Project X: Accelerator Overview

The Strategic Context and Fermilab's Future

For many years Fermilab has operated both the highest-energy particle collider and the highest-intensity accelerator-based neutrino beam in the world. Now the LHC has surpassed the Tevatron in energy and Japan's J-PARC facility is embarking on a long-baseline neutrino program in strong competition with the Fermilab program. Within this international context, the US high energy physics community has adopted a strategic plan for the coming decades that emphasizes research on three frontiers: the Energy Frontier, the Intensity Frontier and the Cosmic Frontier. The plan recognizes that for the foreseeable future Fermilab will be the sole US site for accelerator-based particle physics research. Fermilab's strategy is fully aligned with the US plan. This plan features the development of a high-intensity proton facility, denoted Project X, that will support a world-leading Intensity Frontier Program at Fermilab over several decades while laying the groundwork for eventual construction of a Neutrino Factory or Muon Collider at the Energy Frontier.

Evolution of the Fermilab Accelerator Complex

Project X is a multi-MW proton accelerator facility proposed for construction at Fermilab and is an integral part of the 2011 Fermilab Strategic Plan (A Plan for Discovery, https://www.fnal.gov/directorate/plan_for_discovery/). Project X forms the platform for future development of the Fermilab accelerator complex. Project X utilizes an H- linear accelerator based on superconducting rf technologies to provide long-term opportunities at both the Intensity and Energy frontiers. Project X will support a diverse Intensity Frontier program, creating opportunities for long-term world-leading programs in neutrino physics and other beyond-the-standard-model phenomena. The technology for Project X also opens opportunities beyond traditional particle physics applications, for example in cold-neutron physics and accelerator-driven subcritical systems (ADS) for energy generation and the transmutation of waste. The development of Project X builds on the significant investment in technologies required for the proposed International Linear Collider, preserving Fermilab's capability to serve as a major contributor to such a possible future accelerator. The development of a multi-MW proton facility will also provide the basis for a future Muon Collider or Neutrino Factory.

Project X Mission Goals and Reference Design

The design of Project X is based on four mission elements derived from the High Energy Physics Advisory Panel's P5 report on the future of US particle physics:

1. Long-baseline neutrino experiments: Provide in excess of 2 MW of proton beam power onto a neutrino production target at any energy between 60 – 120 GeV.
2. Rare processes experiments: Provide MW-class, multi-GeV, proton beams supporting multiple precision experiments with kaons, muons, and neutrinos simultaneous with the long-baseline neutrino program.
3. Muon facilities: Provide a path toward a muon source for a possible future Neutrino Factory and/or a Muon Collider.
4. Nuclei and nuclear energy: Provide opportunities for implementing a program of Standard Model test with nuclei, ultra-cold neutrons, and nuclear energy applications.

The development of a design concept for a high intensity proton facility has gone through several iterations. These iterations have culminated in a concept, designated the Project X Reference Design, that supports the mission elements listed above in an innovative and flexible manner. The Reference Design is based on a 3 GeV superconducting CW linac, a superconducting pulsed linac for acceleration from 3-8 GeV, modifications to the existing Recycler and Main Injector Rings at Fermilab, and development of an initial 3 GeV experimental facility. The 3 GeV linac operates at an average current of 1 mA, providing up to 3 MW of beam power to the rare processes and nuclear programs. The utilization of a pulsed linac for acceleration from 3-8 GeV provides input to the Main Injector complex in support of the long baseline neutrino program while additionally providing a platform for future programs of interest to the US high energy physics community, in particular future muon based facilities. A unique feature of the Reference Design is the utilization of a wideband chopper in the linac front end, paired with a transverse splitter at 3 GeV. This configuration allows delivery of variable bunch patterns to multiple experiments simultaneously.

The Reference Design provides a facility that will be unique in the world with unmatched capabilities for the simultaneous delivery of very high beam power with flexible beam formats to multiple users. These capabilities lie beyond what is believed to be achievable with synchrotron based facilities, and are beyond any facility either operational or under design in the world today.

R&D Program

An intensive R&D program is underway to validate the design choices made in support of the Project X facility design, and to establish fabrication method for major sub-systems and components. The primary elements of the R&D program include:

- Development of a wide-band chopper, capable of removing bunches in arbitrary patterns at 162.5 MHz, and demonstration of these capabilities in an integrated systems test;
- Development of superconducting radiofrequency acceleration modules at four different frequencies (162.5, 325, 650, 1300 MHz);
- Development of cost effective rf systems for each of four different frequencies and with duty factors ranging from 5% to 100%;
- Development of instrumentation;
- Development of an H- injection system, capable of injecting pulses of duration 4.4 – 26 msec into the Recycler;
- Development of room temperature radiofrequency acceleration systems for utilization in the Main Injector;
- Development of mitigation strategies for electron cloud effects in the Main Injector.

