Project X R&D Plan

DRAFT
January 31, 2008

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I. Introduction

Project X is a high intensity proton facility conceived to support a world-leading program in neutrino and flavor physics over the next two decades at Fermilab. Project X is an integral part of the Fermilab Roadmap as described in the Fermilab Steering Group Report (http://www.fnal.gov/pub/directorate/steering/index.shtml).

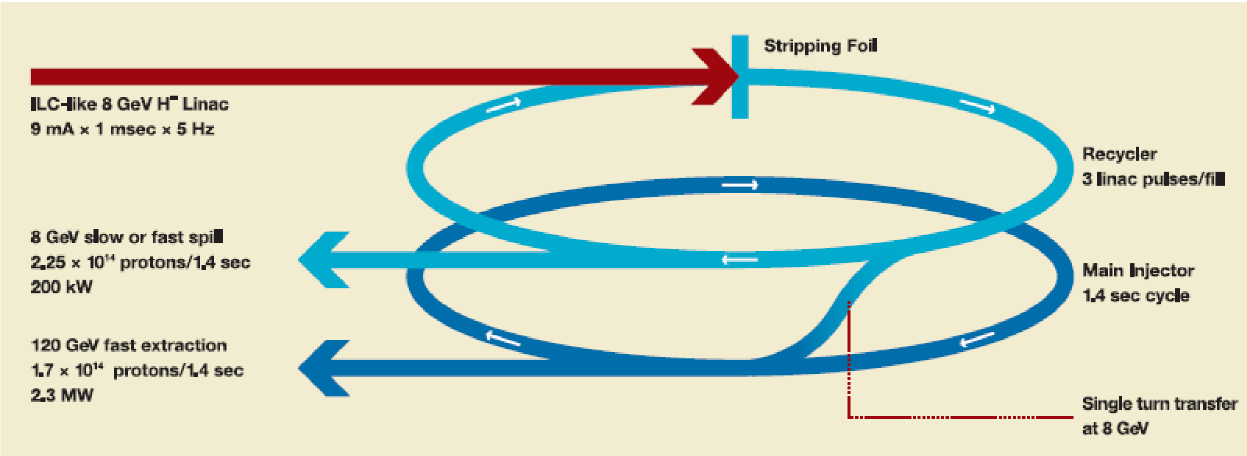


Figure I.1: Schematic view of Project X

Project X is based on an 8 GeV superconducting H^- linac, paired with the existing (but modified) Main Injector and Recycler Ring, to provide in excess of 2 MW of beam power throughout the energy range 60 – 120 GeV, simultaneous with at least 100 kW of beam power at 8 GeV. The linac utilizes technology in common with the ILC over the energy range 0.6 – 8.0 GeV. Beam current parameters can be made identical to ILC resulting in identical rf generation and distribution systems. This alignment of ILC and Project X technologies allows for a shared development effort. The initial 0.6 GeV of the linac draws heavily on technology developed by Argonne National Laboratory for a facility for rare isotope beams. It is anticipated that the exact configuration and operating parameters of the linac will be defined through the R&D program and will retain alignment with the ILC plan as it evolves over this period.

Utilization of the Recycler Ring as an H^- stripper and accumulator ring is the key element that provides the flexibility to operate the linac with the same beam parameters as the ILC. The linac operates at 5 Hz with a total of 5.6×10^{13} H^- ions delivered per pulse. H^- 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 ms injection, the orbit moves off the stripping foil and circulates for 200 msec, awaiting the next injection. Following three such injections a total of 1.7×10^{14} protons are transferred in a single turn to the Main Injector. These protons are then accelerated to 120 GeV and fast extracted to a neutrino target. The Main Injector cycle takes 1.4 seconds, producing approximately 2.3 MW of beam power at 120 GeV. At lower proton energies Main Injector cycle times can be shorter, allowing a beam power above 2 MW in the range of proton energy between 60 GeV and 120 GeV. In parallel, because the loading of the Recycler only requires 0.6 seconds, up to four linac cycles are available for accumulation and distribution of 8 GeV protons from the Recycler. Total available 8 GeV beam power lies in the range of 100-200 kW, depending on the energy in the Main Injector.

Primary modifications to the existing accelerator complex 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, in the Recycler Ring. The Main Injector would need a new RF system, measures to preserve beam stability through transition, and measures to mitigate electron cloud effects. Finally, substantial modifications to the existing NuMI target station will be required to support >2 MW operations.

It is anticipated that Project X configured as described above would initially support high intensity neutrino beams to the NOvA experiment, in parallel with at least one new 8 GeV based flavor/rare decay experiment. Depending upon future directions flexibility is retained for delivering neutrinos toward the DUSEL site and/or protons into the Tevatron.

The purpose of this document is to describe an R&D plan that would position the U.S. to initiate construction of Project X in the 2012 time frame, assuming a go ahead decision in roughly 2010. The organization of this document is as follows:

II. Goals: Describes goals of the R&D and preliminary design period (2008-2011). Included are design, technical development, project documentation, and organizational goals. These are described in the context of an overall set of performance goals for Project X.

III. R&D Plan Elements: Describes the essential technical elements of the plan, including major subsystem performance requirements, associated accelerator and technology issues, and the plans for addressing these issues.

IV. R&D Plan: Describes how the plan elements are assembled into a time-ordered plan, defines the associated resources required to support this plan, and describes the alignment of activities undertaken within the Project X, SRF/ILC, and HINS programs. Also describes how the R&D plan will be organized and executed by the prospective participating institutions.

II. Goals of the R&D Program

The overall goal of the Project X R&D program is to provide support for a Critical Decision 1 (CD-1) in 2010, leading to a CD-2/3a in 2011. In order to achieve this goal the program will support design and technical component development, development of all project documentation mandated by DOE 413.3, and formation of a multi-institutional collaboration capable of executing both the R&D plan and the provisional construction project.

The R&D program supports a facility scope that includes:

- A new 8 GeV, superconducting, H^- linac;
- A new beamline for transport of 8 GeV H^- from the linac to the Recycler Ring;
- Modifications to the Recycler Ring required for 8 GeV H^- injection, accumulation, and delivery to the Main Injector;
- Modifications to existing beamlines to support transfer of 8 GeV protons from the Reycler to the Main Injector;
- Modifications to the Main Injector to support acceleration and extraction of high intensity/high power proton beams over the range 60-120 GeV;
- Modifications to the NuMI facility to support operations at 2 MW beam power;
- Modifications to the Recycler Ring to support a new extraction system that will allow delivery of 8 GeV protons in support of a dedicated flavor program.

II.1 Technical Goals

The primary technical goal is completion of a Conceptual Design Report supported by a technology development program for CD-1, followed by a Technical Design Report demonstrating a fully developed baseline scope, cost estimate, and schedule for CD-2, for a facility with the capability of delivering in excess of 2 MW of beam power over the energy range 60 – 120 GeV, simultaneous with at least 100 kW of beam power at 8 GeV.

High level performance goals associated with Main Injector operations at 120 GeV are listed in Table II.1. These parameters are consistent with lower energy beam power goals described above through a shortening of the cycle time as the energy is lowered.

Table II.1: Performance Goals for the Project X Accelerator Facility

Linac		
Particle Type	H^-	
Beam Kinetic Energy	8.0	GeV
Particles per pulse	5.6×10^{13}	
Pulse rate	5	Hz
Beam Power	360	kW
Recycler		
Particle Type	protons	
Beam Kinetic Energy	8.0	GeV

Cycle time	1.4	sec
Particles per cycle to MI	1.7×10^{14}	
Beam Power to MI	154	kW
Particles per cycle to 8 GeV program	2.2×10^{14}	
Beam Power to 8 GeV program	206	kW
Main Injector		
Particle Type	protons	
Beam Kinetic Energy (maximum)	120	GeV
Cycle time	1.4	sec
Particles per pulse to MI	1.7×10^{14}	
Beam Power at 120 GeV	2300	kW

More specific goals of the technical program include:

- A complete preliminary design of the Project X facility including all technical and conventional construction elements, systems integration, and an installation and commissioning plan;
- Identification of key accelerator physics and engineering challenges and validation of performance of critical technology items through a supporting technology development program incorporating simulations, experimentation, and prototype construction as appropriate;
- Development of a technical/cost/schedule baseline for a Project X construction project;
- Preliminary identification of performance upgrade paths;
- Alignment with SRF/ILC program: The primary goal is to develop a capability, integrating U.S. industrial participation, to produce 1.3 GHz cryomodules at a rate of one per month by 2013. Such a step could represent the initial step in U.S. industrialization of cryomodules for the ILC. The Project X linac will be designed to accommodate accelerating gradients in the range 23.6 – 31.5 MV/m, with the final design gradient determined prior to CD-2, taking into account the evolution of the ILC program.

II.2 Management/Organizational Goals

The primary management goals are the formation of a multi-institutional collaboration to carry out the Project X R&D program and the preparation of a plan for construction, and development of all project documentation and organizational structures required by DOE 413.3. These goals are developed within an overall timeline as follows:

2008: Develop design and engineering concepts
Form Project X R&D Collaboration
Achieve CD-0 approval

2009: Initiate work on a Conceptual Design Report
Start R&D on technical components, in coordination with the ILC, SRF, and HINS programs

Continue accelerator physics and engineering design
Initiate project documentation

2010: Finish Conceptual Design Report
Achieve CD-1 approval
Continue R&D; initiate industrialization activities
Form collaboration to undertake project construction
Continue project documentation

2011: Develop preliminary design and Technical Design Report
Establish project baseline
Achieve CD2/3a approval
Initiate long lead (cryomodule) procurements

The intention is to complete the Project X design and R&D with significant participation from outside of Fermilab, both in the organization and execution of the program. The goal is to give collaborators complete and contained sub-projects, meaning they hold responsibility for design, engineering, estimating, and potentially construction if/when Project X proceeds.

