Project X Accelerator Facility
Supporting Document

Project X is a high intensity proton facility that will support a world-leading program of Intensity Frontier physics over the next several decades at Fermilab. The capabilities of Project X go well beyond other facilities in the planning stages elsewhere in the world. In particular Project X is completely unique in its ability to deliver, simultaneously, up to 6 MW of site-wide beam power to multiple experiments, at multiple energies, and with flexible beam formats. Project X will support a wide range of experiments based on neutrinos, muons, kaons, nucleons, and nuclei. In addition, Project X will lay the foundation for the long-term development of a Neutrino Factory and/or Muon Collider.

Reference Design Capabilities

A complete concept for Project X has been developed and is documented in the Project X Reference Design Report (Project X RDR). The major components of Project X are:

- A 3 GeV Continuous Wave (CW) superconducting H^- linac with 1 mA average beam current.
  The CW linac accelerates 2 mA to 1 GeV and 1 mA to 3 GeV. The linac includes flexible provision for variable beam structures delivered to multiple users simultaneously. The CW linac directly supports the muon, kaon, nucleons, and nuclei programs at 1 and 3 GeV, and supplies beam to the pulsed linac.

- A 3-8 GeV superconducting pulsed linac accelerating a peak current of 1 mA with a 4.4% duty factor.
  The CW linac provides beams to the Main Injector/Recycler complex in support of the long baseline neutrino program. In addition the pulsed linac established a path toward a future Neutrino Factory or Muon Collider

- Upgrades to the Recycler and Main Injector to support 2 MW of beam power.
  H^- beams from the pulsed linac are accumulated in the Recycler, and then transferred and accelerated in the Main Injector. The Main Injector provides ≥ 2 MW to the long baseline neutrino program at energies between 60-120 GeV.

The capabilities associated with these three major facility components are summarized below.

CW Linac		
Particle Type	H^-	
Beam Kinetic Energy	3	GeV
Average Beam Current	1	mA
Linac Pulse Rate	CW	
Beam Power to 1 GeV Program	1	MW
Beam power to 3 GeV Program	2.87	MW
Pulsed Linac		
Particle Type	H^-	
Beam Kinetic Energy	8	GeV
Average Beam Current	1	mA
Linac Pulse Rate	10	Hz
Linac Pulse Width	4.4	msec
Cycles to Recycler/Main Injector	6	
Total Beam Power at 8 GeV	0.35	MW
Beam Power to 8 GeV Program*	0.17	MW
Main Injector		
Particle Type	p	
Beam Kinetic Energy	60-120	GeV
Cycle Time	0.6-1.2	sec
Beam Power	2.4	MW

* Beam power available for an 8 GeV experimental program with simultaneous operations of the Main Injector at 120 GeV. For Main Injector operations at 60 GeV the beam power available for an 8 GeV program is reduced to 0.

Operating Scenarios

Utilization of a CW linac to support the low energy programs creates a facility that is unique in the world, with performance that cannot be matched in synchrotron-based or cyclotron-based facilities. The CW linac is capable of providing, simultaneously, high duty factor proton beams to the materials/nuclei program at 1 GeV and to the precision experiments program at 3 GeV, and low duty factor beams to the 3-8 GeV pulsed linac. The capabilities by program are summarized below.

Program	Proton Beam Energy (GeV)	Train Frequency (MHz)	Pulse Width (nanoseconds)	Beam Power (MW)
Neutrinos	60-120	1×10^{-6}	9000	Up to 2.3 MW
Kaon Decays	3	20-30	0.1-0.2	Up to 1.5 MW
Muon Conversion	1-3	1-2	<100	Up to 750 kW

Nuclei/Neutrons	1-3	10-20	0.1-0.2	Up to 1 MW
Materials/Energy	1	10-20	0.1-0.2	Up to 1 MW

The CW linac macroscopic timeline is shown in Figure 1. There are two relevant timeline intervals: (1) the 4.4-msec long time interval associated with the 10 Hz injection rate to the pulsed linac; and (2) the ~95-msec long time interval associated with the 1 and 3 GeV experimental program. The beam is directed into the pulsed linac by a pulsed dipole with a rise time of 0.5 msec, with beam from the linac interrupted during these periods.