Project X Collaboration

A national collaboration with international partners has formed to develop Project X. The national collaboration comprises Argonne National Laboratory, Brookhaven National Laboratory, Cornell University, Fermilab, Lawrence Berkeley National Laboratory, Michigan State University, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, Thomas Jefferson National Accelerator Facility, SLAC National Accelerator Laboratory, and the Americas Regional Team of the ILC Global Design Effort.

Additionally, Fermilab has formed a collaboration with four Indian Institutions for the development of the Project X design and associated technologies. The Fermilab-Indian collaboration comprises the Bhabha Atomic Research Center (Mumbai), Inter-University Accelerator Center (New Delhi), Raja Ramanna Center for Advanced Technology (Indore), and Variable Energy Cyclotron Center (Kolkata).

Staging

Financial and budgetary constraints have led to consideration of a staged approach to Project X. Development of a staging plan for Project X is based on application of the following principles:

- Each stage should have a cost significantly below $1B.
- Each stage should present compelling physics opportunities.
- Each stage should utilize existing elements of the Fermilab complex to the extent possible.
- At the completion of the final stage the full vision of a world leading intensity frontier program at Fermilab should be realized.

A three stage approach to the Reference Design consistent with the above principles has been developed and is described below.

Stage 1

Stage 1 of Project X comprises a newly constructed 1 GeV superconducting linac injecting directly into the existing Booster. A pulsed linac configuration (~10% duty factor) could provide substantially improved performance within the Main Injector and Mu2e programs, while also providing a platform for the latter stages leading to the Reference Design. Injection into the Booster at 1 GeV is projected to result in a 50% increase in the per pulse proton intensity delivered to the Main Injector complex, relative to current operations. Stage 1 thus establishes the potential for delivering up to 1200 kW onto a long baseline neutrino target (either NuMI or LBNE). Depending upon the operating energy of the Main Injector and the allocation of the Main Injector timeline between neutrino production and a possible rare kaon experiment, significant power could also be devoted to a program based on 8 GeV protons. The balance of available linac beam can be delivered to the Muon Campus currently under development, providing a factor of ten increase in beam power available to the Mu2e experiment. A modest enhancement (10-15% of the Stage 1 cost) of the linac to enable CW operations at 1 mA average current supports newly developed experimental programs devoted to nuclear electric dipole moments (edm), ultra-cold neutrons, and possibly nuclear energy applications.

An additional substantial benefit of Stage 1 is that the existing 400 MeV linac will be retired from service, removing a substantial operational risk within the Fermilab proton complex.

Stage 1 provides simultaneously: 1.2/0.9 MW of beam power at 120 /60 GeV, 40 kW at 8 GeV, and 1.0 MW at 1 GeV.

Stage 2

Stage 2 is based on extension of the CW linac to 3 GeV, still with an average current of 1 mA. Stage 2 provides 3 MW of beam power at 3 GeV, with the capability of delivering flexible beam formats to multiple experiments. It is anticipated that a Main Injector based kaon experiment

would be relocated to the 3 GeV linac in Stage 2. Also accommodated are a number of muon and nuclei based experiments. Injection into the Booster at 1 GeV will be retained, as will the available beam power at 1 GeV.

To support the Stage 2 performance the initial 1 GeV of the linac will be upgraded to 2 mA capability, with 1 mA available at 1 GeV and 1 mA transmitted into the 1-3 GeV linac section. In addition the Booster will be upgraded to 20 Hz capability.

Stage 2 provides simultaneously: 1.2/1.2 MW of beam power at 120 /60 GeV, 80 kW at 8 GeV, 3 MW at 3 GeV, and 1.0 MW at 1 GeV.

Stage 3

Stage 3 completes the Reference Design via construction of a pulsed linac for acceleration of beam from 3 GeV to 8 Gev. This beam is delivered to the Recycler/Main Injector complex in support of the long baseline neutrino program. At Stage 3 more than 2MW of beam power is available at any energy between 60-120 GeV. Upgrades to the Recycler/Main Injector are required to support the increased beam power. Enhanced capability for delivery of 8 GeV beam, directly from the pulsed linac, is also created at this Stage. Beam capabilities at 1 and 3 GeV remain as in Stage 2.

In addition, with the completion of Stage 3 the existing 8 GeV Booster can be retired from service, taking the second substantial operating risk in the current program along with it.

Stage 3 provides simultaneously: 2.4/2.4 MW of beam power at 120 /60 GeV, 170 kW at 8 GeV, 2.9 MW at 3 GeV. and 1.0 MW at 1 GeV.

Stage 4

Stage 4 is an upgrade to the Reference Design based on an increase in the current and duty factor of the pulsed linac. Stage 4 is primarily aimed at providing a 4 MW capability at 8 GeV, as required for a Neutrino Factory or Muon Collider. However, the beam power produced could also be utilized in support of an 8 GeV neutrino program. Stage 4 has the secondary impact of providing sufficient beam to the Recycler/Main Injector complex to support 4 MW operations at 60-120 GeV, contingent upon appropriate upgrades to those accelerators and the LBNE target station. Note that Stage 4 requires very significant R&D outside the scope of the current Project X program.