III. R&D Plan Elements

III.1 Project X Major Systems and Requirements

Overall Requirements

The basic scheme of Project X is an 8 GeV Linac operating with ILC-like parameters, H-stripping and proton accumulation in the Recycler, with beam distributed to the Main Injector for acceleration to 120 GeV and to an 8 GeV slow spill program.
The overall requirements for Project X are shown in Table 1.

Req. No.	Description	Req.	Unit	Reference Requirements			
1.0	**General**						
1.1	120 GeV Beam Power	2.3	MW				
1.2	8 GeV Beam Power	360	kW				
1.3	8 GeV Slow Spill Beam Power	200	kW				
1.4	8 GeV Slow Spill Duty Factor	55	%				
1.5	120 GeV Availability	75	%				
1.6	8 GeV Availability	80	%				

Table 1. General Requirements for Project X.

Overall Issues

The major issues of Project X were first discussed in a preliminary report that was delivered to the Fermilab Directorate Long Range Steering committee and the Fermilab Accelerator Advisory Committee in August of 2007. The report can be found at:

http://projectx.fnal.gov/AACReview/ProjectXAacReport.pdf

A subsequent workshop that discussed the accelerator physics and technology aspects of Project X was held in November 2007. The workshop was attended by 175 people from 28 different institutions. Many more detailed issues of Project X were discussed at the workshop. The workshop report can be found at:

http://projectx.fnal.gov/Workshop/ProjectXWorkshopReport.pdf

Project X is a large project in which the accelerator portion of Project X is comparable in scope to the Main Injector project. For a project of this size there are many technical issues to be investigated. These issues are outlined in the following sections.

Overall Plan Elements

The major components that comprise Project X are:

- A front end linac operating at 325 MHz.
- An ILC-like linac operating at 1300MHz.
- An 8 GeV transfer line and H- Injection system.
- The Recycler operating as a stripping ring and a proton accumulator.
- The Main Injector acting as a rapid cycling accelerator.
- A slow extraction system from the Recycler.
- 120 GeV Neutrino beamline.
- Civil Construction and Utilities
- Controls

III.2 325 MHz Linac

325 MHz Linac Requirements

The Low Energy Linac comprises the front end of the proposed 8 GeV Project X linac; it includes the ion source and the entire accelerator upstream of the 1.3 GHz cavity cryomodules. The Low Energy Linac is required to deliver one-millisecond pulses of 5.6E13 H- ions at 420 MeV and at pulse rates up to 5 Hz. The output beam must provide transverse emittance and longitudinal bunch parameters as required by the 1.3 GHz High Energy Linac. The one-millisecond pulse must incorporate a Recycler RF bucket frequency structure to facilitate pseudo bunch-to-bucket transfer and also a Recycler revolution frequency structure to provide a 700 microsecond abort/extraction gap in the Recycler ring. The Low Energy Linac is required to have 98% availability. Specific requirements are listed in Table 2.

Req. No.	Description	Req.	Unit	Reference Requirements			
2.0	**325 MHz Linac**						
2.1	Average Beam Current	9	mA	1.2			
2.2	Pulse Length	1	mS	1.2			
2.3	Repetition rate	5	Hz	1.2			
2.4	325 MHz Availability	98	%	1.6			
2.5	Peak RF Current	14.4	mA	2.1	2.11	2.13	2.14
2.6	Final Energy	420	MeV	3.6			
2.7	Energy Variation (rms)	1	%	3.10			
2.8	Bunch Phase jitter (rms)	1	degree	3.11			
2.9	Linac Species	H-		4.1			
2.10	Transverse Emittance (95% normalized)	2.5	π-mm-mrad	5.7	5.8		
2.11	Macro Bunch Duty Factor	67	%	5.10	5.12		
2.12	Macro Bunch Frequency	53	MHz	5.12			
2.13	Micro Pulse Length	10.4	uS	5.13			
2.14	Micro Pulse Period	11.1	uS	5.13			

Table 2. Requirement Table for the 325MHz Linac. Requirements that are derived from other requirements have the reference requirement listed in red.

325 MHz Linac Issues

Many technologies and components applicable to the Low Energy Linac are expected to be developed under the High Intensity Neutrino Source (HINS) R&D program that has been ongoing since FY06. The technology selection for the Low Energy Linac is an early element of the Project X R&D effort. This plan is written assuming that the HINS technology will be selected and therefore includes only items beyond the scope of or not completely developed by HINS. If an alternative technology is selected or should the HINS effort reveals technical show-stoppers or terminate prematurely, the Project X R&D plan must be changed accordingly.

The issues raised by the Level 1 requirements for the Low Energy Linac are technological, engineering, and cost-benefit issues; no new accelerator physics issues are posed by a 420 MeV, 5.6E13 particles per pulse, 5 Hz, H- Linac. Completing a practical end-to-end accelerator physics design for the combined Low and High Energy Linac is the primary effort. For the Low Energy Linac, this includes selection of an engineering technology that is cost effective and yet sufficiently flexible to allow an upgrade path.

The beam duty cycle and machine availability requirements push the envelope of any existing H- ion source; development in this area is necessary and indicates collaborative efforts with SNS ion source efforts. Assuming the HINS technology is adopted, the critical Low Energy Linac component falling outside the scope of the HINS program is the superconducting triple-spoke accelerating cavity. This cavity will need to be designed, prototyped, constructed, tested, and characterized under Project X R&D. RF power distribution and control for the 325 MHz triple-spoke cavities and cryomodules also require development, since the power levels are higher than those encountered in the HINS program. Beam diagnostics for the triple-spoke section and otherwise outside the scope of HINS must be developed.

Finally, to reach CD-2 stage at the end of the Project X R&D plan, considerable effort must be expended to establish sub-system requirements and specifications, to define interfaces and assure proper integration of systems, to develop cost estimates sufficiently accurate to baseline the project, and to generate CD-2 documentation.

Assumptions

The Low Energy Linac R&D for Project X assumes completion of the HINS R&D program consisting of a 60 MeV, 325 MHz superconducting demonstration linac constructed in the Meson Detector Building by the end of 2011. It assumes that both the SCRF infrastructure and skills base provided for HINS and the 325 MHz SCRF facilities created as a part of HINS remain available for Project X R&D; Project X covers only the incremental costs. It assumes that "partner Labs" collaborate in Project X R&D activities and includes the partner lab effort in estimates here as well as the local effort to organize and coordinate the collaborative tasks.

The timeframe for Project X Low Energy Linac R&D described here (separate from HINS) assumes that it must be completed by end of FY2011 to support Project X CD-2 baseline in that year.

325 MHz Linac Plan Elements

Physics Design

This element is to establish the physics design of the Low Energy Linac to meet the top level Project X beam requirements of energy, intensity, emittance, and temporal structure. The Low Energy effort will help establish and must then meet the beam interface requirements to the High Energy Linac. Additionally there are requirements for operational availability, acceptable beam losses, and radiation shielding that must be considered. Specifications must be established for beam measurements and diagnostics systems required to validate performance and facilitate operation. The basic physics design must be completed in FY09 so that accelerator system requirements are available as a basis for system designs. Ongoing physics integration support will be required throughout the Project X R&D effort.

A specific task within this WBS element is a technology study to determine whether the HINS design or an alternative should be adopted for the Project X front-end. This is a cost-benefit study requiring accelerator physics and engineering effort. This task is closely coupled to the physics design and must be accomplished on a similar time scale so as to set the foundation and direction for required R&D.

- **Deliverable** – documented and justified decision on physics approach to design of beam accelerating structures and focusing elements to meet Project X Low Energy Linac requirements.

- **Deliverable** – CD-1 and CD-2 level physics design of Low Energy Linac, specification of sub-system requirements, interface and integration specifications, documentation, and cost estimates for Linac to meet Project X Low Energy Linac requirements.

Ion Source

This task is to develop, prototype and test an H- ion source with required emittance, beam current, pulse length, and duty cycle and operational lifetime for the Project X Linac. Low energy beam diagnostic equipment to measure and verify source beam parameters, including and especially emittance, are included.

- **Deliverable** – tested and documented design of ion source to meet Project X Low Energy Linac requirements.

Cavities

This is the task to develop the 325 MHz triple-spoke superconducting cavity design and processes. Two prototype triple-spoke cavities with helium vessels, power couplers, and slow and fast tuners will be constructed. Mechanical, vacuum, cryogenic, low level RF, and high RF power testing is to be done. Measurements of Lorentz de-tuning under full pulsed RF power conditions are made. It is assumed that triple-spoke cryomodules require no specific R&D and will not be prototyped prior to start of project construction.

- **Deliverable** – documented design and working prototype of triple-spoke cavity with helium vessel, power coupler, and tuners to meet Project X Low Energy Linac requirements.

Low Energy Linac RF Systems

This element includes an engineering and beam physics study to determine cost vs. benefit of the “one klystron, many cavity” design approach used in the HINS design.

- **Deliverable** – documented and justified decision on approach to supply of 325 MHz RF power to the accelerating structures to meet Project X Low Energy Linac requirements.

A second effort in this element is to develop the 325 MHz RF power distribution system required in the triple-spoke section of the Linac, including vector modulators of suitable power handling capability. Components will be developed and prototyped. Testing at low and high RF power levels will be done.

- **Deliverable** – verified and documented design with prototypes of 325 MHz RF power distribution system including vector modulators with prototypes as necessary to meet Project X Low Energy Linac requirements.

This element also includes development of the low-level RF system beyond that accomplished by the HINS R&D effort for the entire 325 MHz Low Energy Linac. Hardware and software components, including RF reference signal distribution, will be specified, developed, simulated, prototyped, and tested.

- **Deliverable** – tested and documented design of 325 MHz low level RF system to meet Project X Low Energy Linac requirements.

Finally, this element includes the systems integration and interface development effort required for the entire Low Energy linac 325 MHz RF system.