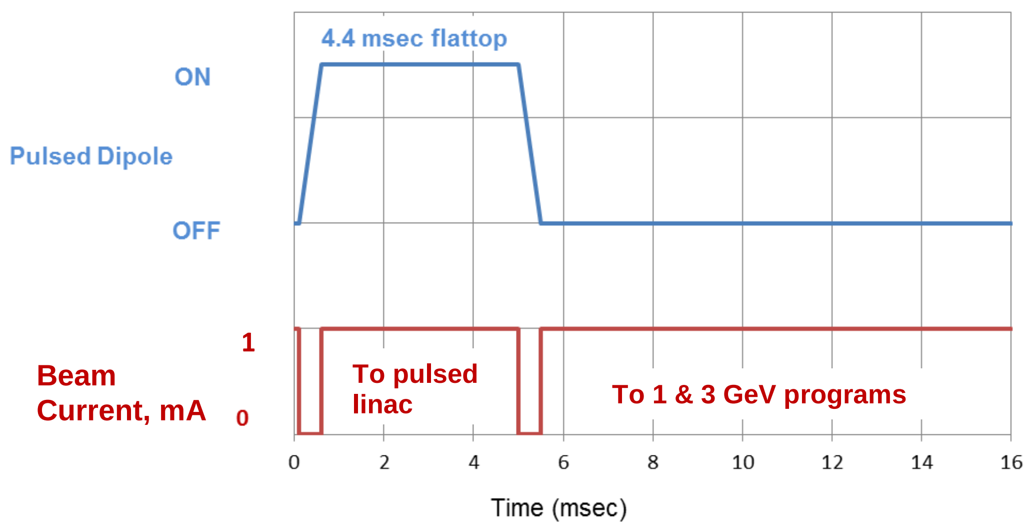

Figure 1: Schematic timeline for linac beam current (first 16 ms of the 100 ms cycle). The pulsed magnet's rise and fall time is 0.5 ms.

Beams to the 1 and 3 GeV programs are provided via radio-frequency (rf) separators, a technique pioneered and perfected at TJNAF. The CW beam is delivered to four experimental facilities simultaneously by selectively filling appropriate rf buckets (with 6 nsec spacing) at the front end of the linac and then separating them for delivery to four different target halls[1]. The selective filling of buckets in order to provide different bunch patterns to different experiments breaks new ground, and is an essential element in the unique capabilities of Project X. Several front end subsystems are employed to provide this capability. Details remain beyond the domain of this document, but here we briefly describe the essence of this capability.

[1] In this document we consider one end user at 1 GeV and three at 3 GeV. However the number of users can be increased, as required, by the serial installation of additional RF separators.

A “wide-band” chopper is employed in the front end of Project X to selective gate bunches emanating from the Radio Frequency Quadrupole (RFQ) into the CW linac. An example of how this could work at 1 GeV is given in Figure 2. The top diagram shows the bunch pattern in the linac as created by the chopper; this pattern is de-convolved into a beam supporting the materials/energy/nuclei program (black bunches) and a beam supporting a next generation mu2e experiment (red). The individual bunch intensity is 14×10^7 with a 50 psec (FW) bunch length. The total beam power delivered is 910 kW (black) and 90 kW (red). This system is capable of being cascaded; in particular a second separator system at 3 GeV allows the support of at least three experimental programs at 3 GeV simultaneous with operations of the 1 GeV programs.

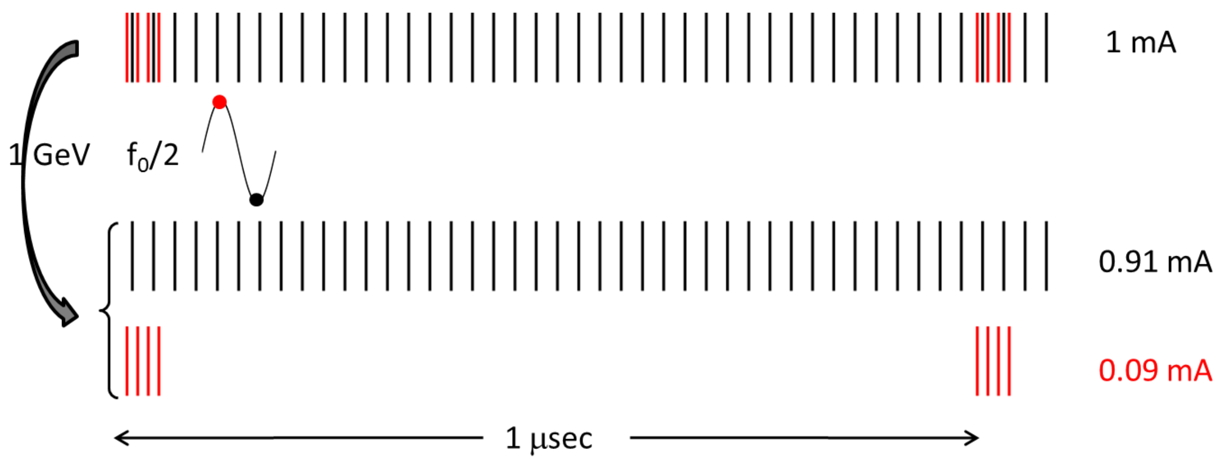

Figure 2: A 1 μsec period in the 1 GeV CW linac at Stage 1.