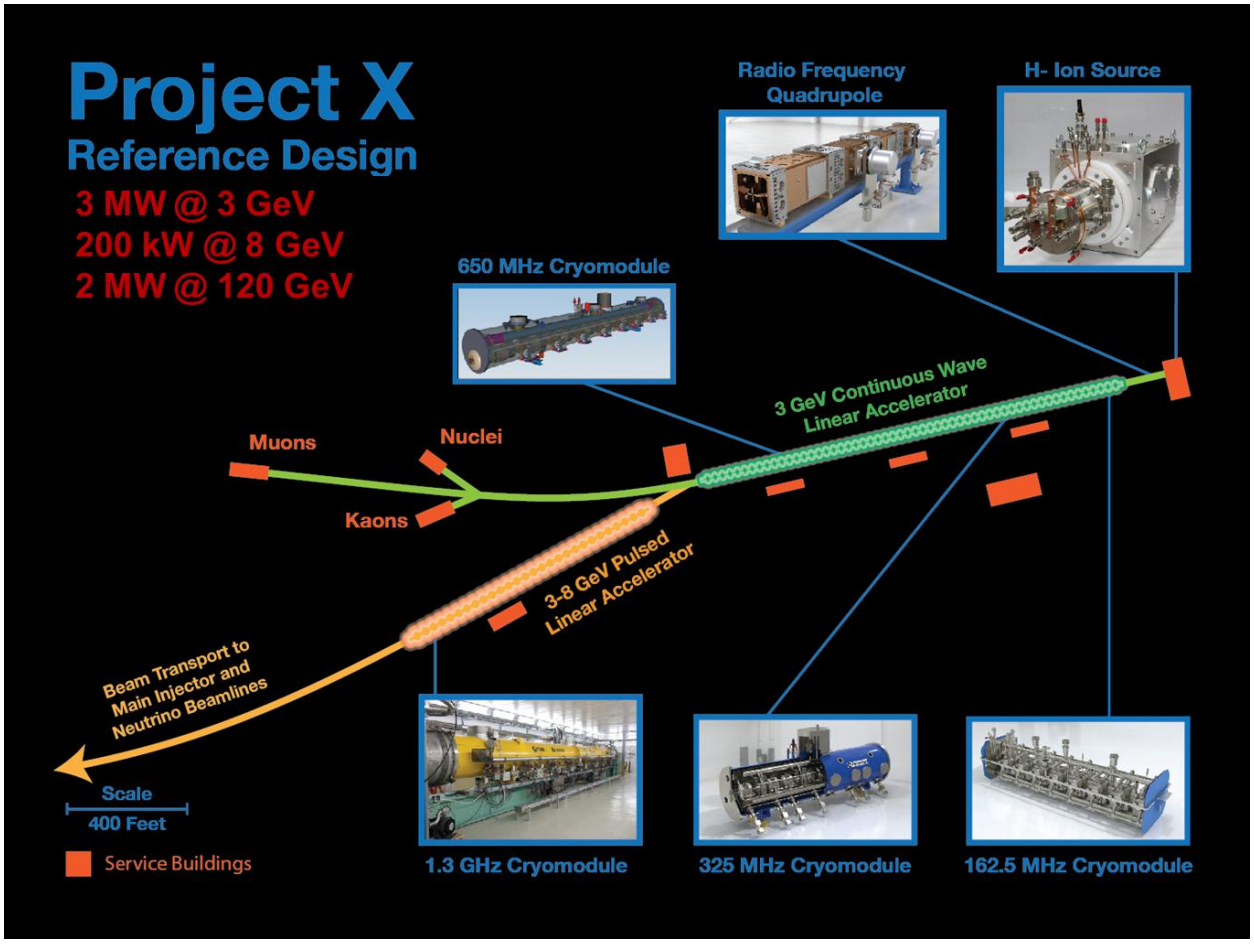
Construction

The earliest start date for Project X construction as communicated to Fermilab by the Department of Energy is FY2017. Project X could be constructed over a five year period if sufficient funds were available; however, the staging approach would result in a more extended implementation with construction interleaved with operations in support of the physics research programs.

Other Applications

The technologies required for Project X have broad potential applications in areas beyond research in elementary particle physics, including:

- Rare isotope production for nuclear physics
- Neutron sources
- Accelerator-driven energy systems
- X-ray FELs
- Energy recovery linacs
- Muon facilities for materials research



Project X, a high-power proton facility, will support world-leading programs in long-baseline neutrino physics and the physics of rare processes. It will be unique among accelerator facilities worldwide in its flexibility to support multiple physics programs at the intensity frontier. Project X is based on a 3 GeV continuous-wave superconducting H- linac. Further acceleration to 8 GeV, injected into Fermilab's existing Recycler/Main Injector complex, will support long-baseline neutrino experiments. Project X will provide 3 MW of total beam power to the 3 GeV program, simultaneously with 2 MW to a neutrino production target at 60-120 GeV. A multi-laboratory collaboration with international participation has undertaken the development of Project X.