- **Deliverable** – CD-1 and CD-2 level technical specifications, interface and integration specifications, documentation, and cost estimates for RF power, RF power distribution, and RF control systems to meet Project X Low Energy Linac requirements.

Magnets Systems

Focusing and steering magnets and power supply systems integration are not expected to require hardware prototype R&D. Activity in these elements is primarily the development of system and sub-systems requirements, technical, interface and integration specifications, CD-1 and CD-2 level documentation, and cost estimates for beam line magnets and power supply systems, cryogenics systems, and controls systems to meet Project X Low Energy Linac requirements.

- **Deliverable** – CD-1 and CD-2 level technical specifications, interface and integration specifications, documentation, and cost estimates for beam line magnets and power supply systems to meet Project X Low Energy Linac requirements.

Cryogenics

- **Deliverable** – CD-1 and CD-2 level technical specifications, interface and integration specifications, documentation, and cost estimates for cryogenics plant, infrastructure, and interface components and systems to meet Project X Low Energy Linac requirements.

Controls

- **Deliverable** – CD-1 and CD-2 level technical specifications, interface and integration specifications, documentation, and cost estimates for control systems to meet Project X Low Energy Linac requirements.

Beam Instrumentation

The goals of this task are to develop, prototype and test specific beam instrumentation concepts, plans and devices suitable for the Project X superconducting linac and to develop a complete beam instrumentation plan for the Low Energy Linac. A particular concern is development and specification of beam pick-ups that are compatible with the ultra-clean superconducting RF environment.

- **Deliverable** – specific Low Energy Linac beam instruments with documentation and demonstrated working prototypes meeting Project X Low Energy Linac requirements.
- **Deliverable** – CD-1 and CD-2 level technical specifications, interface and integration specifications, documentation, and cost estimates for beam instrumentation and diagnostics systems to meet Project X Low Energy Linac requirements.

325 MHz Linac Schedule

The basic accelerator physics design and the HINS vs. alternative technology study will begin in FY08.

The basic machine design and technology decisions will be completed in FY09. Ion source development, triple-spoke cavity electromagnetic and mechanical design and material procurement, low level RF development and systems integration efforts for other Low Energy Linac accelerator systems will begin in FY09.

Ion source prototyping and testing continues in FY10. Triple-spoke prototype fabrication, vector modulator and RF distribution system development, and beam instrumentation prototype design and fabrication begin in this year. Efforts will be applied to produce required CD-1 documentation and review materials for all systems in FY10.

FY11 brings the completion of fabrication and processing and the start of testing of the triple-spoke cavities in the HINS test cryostat. Ion source development, RF power distribution system design development, beam instrumentation prototyping will climax in FY11. Final CD-2 level documentation, cost estimates, and review preparations for all LEL systems will be produced.

III.3 1300 MHz Linac

1300 MHz Linac Requirements

The 1300 MHz Linac is an ILC-like linac that can support a beam current of 9mA, a pulse length of 1mS, and a repetition rate of 5 Hz to an energy of 8 GeV. In the present design, the high-energy linac consists of two distinct parts: the ILC-like (1.2 – 8GeV) and non ILC-like (0.42-1.2 GeV). The non ILC portion is also called Squeezed ILC (S-ILC) for its "squeezed" ILC cavity shapes, optimized for $\beta = 0.81$. While the ILC-like cavities and cryomodules are being developed by the ILC effort, the S-ILC R&D is Project-X specific and will comprise a significant portion of the Project X R&D program. Similarly, the Project-X specific rf distribution system (with fast phase-shifters) comprises the second largest area (in terms of cost) of the R&D program.

The proposed R&D program is designed to specifically address major technical requirements and to verify design choices, shown in Table 3.

Req. No.	Description	Req.	Unit	Reference Requirements			
3.0	**1300 MHz Linac**						
3.1	Average Gradient (ILC portion)	26	MV/meter				
3.2	Average Gradient (S-ILC portion)	23	MV/meter				
3.3	Average Beam Current	9	mA	1.2			
3.4	Pulse Length	1	mS	1.2			
3.5	Repetition rate	5	Hz	1.2			
3.6	1300 MHz Availability	88	%	1.6			
3.7	Initial Energy	420	MeV	2.6			
3.8	Length (approx.)	700	meters	3.1	3.13		
3.9	Peak RF Current	14.4	mA	3.3	3.15	3.17	3.18
3.10	Linac Species	H-		4.1			
3.11	Energy Variation (rms)	1	%	4.9			
3.12	Bunch Phase jitter (rms)	1	degree	4.9			
3.13	Final Energy	8	GeV	4.10			
3.14	Transverse Emittance (95% normalized)	2.5	π-mm-mrad	5.7	5.8		
3.15	Macro Bunch Duty Factor	67	%	5.10	5.12		
3.16	Macro Bunch Frequency	53	MHz	5.12			
3.17	Micro Pulse Length	10.4	uS	5.13			
3.18	Micro Pulse Period	11.1	uS	5.13			

Table 3. Requirements for the 1300MHz Linac

1300 MHz Linac Issues

The requirements for cavity gradient for Project X are less stringent than the ILC. While the ILC target gradient is 31MV/meter, a gradient of 24 MV/meter would be suitable for Project X because of the much shorter length of the Project X linac. A gradient of 24 MV/meter is readily achievable at the current level of superconducting RF (SCRF) technology.

The more important issue is the production rate of cryo-modules. The high energy end of the Project X linac requires about 40 ILC-like cryo-modules. The present ILC cryo-module production rate is about one cryo-module per year with a two year lead time on the procurement of cryo-module components. To support a timely construction of Project X, the cryo-module production rate should be about one cryo-module per month with a lead time on the procurement of cryo-module components less than one year. This goal is in line with the goal of developing ILC superconducting RF infrastructure at Fermilab.

1300 MHz Linac Plan

Major goals of the 1.3 GHz linac R&D program are:

- Develop, procure and test (without beam) in FY12 a single S-ILC cryomodule prototype.
- Develop, procure and test (with beam) in FY12 an ILC-like rf unit.
- Develop, procure and test in FY11 a prototype for the rf distribution system with fast phase-shifters.
- Complete a conceptual design report in FY10
- Initialize industrialization activities for linac components in FY10
- Improve Project X cost estimate by prototyping critical technical elements in FY11

The R&D program plan assumes that the ILC-like cavity and cryomodule development and procurement is developed elsewhere. However, Project X will use 3-4 prototype ILC cryomodules to conduct a systems test with beam. Similarly, it is assumed that the RF power system R&D elements, common with the ILC, are developed by the ILC and/or SCRF programs.

Physics Design

- Establishes requirements and design parameters for the high-energy linac, establishes interfaces to other Project X systems (low-energy linac, transfer line, global).
- Specifies requirements and tolerances for linac elements.
- Identifies elements requiring research and development.
- Considers various alternative designs.

Lattice design

- Development of preliminary linac lattice model.
- Specifies optics interfaces.
- Establishes the quantity and the types of cryomodules and cavities needed.

Beam dynamics modeling

- Development of preliminary beam transport model for the linac.
- Specifies tolerances for various elements (magnets, rf, aligment, stability, etc).
- Analysis of transient behavior of the RF fields in the 1300 MHz section.

- Study of possible static feedback and feed forward systems to cope with different beam loading in and field levels in the accelerating cavities

Beam loss modeling

- Based on specified beam parameters, develop a linac beam loss model.
- Specifies loss rates for shielding calculations.

Static and dynamic tuning modeling

- Based on specified beam parameters, develops a preliminary model for linac tuning (e.g., at start-up, after repairs).
- Specifies beam instrumentation requirements.

Failure modeling

- Determines critical linac elements.
- Determines a number of spares needed.

Linac technical design

- Establishes preliminary technical design for linac subsystems.
- Identifies elements that require prototyping.
- Designs, procures, and tests prototypes.
- Improves cost estimates.
- Identifies and proposes alternatives.

Cryomodules

- Based on specified beam parameters, determines which cryomodule elements require research and/or development and/or prototyping.
- Provides design, procurements and tests for those elements.
- Improves cryomodule cost estimates.
- Proposes alternatives.

Cavities

- Includes cavity modeling, design and prototyping.
- Coupler modeling, design and prototyping.

Magnets

- Includes design, procurement, prototyping of SC focusing magnets and correctors in a cryomodule.

Cryogenic design

- Provides cryo system requirements.
- Identifies linac-specific cryo components that need prototyping.
- Designs, procures and prototypes those components.
- Provides preliminary design and cost estimate for cryomodule insulation vacuum.

Instrumentation

- Includes design, procurement, prototyping of beam instrumentation in a cryomodule.

Installation

- Provides preliminary plan and cost for the linac installation.

Vacuum systems

- Provides preliminary design for linac vacuum systems (beam vacuum and coupler vacuum).

RF Power systems

- Establishes preliminary technical design for RF power systems.
- Identifies elements that require prototyping.
- Designs, procures, and tests prototypes.
- Improves cost estimates.
- Identifies and proposes alternatives.
- Integration

Klystrons

- Develops requirements for linac Klystrons.
- Procures, tests prototypes.
- Improves cost estimates.

Distribution system

- Develops requirements for linac RF distribution system.
- Procures, tests prototypes.
- Improves cost estimates.

Modulators

- Develops requirements for linac modulators.
- Procures, tests prototypes.
- Improves cost estimates.