Staging

Financial constraints have led to development of a staged approach to Project X, based on application of the following principles:

- Each stage must present compelling physics opportunities;
- Each stage should be constructible for significantly less than $1B;
- Each stage should utilize existing elements of the Fermilab complex to the extent possible;
- Each stage should be constructible with minor interruptions to the programs supported by prior stages;
- 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 discussed with the Department of Energy. The sequence is as follows:

Stage 1: Construction of a 1 GeV CW linac operating with an average current of 1 mA, providing beams to the existing 8 GeV Booster, to the muon campus currently under construction, and to a new 1 GeV experimental facility.

Stage 2: Addition of a 1-3 GeV linac operating with an average current of 1 mA providing beam to a new 3 GeV experimental facility, and accompanied by an upgrade of the 1 GeV linac to 2 mA average current and the Booster to 20 Hz capabilities.

Stage 3: Addition of the 3-8 GeV pulsed linac, accompanied by upgrades to the Recycler and Main Injector.

The siting and configuration associated with the Project X Reference Design is strongly influenced by the staging plan and a particular siting has been identified that maintains consistency with this plan. The siting is shown in Figure 3. As displayed in the figure the 1 GeV, 1-3 GeV, and 3-8 GeV linacs are physically distinct. Further details on the staging plan, in particular the performance at each stage, can be found in Project X Performance by Stage.

