[7] International Scoping Study of a Future Neutrino Factory and Super-beam Facility, September 2006, http://www.hep.ph.ic.ac.uk/iss/