Fast phase shifters

- Develops requirements for linac fast phase shifters.
- Procures, tests prototypes.
- Improves cost estimates.
-

Controls design

- Provides linac-specific controls requirements

LLRF design

- Models, designs and prototypes a LLRF specific to the high-energy linac.
- Provides linac-specific LLRF requirements .
- In addition, LLRF is also funded under “NML Test Facility Infrastructure” element of SCRF Infrastructure Plan, which contains all beam-related elements (beam inhibits, quench detection, reference line distr., LO distr, etc)

HLRF design

- Provides linac-specific HLRF requirements to Civil Construction and Utilities

Civil design

- Participates in linac-specific civil construction R&D activities

Utilities design

- Participates in linac-specific utilities design R&D activities

Machine protection design

- Develops linac-specific machine protection requirements.
- Integrates it with LLRF, HLRF interlock and exception handling requirements.
- Participates in control system activities

Failure mitigation design

- Provides preliminary design for various linac failure modes (HLRF, cryomodule, cavity, magnets, instrumentation).
- Provides preliminary model for handling radioactive components in need of repair.

System tests

- Essential system tests needed to be completed before or shortly after Project X construction start

RF Unit Tests

- Prepares for a high-power test of the RF unit and RF power distribution system for Project X with beam.

Beta<1 cavities tests

- Prepares for an rf power test (without beam) of a single S-ILC prototype cryomodule.

Controls and timing tests

- System-wide tests for near-final controls and synchronization of linac elements with the rest of Project X

1300 MHz Linac Schedule

FY08

- Physics Design: Initiate work on establishing beam requirements, design parameters, lattice model, interfaces to other Project x areas and on beam loss budget.
- Linac technical design: Initiate conceptual design of S-ILC cavities and cryomodules, magnets, instrumentation, and vacuum systems.
  RF Power Systems: Determine requirements, initiate conceptual studies.
- Integration: Initiate conceptual design of controls, LLRF, HLRF, civil, machine protection integration.
- System Tests: Initiate conceptual design of RF unit system test.

FY09

- Physics Design: Continue with conceptual linac design, provide technical inputs and engineering requirements to technical systems. Continue beam loss modeling. Initiate modeling of static and dynamic tuning, and linac failure scenarios. The goal is to determine installation and alignment tolerances, power-supply regulation sensitivities, and the number of spare elements (as installed).
- Linac technical design: Design, procure and test prototype bare S-ILC cavities (single cell and multi-cell). Design, procure and test prototype S-ILC tuners, couplers. Continue conceptual design of S-ILC cryomodules. Design and procure prototype SC magnets for the linac. Start linac cryo design.
- RF Power Systems: In the ILC R&D (overlapped with Project X): Klystrons - run Toshiba MBK to get reliability data - get data from DESY as well - decide if SBK worth pursing; RF Distribution - test prototype system with first FNAL cryomodule - design PrX version and test prototype parts, build one distribution system for Fermilab Cryomodule 2; Modulator - Design next version of the Marx and continue to run prototype - get data on Bouncer version from DESY. In the PrX R&D (this document): Fast Phase Shifters - Understand requirements and start prototypes in house
- Integration: Continue design studies, provide inputs and requirements to global (general) systems. Start design of utilities and failure mitigation systems to address the availability requirement.
- System Tests: Start procurement of long-term items for S-ILC prototype crymodule

FY10

- Physics Design: Finish the conceptual design report.
- Linac technical design: Test dressed prototype S-ILC cavities. Finish the conceptual design report. Procure industrial prototypes for some components (tuners, couplers) from several companies. Procure and test prototype beam instrumentation. Initiate conceptual design for linac installation and project timeline.
- RF Power Systems: In the ILC R&D (overlapped with Project X): Klystrons - fund two US companies to build prototypes; RF Distribution - work with companies to design simpler (e.g. less welds, integrated parts), build one distribution system for Fermilab Cryomodule 3; Modulator - fund two US companies to build prototypes. In the PrX R&D

(this document): Fast Phase Shifters - test prototypes and work on second generation design. Complete the conceptual design report and cost range studies.
- Integration: Prototype critical elements of the machine protection system. Finish the conceptual design report.
- System Tests: Continue procurement of S-ILC prototype cryomodule parts (cavities, couplers, tuners, etc). Start preparing fixtures for the S-ILC crymodule assembly. Continue work on the design for rf unit and synchronization tests.

FY11

- Physics Design: Provide support to technical areas. Provide estimates for Project cost range.
- Linac technical design: Finish all prototype tests. Finish cost range studies.
- RF Power Systems: In the ILC R&D (overlapped with Project X): Klystrons - do long term testing and work with companies to improve design - order two more as a pre-series production; Modulator - do long term testing and work with companies to improve design - order two more as a pre-series production. In the PrX R&D (this document): RF Distribution - fund two US companies to build production versions to PrX-specific equip for three cryomodules; Fast Phase Shifters - order production versions for one rf unit System - by end of year or in early FY12, have a full rf system driving three cryomodules in operation
- Integration: Finish all prototype tests. Finish cost range studies.
- System Tests: Assemble one S-ILC prototype cryomodule and deliver it to the Cryomodule Test Stand (part of Fermilab SCRF infrastructure). Complete installation of rf unit test equipment, prepare to operate the test program. Install all timing and synchronization test equipment, prepare to run tests.

III.4 8 GeV Transfer Line

8 GeV Transfer Line Requirements

The beam power handling requirements of the transport and injection system is designed to handle the expected full linac intensity of 9 mA average current and 1 ms beam pulse length at a repetition rate of 5 Hz. This translates to an intensity of 3.94×10^{14} particles/sec or an average of 360 kW beam power at 8 GeV. To minimize unnecessary radiation exposure to personnel a level of 100 mrem/hr at 30 cm is considered the maximum localized activation level. We set an average activation level a factor of 5 below this to 20 mrem/hr at 30 cm for bare beam pipe. This translates into an average beam power loss of 50 mW/m or an average uncontrolled loss rate of 1e-7 per meter and transport efficiency of 99.99% of the un-collimated particles. For a 1 km beam line this translates into a total uncontrolled loss of 3.94×10^{10} particles/sec. The length of the transport line has previously been determined to be approximately 1 km due to the siting of the linac inside the Tevatron ring, the limited dipole field of < 500G to prevent the stripping of the weakly bound outer H- electron, and the drift necessary to place a phase rotator cavity as documented in the Conceptual Design Report of 8GeV H- Transport and Injection for the Proton Driver. To assure this low loss level, the transport line should have a large physical (and dynamic) aperture (> $10\varepsilon_L$) and provide a flexible transverse collimation system to contain any large amplitude halo particles generated during the acceleration of H- in the linac. The level of collimation will be determined by halo generation and size of injection foil. The maximum level of collimation is expected to be below 5%.

The momentum spread of the beam from linac is on the order of 0.05% and should not be an issue for the transport line. The momentum aperture of the transport line has been specified to be the same as the Recycler such that the longitudinal collimation system can be set smaller than the Recycler momentum acceptance to protect the Recycler from errant energy pulses. The final energy variation of +/- 0.1% corresponds to the estimated energy variation produced by the debuncher cavity in the transport line for longitudinal painting in energy. The injection stripping efficiency of 98% implies that 2% of the incident H- will exit the foil as H- or H0 and be sent to the injection absorber. This implies a 7.2 kW load on the injection absorber due to unstripped ions by either the foil or laser. A reduced efficiency or H- missing the foil (as in halo) add beam power load to the injection absorber. A conservative approach is to design the absorber for 10% full power or 36 kW peak. Specific requirements for the 8 GeV transfer line and injection system are listed in Table 4.

Req. No.	Description	Req.	Unit	Reference Requirements	
4.0	**8 GeV Transfer Line**				
4.1	Injection Stripping efficiency	98	%		
4.2	Length (approx.)	1000	meters		
4.3	Maximum average activation level	20	mrem/hr		
4.4	Availability	98	%	1.6	
4.5	Momentum Aperture	+/- 0.8	%	3.10	
4.6	Minimum Transverse Aperture	25	π-mm-mrad	3.13	4.3
4.7	Maximum Dipole Field	0.05	T	4.1	4.3
4.8	Transfer Efficiency	99.99	%	4.3	
4.9	Final Energy Variation	+/- 0.11	%	5.10	
4.10	Energy	8	GeV	5.1	

Table 4. Requirement table for the 8 GeV transfer line and injection system.

8 GeV Transfer Line Issues

The main issues for transport and injection of the H- particle beam are:

- The control and mitigation of uncontrolled losses due to single particle loss mechanisms in the transport line.
- Uncontrolled losses in the injection region due to the injected and circulating ion interaction with the stripping foil.
- The stripping efficiency and lifetime of the injection foil or the stripping efficiency of laser stripping injection system.
- The collection of the stripped electrons and neutrals from the injection process.

8 GeV Transfer Line Plan

The plan for the transport line and injection system R&D program is broken up into six level 2 tasks:

1. Physics Design
2. Component Design
3. Power supply design
4. Vacuum system design
5. Controls

6. Instrumentation

The goal for the Physics Design is to mitigate risks associated with the main four major issues discussed above and produce a defensible technical design with detailed specifications of all the necessary components for the transport and injection system to be constructed and commissioned. Progress in this first level 2 task is required prior to significant progress in the other level 2 tasks. Once specifications for the components are given the detailed design will begin.

Transport Line

The R&D plan for the level 2 Physics Design of the transport line centers around the following main topics:

- A risk assessment of meeting operational goals for uncontrolled H- beam loss and mitigation strategies during transport.
- The design of transverse collimation system for large amplitude particles.
- The design of a longitudinal collimation system for protection of the Recycler against errant beam energies.
- Modifying the existing Proton Driver transport line design into the Main Injector for injection into the Recycler.
- The design of a passive energy correction system (using a normal conducting superstructure) for longitudinal matching and painting into the Recycler RF injection bucket.
- The design of the injection dump line.
- Detailed component specifications and designs.

The physics design of the transport line should proceed quickly based upon the work for the Proton Driver transport line. The physics design for the transport line will continue with optical and civil designs for the Proton Driver transport line and including modifications required for injection into the Recycler, collimation design, injection dump transport line, and longitudinal phase rotation. This task must be coordinated with the injection system design and the Recycler R&D lattice modifications. As designs mature start-to-end simulations from the RFQ to the injection foil, including Lorentz stripping, black-body radiation, gas stripping, collimation, and RF phase rotation will be carried out.