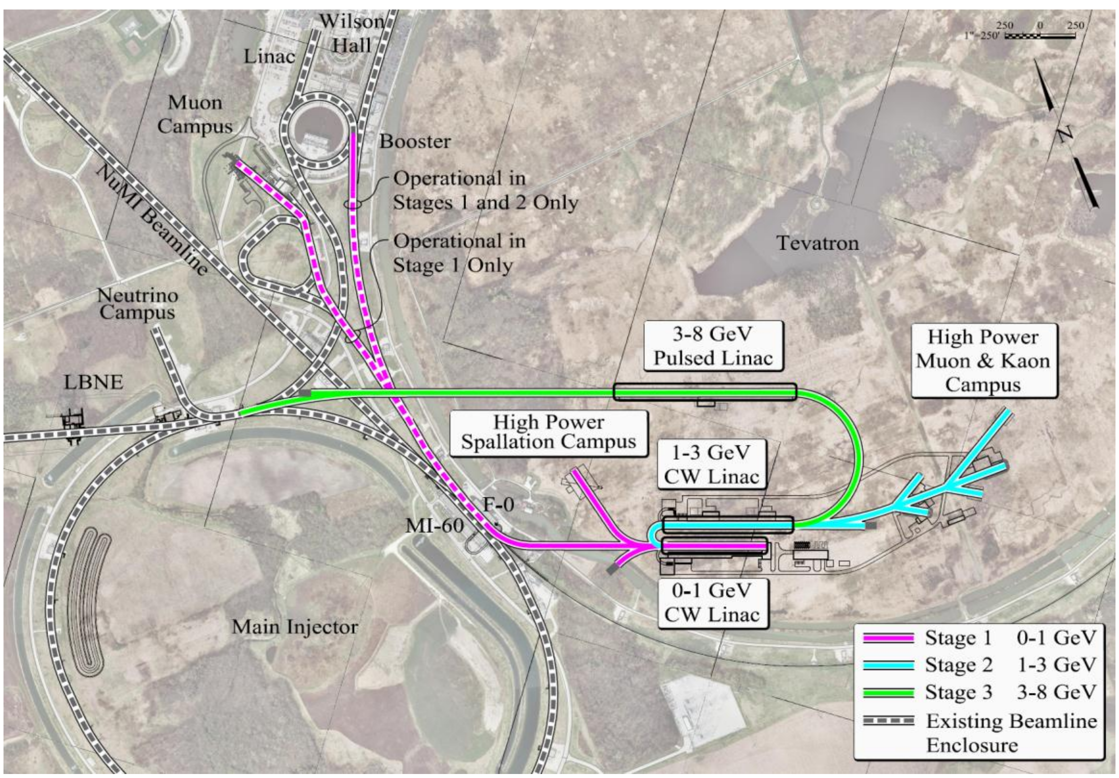

Figure 3: Site layout for Project X

Status of the Development Program/Readiness to Construct

Project X capitalizes on the very rapid development of superconducting rf technologies over the last 20 years, and their highly successful application to high power H^- acceleration at the Spallation Neutron Source at SNS. As a result of these developments excellent simulation and modeling tools exist for designing the Project X facility with high confidence that performance goals can be achieved, and the primary supporting technologies required to construct Project X exist today.

Fermilab, with national and international collaborators, have undertaken a development program aimed at mitigating technical and cost risks associated with Project X. The primary elements of this program are:

- Accelerator Configuration and Performance Projections

  A complete beam based design of the Project X facility has been developed based on comprehensive electromagnetic modeling of components, and modeling and simulations of beam transmission through the complex. The configuration established through this program provides the context for all sub-system component development.

- Front End (0-25 MeV)

  The unique capabilities of Project X are derived from the performance of the Front End. A program of individual and integrated systems testing of components has been initiated (PXIE – Project X Injector Experiment).

- H^- Injection

  H^- injection into the first circular ring of Project X (the Booster in Stage 1, the Recycler in Stage 2) represents a particular challenge. Multiple concepts are being developed and tested, both through simulations and hardware development.

- High Intensity Recycler/Main Injector Operations

  The Recycler/Main Injector complex will be required to accelerate a factor of three more beam in the Project X era than current operations. Issues such as space-charge, electron cloud, and a variety of potential beam instabilities are being investigated.

- High Power Targets

  Project X requires the development of targets capable of handling MWs of beam power. The development program has evolved from the LBNE development program, and includes an international consortium (RaDIATE – Radiation Damage In Accelerator Target Environments).

- Superconducting rf

  Six different accelerating structures operating at four different frequencies are required. A comprehensive program, originally initiated under ILC and undertaken with national and international partners, has been underway for a number of years.

The overall structure and goals of the Project X development program are based on being prepared for a 2017 construction start. Essentially all elements listed above are required for Stage 1 implementation. A comprehensive description of the status of the Project X development programs is not possible within this document. However, the highest priority items are highlighted here.

<u>Accelerator Configuration and Performance Projections</u>

Detailed beam simulations have been carried out starting from the ion source, through the linacs and into the Recycler/Main Injector complex. The linac performance demands are not state –of-the-art – the beam current, 1 mA, is significantly smaller than what is accelerated today within the SNS linac. Nonetheless, appropriate attention needs to be paid to emittance dilution, halo formation, and beam losses. Two examples are given below: Figure 4 shows a simulation of beam characteristics from the ion source through the RFQ exit at 2.1 MeV. The envelopes shown are 3σ, as calculated at the nominal beam current in this section (5 mA). The LEBT is operated in a mixed neutralized/ un-neutralized configuration, as is the currently preferred plan.