Injection System

The R&D plan for the level 2 Physics Design of the injection system is tied closely with level 2 design of the transport line and that of the Recycler R&D in that the injection straight section must be compatible with the chicane design and the injection beam dump transport line. There are many detailed aspects that need to come together for a viable injection system. The two potential techniques for stripping both electrons off the H- for injection will be investigated are the use of a thin foil, currently the default process, and laser stripping process that has been demonstrated at SNS for 1 GeV H-.

The choice of stripping foil thickness is based on predicted stripping efficiencies and the transverse orientation and dimensions depend on choices for transverse painting. Stripping efficiencies have been measured up to 800 MeV with good agreement although there are no measurements above 800 MeV. The lack of measurements poses a risk of sending a larger than predicted number of particles to the injection absorber. The foil lifetimes are strongly dependent on the foil material foil construction, and the injected beam size and intensity. The scattering of the circulating beam on the foil creates losses in the injection region and activates components. A plan for mitigating these losses is needed. Simulations on foil temperatures for higher initial beam currents have carried out, but additional simulations for the specific beam parameters for Project X will be investigated.

Calculations and simulations for the laser stripping technique at 8 GeV will be performed and will determine requirements for the laser system, interaction region, injected and circulating beam parameters, and magnet systems used. The calculations and simulations will be based upon the SNS experience. Ultimate stripping efficiency will be predicted and the simulations performed for SNS experiments will be extended to Project X energy and beam structure. These parameters will then feed into the design of the laser system and hardware necessary.

The injection process itself consists of both transverse and longitudinal phase space painting. The Proton Driver project utilized a combination of horizontal painting and vertical injection steering to minimize the required vertical aperture and reduce the complexity of painting in the ring in both dimensions to produce a uniform transverse distribution in x and y. Initial tracking simulations of the transverse painting for Proton Driver produced promising results but they did not include transverse space charge and only contained a limited sample of the transverse phase space. Once the new Recycler injection lattice has been defined, these simulations need to be validated by the inclusion of transverse space charge and better statistics. The engineering challenge for the transverse painting will be in the painting magnets and their power supplies as they will be required to remove the circulating beam from the foil between 5Hz injections. ESME simulations have been carried out for longitudinal phase space painting only in phase for micro-bunch injection for Proton Driver into the Main Injector. These simulation results will make a good starting point for continued progress toward longitudinal injection design. Future simulations need to incorporate new longitudinal emittance and beam distribution requirements and include painting in energy and broad band impedance effects. The results of longitudinal painting in energy will lead to specifications for the normal conducting RF superstructure utilized for phase rotation and energy and phase jitter correction.

Component

The level 2 Component Designs include:

- transport line magnets
- injection chicane magnets
- painting magnets
- foil support and changer
- electron catcher
- beam absorbers (both collimators and absorbers)
- debuncher cavity design.

These items present a range of technical challenges, some of which will require a significant engineering effort while others only design efforts. All magnets will have at least 2D magnetic models, with the chicane magnets being modeled in 3D in a complete injection system. Based upon the results of the 3D calculations of the chicane magnets, an effort to build these magnets in a prototyping stage or early in the project to allow for field shimming might be expected. Once the magnet requirements and magnetic and mechanical designs are complete, the question of prototypes can better be answered. It is expected that painting magnets and the foil support and changer system will require prototyping. This activity could start once the physics design of injection system design is complete. This is expected to be a significant activity. The debuncher cavity will be similar to previous cavity structures designed by SLAC so it is thought that the cavity design would not need to be done.

Power Supplies

The level 2 Power Supply Designs include both DC power supplies for the dipoles, quads, and trims, 5 Hz power supplies for switching the beam into the linac dump line, pulsed supplies for the painting magnets. The DC supplies should be straight forward, as well as the 5Hz supply for the switching magnets, but the pulsed supplies for the painting magnets will require some significant design effort. It is expected that this will result in a prototyping effort. There will be effort for the debuncher cavity klystron/modulator system, but it should be sufficiently close to present systems that a prototype is not required.

Vacuum System

The level 2 Vacuum system design includes the vacuum beam pipe and pumping systems and the cryogenic beam screen. Although there are examples of cryogenic screens inside vacuum vessels, a significant design effort will be required to understand the implementation for the transfer line such as cryogenic bypasses around quads, the number of cryogenic feeds, the length of each sub section, and bringing the cryogenics out of the vacuum system. The design effort includes the prototyping of a section of transport line to verify operation.

Controls

The level 2 Controls System design will be integrating the transport and injection system into the existing Fermilab Controls system. This task provides the design of computer links to all required hardware, timing signals, motion control support for collimators, and all the necessary communication between the central system and remote systems. Basic computer control software including dataloging are included.

Instrumentation

The level 2 Instrumentation design plan includes the design the position detectors, loss monitors, profile monitors, beam absorber temperature sensors, motion control systems, and video systems for the injection foil changer. Specifications for application software for diagnostics and operation are included.

8 GeV Transfer Line Schedule

FY08

The first year will be mainly focused on the physics design and component specification for the both the transfer line and injection systems. It is expected that multiple groups will be involved in the design of the optics of the transport line and injection layout, transverse painting simulations, longitudinal painting simulations, evaluation of foil stripping and laser stripping techniques. Careful coordination between the different topics will be important. It is expected that at the end of this period, a consistent design based upon one of the selected injection stripping technique will be produced with design contingencies. The majority of the labor during this period will consist of scientist and will include some mechanical and electrical engineering support and drafting support. A series of informal design reviews should be held as needed.

FY09

Based upon the design effort during the first year, component specifications will be generated and component designs started. Design effort should continue in an iterative manner with component design efforts. Specifically, the design effort on the chicane magnets, painting magnets, foil support and changer, electron catcher, power supply design, vacuum system design, and instrumentation design should commence. Component requirements should be well understood by this time.

FY10

Scientist support for continued component, power supply, and vacuum design and the start of prototyping will be required in a coordination of design effort. The prototyping of the painting magnets, foil support and changer and electron catcher would begin this third year. The prototyping for the cryogenic beam tube would begin the third year. The controls system design should be initiated this year as well as the continued effort for instrumentation design.

FY11

The last year finishes all the prototyping and verification of system performance for the operation of the foil support/changing system, and cryogenic shield prior to the final technical design document. Major prototype efforts will include the completion of the foil support/changer and electron catcher prototype and finishing the cryogenic prototype testing. The last six months should be spent in preparation of the TDR.

III. 5 Recycler

Recycler Requirements

The Fermilab Recycler is a fixed energy 8 GeV storage ring using strontium ferrite permanent magnets in the Main Injector tunnel. It was designed to provide more antiprotons for the Tevatron collider program, through the use of stochastic and electron cooling. For the Nova program, the Recycler will be converted from an antiproton storage ring to a proton accumulator for single turn injection into the Main Injector. The R&D plan presented in this document assumes that the upgrades in the Nova program are being carried out.

The Recycler will operate as a stripping ring and a proton accumulator, taking 3 pulses from the linac, capturing in 53 MHz RF buckets, and performing a single turn extraction into the Main Injector. In addition, a slow extraction system for an 8 GeV fixed target program will be implemented. The injection and stripping systems are described in Section 0 and the slow extraction system is described in Section 0. The requirements for the Recycler are listed in Table 5.

The most demanding requirements are the peak beam current of 2.4 A and the maximum space charge tune shift of 0.05. These requirements drive the plan for the injection painting system to achieve a K-V transverse distribution (which is discussed in the R&D plan for the transfer line and injection area). The beam current requirements lead to significant questions regarding electron cloud generation and mitigation. As the RF requirements for the Recycler are similar to those of the requirements for the Main Injector, the R&D on this system is described in Section 0.

Req. No.	Description	Req.	Unit	Reference Requirements			
5.0	**Recycler**						
5.1	Energy	8	GeV				
5.2	Storage Efficiency	99.5	%				
5.3	Average Recycler Beam Current	0.6	A	1.2			
5.4	Availability	95	%	1.6			
5.5	Injection Rate	5	Hz	2.3			
5.6	Maximum Space Charge Tune Shift	0.05		5.2			
5.7	95% normalized transverse emittance	25	π-mm-mrad	5.6			
5.8	r.m.s. normalized transverse emittance	13	π-mm-mrad	5.6			
5.9	Bunching factor	2		5.6			
5.10	Longitudinal emittance per Bunch	0.5	eV-Sec	5.6	5.12		
5.11	Cycle Time	1.4	S	6.1			
5.12	RF Frequency	53	MHz	6.2			
5.13	Abort Gap Length	700	nS	6.3			
5.14	Peak Recycler Beam Current	2.4	A	6.5			

Table 5. Requirements for the Recycler

Recycler Issues

At the specified peak beam current, along with the RF structure of the beam, electron cloud induced instabilities could be an important limitation to the maximum proton flux. As the mitigation of electron cloud instabilities is not fully understood, we will be undertaking R&D in understanding the generation of the electron cloud (through simulation and measurements), mitigation of the generation (e.g., coating beam tubes, clearing electrodes), and damping of the instabilities.

With a new injection insert in the Recycler Ring, we anticipate that we may need more flexibility in the lattice design. The Recycler is built with both permanent magnet dipoles, permanent magnet combined function devices, powered dipole correctors, and a tune trombone of powered quadrupoles. R&D effort on lattice design and magnet / power supply design is included to allow this flexibility.

With the increased beam intensity and changes to the cycle, we anticipate changes to the controls and instrumentation specific to the Recycler (e.g., beam position monitors, intensity monitors).

Recycler Plan

The R&D plan for the Recycler consists of elements for physics design questions (lattice & optics, electron cloud instability mitigation), controls and instrumentation development, and magnet and power supply design. Most of these elements cover development in areas where we are knowledgeable about the generalities (e.g., lattice design) but need to invest scientific and engineering time in the specifics (e.g., magnet specification, construction, and installation). The electron cloud instability mitigation is an open question, requiring research into the generation, mitigation, and damping.

We propose a breakdown into 4 sections for R&D:

1. Physics Design
2. Controls Development

3. Instrumentation Development
4. Magnet & Power Supply Development

The Physics Design tasks will investigate the lattice design and optics and the electron cloud issues specific to the Recycler. A comprehensive electron cloud R&D program will be developed based on simulations, experiments, and equipment tests. A joint program will cover both Recycler and Main Injector and will incorporate collaborators in both the Project X and ILC programs. A program of experimentation at the Main Injector, CESR, RHIC, and/or CERN is anticipated. The Controls and Instrumentation development tasks will investigate and develop necessary upgrades to the existing Recycler controls and instrumentation. The Magnet & Power Supply development will investigate and develop necessary magnets and power supplies to meet the lattice design requirements coming from the Physics Design task. The lattice design, controls and instrumentation development, and magnet & power supply development are classified as the development of specific solutions with known techniques. The electron cloud investigation includes research time, as we do not completely understand the parameters of the problem.

Recycler Schedule

FY08

In the first year the work will be concentrated on Physics Design. By the end of the year the lattice changes should be specified since this item drives the R&D on Magnet and Power Supply. On the electron cloud task the methods of mitigation specific to Recycler (e.g. coating of the beam pipe), accompanied by a program of beam experimentation, will be iniitated.

FY09

Magnet and Power Supply development starts in parallel with finalization of the machine optics. As more information from the continuing work on Electron Cloud becomes available, requirements for instrumentation are being worked out.

FY10

During the third year the prototyping Electron Cloud mitigation is accomplished. Development of the optics and instrumentation changes makes it possible to start work on the Controls task.

FY11

After completion of the R&D on Electron Cloud, the feasibility of mitigation methods and their cost should be available. Power Supply and Magnet prototypes are tested and the requirements on Instrumentation and Controls are set. Given the input from R&D on RF, Injection and Extraction, the operations scenario is developed.

III.5 Main Injector

Main Injector Requirements

The Main Injector will receive 1.7×10^{14} protons from the Recycler in a single turn and will accelerate them at 120 GeV in 1.4 seconds. This is about 3.5 the beam intensity Main

Injector will be required to accelerate for the NOvA program. The requirements for the Main Injector are listed in Table 6.

The most demanding requirements are the peak beam current of 2.4 A, the maximum space charge tune shift of 0.05 along with the 120 GeV beam power. The beam power along with the bunching factor drive the RF system design. The beam current requirements along with the bunch spacing raise questions about electron cloud instabilities. The high acceleration efficiency requirement leads to questions about controlling the transition crossing.

Req. No.	Description	Req.	Unit	Reference Requirements			
6.0	**Main Injector**						
6.1	120 GeV cycle Time	1.4	S				
6.2	RF Frequency	53	MHz				
6.3	Abort Gap Length	700	nS				
6.4	Acceleration Efficiency	99	%				
6.5	Main Injector Beam Current	2.4	A	1.1			
6.6	Final Energy	120	GeV	1.1			
6.7	120 GeV Beam Power	2.3	MW	1.1			
6.8	Availability	87	%	1.5			
6.9	Injection Energy	8	GeV	5.1			
6.10	Longitudinal emittance per Bunch	0.5	eV-Sec	6.2	6.11		
6.11	Space Charge Tune Shift	0.05		6.4			
6.12	95% normalized transverse emittance	25	π-mm-mrad	6.11			
6.13	r.m.s. normalized transverse emittance	13	π-mm-mrad	6.11			
6.14	Bunching factor	2		6.11			

Table 6. Requirements for the Main Injector

Main Injector Issues

The maximum peak current required assumes 3 times the protons per 53MHz bunch in Main Injector than the current operation. Electron cloud instabilities could be a limitation to the maximum MI intensity as in the Recycler. Currently in MI with 1E11 particles per 53MHz bunch electron cloud is not a problem because the bunch intensity is below the threshold.

The current Main Injector RF system does have the power to accelerate the required beam intensity to 120 GeV in 2.4 (even with the addition of a second power tube per station). I addition to achieve the required bunching factor a substantial second harmonic RF system will be needed. Finally there is a possibility of changing the RF frequency because of electron cloud issues.

We expect that the current Main Injector dampers will be able with some modifications to damp most of the other instabilities. Crossing transition without beam loss will require a gamma-t jump.

Main Injector Plan

The R&D plan for the Main Injector consists of elements for physics design questions (control of instabilities and transition crossing), electron cloud investigation, instrumentation development, and RF design.

The RF design will concentrate on the new RF system required, with the ultimate goal of producing and testing prototype cavities (one for the fundamental frequency and one for the second harmonic).

A joint program covering e-cloud issues in MI and Recycler, including simulations and measurements, will be undertaken as described in III.4 to develop a better understanding of the generation of electron cloud and the dependence on various parameters (SEY, bunch spacing, intensity, RF frequency etc.). The possibility of coating of the MI beam pipe needs to be investigated. The instrumentation development will concentrate on developing new electron cloud detectors along with examining the possible modifications to MI instrumentation if the RF frequency is changed.

Main Injector Schedule

FY08

- New MI RF system: Optimize the existing 53MHz cavity design and draw out the HLRF system architecture. Start initial paper design of a second harmonic cavity. Initiate design for a higher fundamental frequency cavity.
- Electron Cloud: Run simulations for e-cloud in MI using two different programs (POSINST, ECLOUD). Compare the effects of smaller SEY and higher rf frequencies. Continue the e-cloud measurements in MI using the existing detector and including the EM wave propagation method. Investigate the possibility of coating the MI beam pipe and estimate the amount of effort and cost. The possibility of doing experiments in other machines with the MI project-X parameters will be investigated.

FY09

- New MI RF system: Select the new rf frequency. Finalize the cavity and tuner design. Schedule cavity design review. Start ordering major components for construction of a prototype cavity and tuner. Finish second harmonic cavity design.
- Electron Cloud: Continue the e-cloud simulations. Install new e-cloud detectors. Install a small piece of coated pipe in MI and measure the effect.

FY10

- New MI RF system: Finish assembling prototype cavity and tuner and start low level testing. Schedule second harmonic cavity review and order parts for a prototype cavity.
- Electron Cloud: Continue and refine the e-cloud simulations. Include beam dynamic effects. Coat two MI dipoles in a service building and evaluate the results.

FY11

- New MI RF system: Finish high power cavity testing in test station. Plan to install in MI tunnel for testing. High power test second harmonic cavity in test station.
- Electron Cloud: Formulate a concrete plan for the e-cloud problem and have a review to evaluate it.

III.6 8 GeV Slow Spill

8 GeV Slow Spill Requirements

The expected MI 120 GeV cycle time of 1.4 sec in conjunction with the 5 Hz repetition rate of the linac yields seven linac cycles per MI cycle. Three of these will be used to accumulate approximately 1.7x10^{14} protons for the 120 GeV neutrino program. The remaining four cycles (total of 206 kW at 8 GeV) are available for an 8 GeV experimental program. The injection of each 1 ms linac pulse will be painted transversely (to a 95% normalized transverse emittance of approximately 25 π-mm-mr) and longitudinally into prepared 53 Mhz dual-harmonic Recycler RF buckets. Each of the four injections (with a cycle time of 200 ms) contains approximately 5.6x10^{13} protons or about 52 kW 8 GeV beam power. To allow for an abort gap, only 546 out of 588 buckets are filled at injection which produces 53 Mhz bunch intensities slightly larger than 1x10^{11} protons per bunch. To be able to utilize the full 200 kW for the experimental program requires each injection cycle (of one linac pulse) be extracted within the 200 ms linac period. The theoretical maximum over-all duty factor, assuming a 195ms "spill" for each of the four 200ms cycles, is 56%. Any reduction of the "spill time" reduces the over-all duty factor. All other options of using multiple 5Hz linac cycles for a single Recycler spill cycle only reduce the maximum beam power available to the experimental program.

Recycler extraction for an 8 GeV experimental program is discussed in an internal report on the Accelerator Issues of Project X and presented to the Fermilab Accelerator Advisory Committee in August 07 and at the 1st Project X Accelerator Workshop in November 07. The goal of the Recycler Extraction four year R&D plan is to evaluate the feasibility of resonant and bunched beam extraction or suggest alternative facilities for providing beam to an 8 GeV experimental program and prepare a technical design report of the feasible techniques.

Although there are no approved experiments at this writing, each of the techniques must be evaluated in terms of RF bunch structure, instantaneous beam intensity, spill duration, duty factor, and beam loss. This will allow potential experimental programs to evaluate the compatibility of their experimental needs with the reality of Recycler 8 GeV extraction. This R&D program must utilize the input of the needs of potential experimental programs to assure a match between the needs and what can be provided from either the Recycler or an alternative facility.

Req. No.	Description	Req.	Unit	Reference Requirements			
7.0	**8 GeV Slow Spill**						
7.1	8 GeV Slow Spill Beam Power	200	kW	1.3			
7.2	Peak Spill Rate	280	x10^{12} pps	1.3	1.4	7.5	
7.3	8 GeV Slow Spill Duty Factor	55	%	1.4			
7.4	8 GeV Availability	80	%	1.6			
7.5	Cycle Time	1.4	S	6.1			
7.6	Peak Recycler Beam Current for slow spill	0.8	A	7.2			

Table 7. Requirements for 8 GeV Slow Spill

8 GeV Slow Spill Issues

Resonant Extraction

The initial Recycler 8 GeV half-integer extraction simulations utilized the tracking program written for MI 120 GeV resonant extraction. Although a simplified Main Injector lattice (which to first order closely resembles that of the Recycler) and estimated beam parameters were used, the results allowed a general comparison of the circulating and extracted beam phase space features at the electrostatic septum and extraction Lambertson. Inspection of the phase space at the entrance to the Lambertson showed the lack of a separation between the circulating and extracted phase space. Closer inspection showed this overlap in radial position of the low momentum extracted beam with the high momentum circulating beam. This initial comparison illustrated a number of issues that need to be addressed.