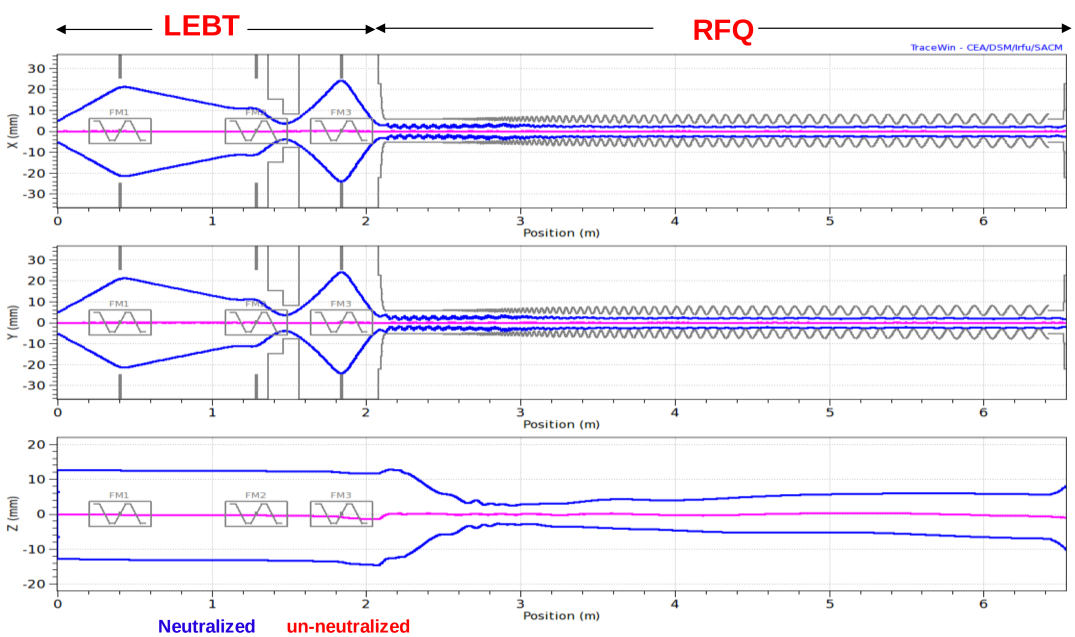

Figure 4: TraceWin simulations of 3σ beam envelopes (horizontal, vertical, and longitudinal; blue traces) from the ion source through the LEBT and RFQ, for a 5 mA beam current.

Figure 5 displays the results of tracking 100,000 particles through the entire length of the CW linac (3 GeV). Based on these studies, and companion studies incorporating intra-beam stripping, vacuum scattering, and vacuum stripping we conclude that total beam loss can be maintained well below the benchmark of 1 W/m.

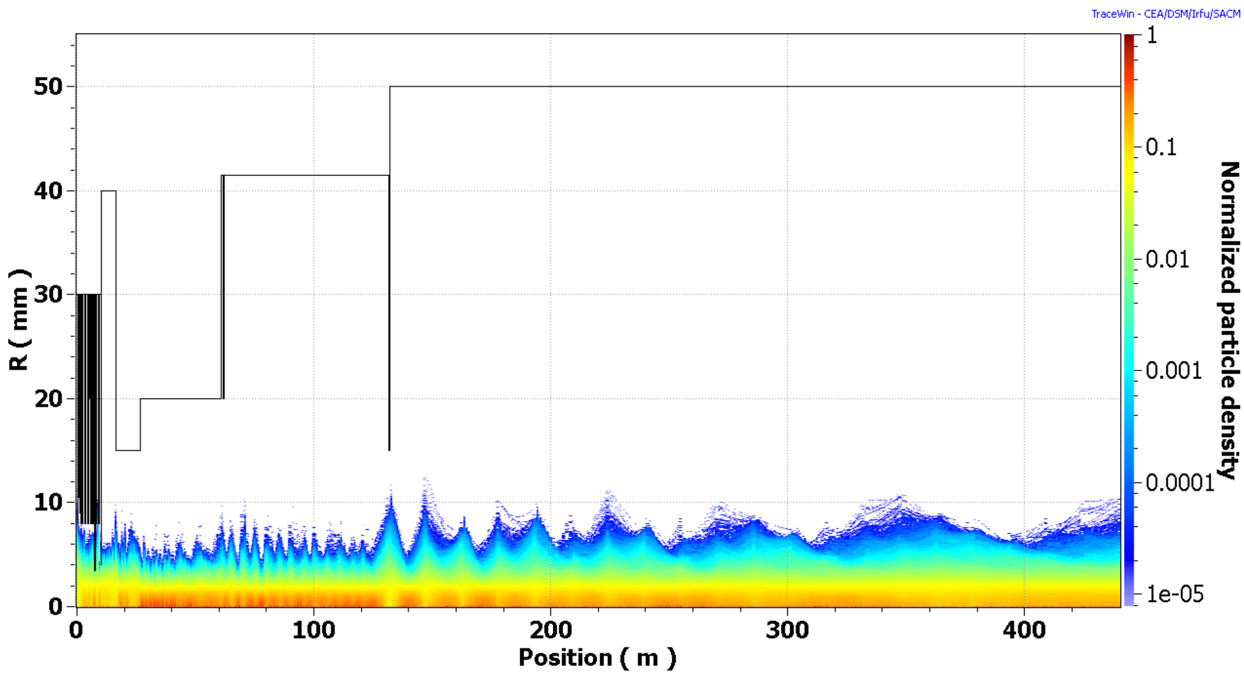

Figure 5: Aperture and particle density distribution along the entire length of the CW linac, based on 100,000 particles tracked by PARTRAN.