The major issue of implementing resonant extraction in the Recycler at 8 GeV is generating an appropriate phase space at the extraction Lambertson <u>and</u> contain both the stable and unstable phase space within the physical aperture during the extraction process. The factors that lead to these issues are: 1) the large transverse beam size at 8 GeV as compared to 120 GeV (σ = 4.7mm vs σ=1.3mm at the septum with a β~50m), 2) the potentially large momentum spread (dp~0.15% vs dp ~0.04%) , 3) the potentially larger chromaticity (ξ=-10 vs ξ=-5) to combat instabilities, 4) the smaller horizontal physical aperture (+/- 59mm in the MI vs +/-47.625mm in the Recycler), and 5) potential increased losses on the electrostatic septum due to the smaller step size at the septum wires.
Other issues that need to be addressed are:

- Lattice requirements in terms of the existing gradient magnet harmonics, any new powered harmonic elements, and any modifications to the Recycler lattice that might be required for implementation of resonant extraction.
- RF beam structure requirements of the potential experiments and how to generate this beam structure and in a timely manner to maximize the spill duration.
- How to initiate the resonant extraction process in a timely manner to maximize spill duration.
- How fast the extraction process can proceed.
- The extraction point within the Recycler and the location of any new experimental facility.
- The loss mitigation and shielding requirements.

Although Fermilab has extensive experience with half-integer extraction, one outcome of the Recycler working group at the Project X Accelerator Workshop, was the suggestion of investigating third-integer resonant extraction. This suggestion has been incorporated into the current R&D plan.

Bunched Beam Extraction

Fermilab currently utilizes bunched beam injection and extraction techniques in the Main Injector and Recycler with magnetic kickers with rise and fall times of 50 to 700 ns and up to 1.6 us and flattop times from 1.6 us to 11 us flattop time. These correspond to box-car injection of booster batches into the MI, extraction of full turn beam to the abort, and Recycler single batch injection/extraction. However, to extract a single bunch from the 53 Mhz bunch train requires a kicker with a rise time on the order of 4-6 ns and pulse width of about 12 ns. As this requires a stripline kicker with a voltage limited to 20-30 kV, a two step extraction system is required. This fast kicker would displace a single bunch across the ground wires of an electrostatic septum which would in turn kick the beam across the septum of a magnetic extraction Lambertson, which might be the same septum/Lambertson combination utilized for resonant extraction.
The major extraction components are:

- The modulator/transformer which meets the rise/fall/flattop specifications and repetition rate.
- The stripline kicker.

- The electrostatic septum/magnetic Lambertson.
- Verification of the extraction design and lattice location.

Of these components all are straight forward with the exception of the modulator/transformer power supply. This will be the main focus of the R&D for bunched beam extraction.

8 GeV Slow Spill Plan

The major tasks (level 2) of the R&D plan include:

1. Physics Design of the extraction system.
2. Component Design.
3. Prototyping.
4. Specification of the Controls
5. Specification of the required instrumentation for the complete extraction system.

Under the Physics Design there are four (level 3) design tasks that should proceed approximately in parallel. These are 1) the evaluation of half integer extraction, 2) the evaluation of third-integer extraction, 3) the evaluation of any required RF manipulation, and 4) the evaluation of the bunch-bunch extraction technique. Regular evaluations on the progress of each technique will determine if continued R&D of the technique is warranted or a redirection of effort is required. Key to the evaluations are the intensity, duty factor, and bunch structure requirements of the potential experimental program(s). The evaluations will conclude with a decision point on the most feasible extraction design(s) capable of meeting the needs of the experimental program(s). These evaluations must specify the parameters for any RF system, magnet, controls, and instrumentation required. Based upon the decision an option is included for experimental verification of the selected design(s), which is included as a fifth (level 3) task.

A predecessor to starting any of the resonant extraction evaluations is the first pass modified Recycler injection lattice and an understanding of the harmonic components of the Recycler magnets. In addition, the extraction point should be specified and expected beam parameters defined. It is anticipated that there will be iterations of lattice design and beam parameters between groups involved with Recycler Ring R&D and Extraction Design R&D. To allow the half and third-integer evaluations to progress in parallel it is expected that two different design groups will participate. The evaluation of any required RF manipulations will be advised by potential experimental needs and feed results to the resonant extraction groups.

The detailed evaluation of the half and third integer extraction must take into account, but not limited to, A) the RF and bunch structure which determines i) the bunching factor and the transverse space charge tune shift, ii) momentum spread, and iii) bunch length, B) existing magnet harmonics, C) the new/additional harmonics required, D) the evaluation of the physical and dynamic aperture which will determine the radius at which the septum may be placed, E) the location of the extraction system and the impact on the existing facility.

There are two major tasks in the bunched beam extraction evaluation which are 1) the evaluation of the feasibility of the concept and 2) the design (and potential prototype) of the modulator/transformer kicker power supply system. The predecessor to this task is the specification of the new Recycler injection lattice, specification of the extraction point, and the expected beam parameters.

The level 2 tasks of Component Design, Prototype, Controls, and Instrumentation would start once the decision on the extraction design has been reached. The specification of performance parameters is expected to be developed during the extraction evaluations. It is anticipated that these tasks could proceed almost in parallel. It is assumed that no significant design work on a magnetic septum is needed as the current septum that will be used for Nova will be used.

8 GeV Slow Spill Schedule

FY08

The first year two groups look at half and third integer Recycler extraction design in parallel. Prior to starting, the Recycler injection lattice with its magnet harmonics must be determined. In addition, the RF manipulations required for various bunch structures is investigated, in conjunction with experimental requirements input, and communicated to the groups evaluating spill options. In addition to the resonant extraction, initial optics calculations for a bunch-by bunch extraction are to be performed. Milestone are included in the plan for continuing evaluations based upon feasibility of meeting the needs of the 8 GeV experimental program. These milestones allow for the redirection of effort in cases where the compatibility with the experimental program is not present. Labor consists of scientist with drafting support

FY09

The promising extraction techniques from the first year R&D program will continue to explore the feasibility and limits. The bunch by-bunch extraction begins to look at component designs which work with the optical design. By the 3/4 mark of the year the half and third integer extraction designs should be at a point where a decision can be made as to which, if any, will meet the performance specifications set out by the accelerator and experiments. This should be a milestone at this point. At about the same point, bunch-bunch extraction should be evaluated for design, feasibility, and need and a decision should be made to continue or stop design and R&D for the fast kicker.

FY10

Depending on the result of the half and third integer resonant extraction choice, an experiment could be designed in the MI to test out the extraction process at 8 GeV during the latter part of 2010. The parameters and machine requirements are not known at this time to determine if this step is even feasible. In addition the design work on the electrostatic septum and the shielding are started. In addition some work is started on the instrumentation and controls.

FY11

The last year in devoted to component design and preparation of the TDR. The harmonic elements are designed during this last year. The work on the prototype electrostatic septum and fast kicker and supplies finishes. Design work on the instrumentation and controls continues.

III.7 Neutrino Beamline

Neutrino Beamline Requirements

For Project X the essential nature of the neutrino production process remains unchanged from existing operations. The first step in the production of neutrinos is directing a beam of 120 GeV protons from Fermilab’s Main Injector onto a production target. Interactions of the proton beam in the target produce mesons (mainly pions and kaons), which are focused toward the beam axis by two magnetic horns. The mesons then decay into muons and neutrinos during their flight through a long decay tunnel. A hadron absorber downstream of the decay tunnel removes the remaining protons and mesons from the beam. The muons are absorbed by the subsequent earth shield, while the neutrinos continue through to an experimental hall at Fermilab and onwards toward "far" detectors.

The initial Project X report outlined two 120 GeV target scenarios; building a completely new neutrino beamline aimed at DUSEL and upgrading the NuMI neutrino beamline. A new target hall aimed at DUSEL could handle greater than 2 MW with current technology, but would require the excavation of a new underground target hall. However, the new target hall to DUSEL options is not considered in this report and the focus is placed on the upgrade of the existing NuMI facility.

The NuMI target hall was designed and built with the capacity to handle 400 kW of beam power and will be upgraded to 700 kW as part of the ANU project for NOvA. For Project X the NuMI beamline is required to accept up to 2.3 MW of beam power from the Main Injector with a cycle time of 1.4 seconds and 1.7×10^{14} protons per pulse on target. With the limited statistics inherent in long range neutrino experiments the reliability of the NuMI facility is an important requirement for the accumulation of a large number of protons on target. The goal of 75% uptime for neutrino production, along with the uptime requirements for the accelerator components, leads to a 80% uptime for the NuMI facility. Experience with the MINOS and NOvA experiments show that the beam, target, and horns must be well aligned in order to maintain a reasonable systematic error resulting from shifts in the neutrino spectrum. This places a requirement of ±1 mm on the relative alignment of the target hall components.