Front End

The Project X Front End must prepare the beam with the appropriate characteristics, including bunch structure, for acceleration through the linac and delivery to either the experimental programs or downstream accelerators. We are undertaking a program of development and systems testing of front end components known as the Project X Injector Experiment (PXIE). All PXIE components are being designed to match Project X specifications, as possible, and it is our expectation that perhaps half of these components could be reutilized in Project X during the construction phase. A layout of PXIE is shown in Figure 6. The primary issues that will be addressed or measured in PXIE include:

- LEBT pre-chopping
- Vacuum management in the LEBT/RFQ region
- Validation of chopper performance
- Bunch extinction
- MEBT beam absorber

- MEBT vacuum management
- Operation of HWR in close proximity to 10 kW absorber
- Operation of SSR with beam
- Emittance preservation and beam halo formation through the front end

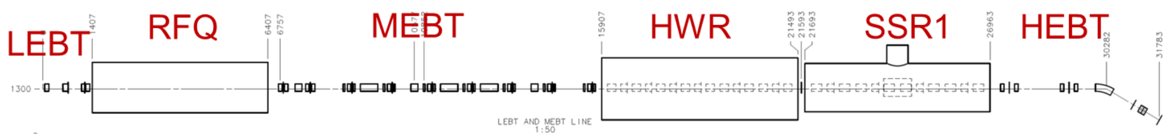

Figure 6: Layout of the Project X Injector Experiment (PXIE). The total length is roughly 35 meters.

<u>Superconducting RF</u>

The Project X linacs utilize six different types of superconducting structures, operating at four different frequencies (Figure 7). For several years Fermilab, with national and international partners, have undertaken a comprehensive development program, initially aimed exclusively at ILC but now encompassing the broader Project X requirements. There has been a significant investment in infrastructure that can be applied effectively to Project X. One legacy of the origins of this program is that all Project X accelerating structures operate at frequencies that are sub-harmonics of the ILC acceleration frequency (1300 MHz).

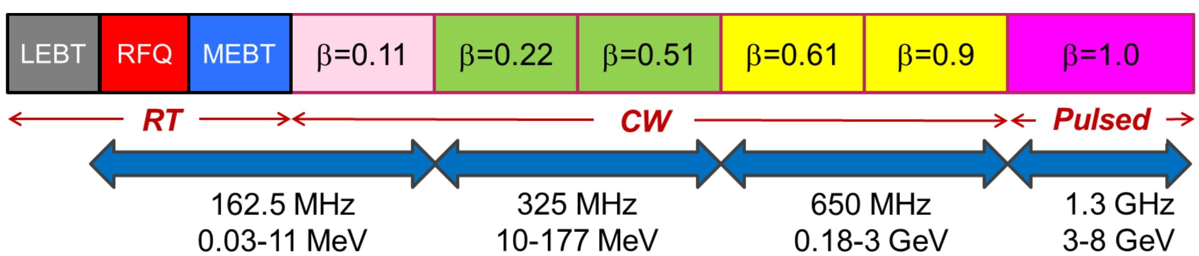

Figure 7: Technology map for the Project X linacs. The section labeled RT operates at room temperature. Everything downstream of this point is superconducting.

Project X accelerating structures fall into two general types depending on the H^- velocity – spoke resonators, associated with acceleration up β=0.54, and elliptical cavities, associated with acceleration from β=0.54 to β=1. Significant progress has been made on all types: electromechanical designs exist for all cavity types and prototypes have been successfully constructed at 325 MHz (β=0.22) and 1300 MHz (β=1.0). Single cell cavities are under test for the 650 MHz cavities. Cryomodule designs exists for 162.5 MHz ((β=0.11) and 325 MHz (β=0.22). Protoype cryomodule exist and have been tested at 1300 MHz as part of the ILC program.

Collaboration

Project X accelerator development is being undertaken by a collaboration of twelve U.S. laboratories and universities and four Indian laboratories, led by Fermilab. The collaboration membership includes:

Argonne National Laboratory
Bhabha Atomic Research Center
Brookhaven National Laboratory
Cornell University
Fermi National Accelerator Laboratory
International Linear Collider/America's Regional Team
Inter University Accelerator Center
Lawrence Berkeley National Laboratory
Michigan State University
North Carolina State University
Oak Ridge National Laboratory
Pacific Northwest National Laboratory
Raja Ramanna Center for Advanced Technlogy
SLAC National Laboratory
Thomas Jefferson National Accelerator Facility
Variable Energy Cyclotron Center