Req. No.	Description		Req.	Unit	Reference Requirements			
8.0	**120 GeV Targeting**							
8.1		120 GeV Beam Power	2.3	MW	1.1			
8.2		120 GeV Availability	80	%	1.5			
8.3		Cycle Time	1.4	S	6.1			

Table 8. Requirements for the 120 GeV Neutrino Beamline

Neutrino Beamline Issues

The requirements placed on the NuMI facility lead to issues in three broad categories. The first is the development of a proton target and magnetic horn system capable of handling 2.3 MW of beam power at 120 GeV. Increasing the beam power from 700 kW in the NOvA era to 2.3 MW for Project X will require new designs for target and horns. The second category of issues is related to increasing the beam power to an already existing facility. Project X will place a factor of 5.7 more beam power into the NuMI facility than the original NuMI design. Since the NuMI beamline was conservatively designed, initial estimates predict that the NuMI target hall could be upgraded to handle about 1-2 MW of beam power by taking advantage of the redundancy in the initial design. Much more engineering effort will be needed to understand the limits of the existing NuMI facility. The third category of issues is related to the reliability and uptime of the NuMI facility. Current experience with the NuMI target station has shown that repairs to activated components are more common than was initially expected. Manual repairs can be done with extreme care and coordination, but with increased activation levels at Project X intensities the installation, repair, removal, and storage of activated components remains problematic. The development of remote handling techniques will be a major (and likely costly) issue.

Initial considerations have already identified a number of specific issues. The most important challenge is the understanding of the limits on the decay pipe window. The decay pipe window is a $1/16^{th}$ inch think aluminum window at the upstream end of the decay pipe and is used to separate the target hall from the decay pipe volume which is filled with helium gas. Thermal stress and radiation accelerated corrosion can limit the lifetime of the window and eventually lead to mechanical failure. Since the window is in an area with high rates of residual radiation and buried by tons of concrete and steel shielding a direct repair is not possible. Therefore a method for replacing the window remotely with robotics must be developed.

A new design for the target is also needed. Initial estimates suggest that a cylindrical graphite target within an aluminum water cooled shell will be able to handle 2 MW of beam power. Further analysis, design, and prototyping of this type of target are needed before a conclusion can be reached on the viability of this target design. Investigation into other target options is also needed including geometric design, cooling systems, window design, and target material choices.

Another issue is related to the increased radiation levels expected from operating the NuMI target hall at 2 MW. This includes the levels of residual radiation, airborne emissions, and ground water protection. An environmental assessment has already been performed for operations at 1.5 MW and no environmental concerns are expected to be problematic for operations at 2.0 MW, but upgrades to the air and water handling systems are probably needed. Perhaps the largest challenge related to the increased radiation levels is the handling of radioactive components. This includes removal of failed components, installation of spares, and the repair of activated components.

Neutrino Beamline Plan

Addressing these issues and developing solutions will be part of a several year R&D plan. The individual elements of the plan are discussed in the next.

Primary Beam Line Profile Monitor Design

Design and prototype profile monitors for the primary beamline that are able to withstand the higher beam power. Analyze the stress and cooling needs of primary beamline window and design a system for the extra cooling of the beampipe window.

Secondary Beamline

Target Design

Examine alternatives to current graphite target material. Calculate target stress for accident conditions. Analyze target windows for stress and cooling requirements. Prototype and test several different cooling schemes for the target. Iterate on the target design to optimize the neutrino production efficiency. Integrate target design. Prototype and test target.

Magnetic Horn Design

Analyze horn heating and stress, and design any necessary cooling upgrades. Analyze variation in horn inner conductor shapes to optimize beam for next generation off-axis detector. Prototype increased cooling. Build and test pulse a prototype horn.

Module Upgrades

Determine alignment stability requirements, and design module support to specified requirements. Analyze module for increased cooling needs. Build and test remote electrical connectors for Budal monitors, thermocouples, and horn magnetic field bdot coils. Test corrosion-resistant radiation-hard surface coatings. Re-design of target motion capability in light of higher corrosion conditions.

Target Chase Cooling

Analyze energy depositions near target to determine requirements for "heat shields". Design water-cooled panels to be inserted in target chase as "heat shields", along with remote water-pipe connections and support RAW skid.

Decay Pipe Window Replacement

Develop plan to enable replacement of decay pipe window. Explore concept of remote installation by robot arms, with access through chase. Prototype the necessary robotics.

Decay Pipe System

Design and prototype a system to re-circulate helium, scrubbing out tritium and air. Design skid to increase water flow through decay pipe cooling lines. Analyze for maximum beam power allowed given increased water cooling flow and helium in decay pipe. Determine need for system to compensate helium pressure for beam heating, and if required, design the system

Hadron Absorber Design

Analyze water-flow failure case, and design mitigation. Boroscope inspection of current state of absorber - check for signs of corrosion. Analyze need for water skid increased heat removal capacity.

Remote Handling

Issues related to component installation, removal and repair in radioactive environment. Design and build prototype remote handling equipment.

Radiological Issues

Perform further analysis of groundwater, surface water, air emissions, RAW systems, prompt and residual radiation, and shielding assessment.

Infrastructure

Analyze target hall air; determine if mitigation is needed to reduce the corrosive atmosphere of the target hall air. Track deterioration of crane rails, drip ceiling, decay pipe passageway rebar, etc, and determine needs for any mitigation.

Neutrino Beamline Schedule

FY08

- Target design begins.

- Study of decay pipe window begins.

FY09

- Target design continues.
- Magnetic horn design begins.
- Module upgrades design begins.
- Study of decay pipe window continues.
- Study of decay pipe system.
- Remote handling study begins.

FY10

- Target design concludes.
- Magnetic horn design continues.
- Module upgrades designs conclude.
- Target chase cooling design begins.
- Study of decay pipe window continues.
- Hadron absorber design begins.
- Remote handling study continues.
- Radiological study begins.
- Infrastructure design.

FY11

- Magnetic horn design concludes.
- Target chase cooling design concludes.
- Study of decay pipe window concludes.
- Hadron absorber design concludes.
- Remote handling study concludes.
- Radiological study concludes.

III.8 Civil Construction and Utilities

Civil Construction Requirements:

- Front End enclosure
- Linac tunnel enclosure to house beamline
- Front End and Linac service buildings for support utilities and assembly/storage/operational space
- Linac Beam Abort enclosure
- Transfer line tunnel
- Transfer Line service buildings
- Tunnel connection to Main Injector tunnel
- Cryogenic facilities (new CHL?)
- Injection Abort enclosure
- Site preparation

- Wetland mitigation
- Plan for One-for-One Replacement Requirement for facility square footage
- LCW and Vacuum Utilities

Civil Construction Issues

1. How does existing design for Proton Driver facilities meet PX requirements?
2. Wetland mitigation options – whether to develop onsite or buy credits off site
3. What existing facilities (Linac, Booster, Antiproton, Tevatron) remain active or in “hot spare” mode, and thus eliminate reuse of existing capabilities, such as cooling, power?
4. How can existing cryo facilities possibly be reused to reduce cost?
5. Is large injection abort required (significant civil construction required) or can it fit into existing tunnel near MI10?
6. Does One-for-One Replacement Requirement need to be satisfied with demolition on the Fermilab site, or can space elimination be found on other DOE lab sites? If on site, which buildings can be demolished and what is the extent of decontamination required?

Civil Construction Plan

1. Conduct systematic review of PX technical requirements with L2 managers and compare to existing design.
2. Post CD-0, conduct NEPA scoping meeting with DOE, meet with Army Corps of Engineers to understand mitigation ratio requirement, evaluate cost of each option.
3. Work with lab management to get agreement on what facilities can be tapped for reuse in PX.
4. see #3
5. Await information from scientists on requirements, then incorporate into plan.
6. Work with DOE Fermi Site Office to understand availability of other space banking from other sites, then work with Fermilab management to determine spaces on site for demolition. Refine and include this cost in the estimate for OPC.

Civil Construction Schedule

FY08

- Update existing Proton Driver design concept information with revised or additional scope with input from L2 managers (includes FESS/Eng) for CD-0 submission
- Revise cost estimate to match revised scope (includes FESS/Eng)
- Determine best approach for hiring of architect/engineer consultant
- CD-0 Approval achieved

FY09

- Begin NEPA process, including writing Environmental Assessment (involves entire project)
- Support submission of EA to DOE (involves entire project, need NEPA FONSI before CD-2)
- Apply for ACOE 404 wetlands permit (must be done for EA submission)
- Further develop criteria, then design and conceptual drawings in support of CDR

- Work on One-for-One Replacement Requirement plans (needed for CD-1 approval)
- Perform architect/engineer selection to help with drafting and graphics for CDR work in this phase (and other work later on)

FY10

- Work through iterations of EA to support achieving FONSI before CD-2
- Finalize conceptual design and drawings and text for CDR for CD-1 Review (includes FESS/Eng, A/E)
- Finalize status of existing facilities that could be reused for PX
- Contract with A/E for T1 work
- Perform Construction Manager selection for preconstruction services (estimating, constructability assessment)
- CD-1 Approval achieved

FY11

- Perform preliminary design (T1) and create drawings and text for input to TDR (includes FESS/Eng, A/E, CM) for CD-2
- Perform soil borings for facilities
- Provide input into resource-loaded schedule with cost estimate and schedule information
- Develop site preparation package to final design (T2) level for expected need for CD-3a approval (FESS/Eng, A/E, CM)
- Begin advanced conceptual design for other construction packages in preparation for CD-3b (FESS/Eng, A/E, CM)
- CD-2/3a Approval achieved

III.9 Controls

Controls Requirements

Project X will have about 9 km of beam line and 1 million device properties. It will have 10x more beam power, and it has some legacy constraints because it uses the Main Injector and Recycler. From these constraints we derive the base requirements:

- The control system shall support 200 users accessing 5000 properties at once.
- The control system shall have no less than 2500-hr MTBF and no more than 5-hr MTTR.
- The control system shall have an extensive machine protection mechanism, including hardware interlocks, software interlocks, access control, and alarms.
- The control system shall have a fast feedback system to control the beam trajectory and thereby minimizing routine beam losses causing components to be activated and radioactive.

The control system for the linac and transfer line must satisfy the following requirements to meet the legacy constraints:

- Timing signals shall be provided in a format that can be accepted by legacy hardware.
- Machine protection system inputs from legacy hardware shall be accepted.
- It shall be possible to acquire data from legacy hardware into applications and into a common archive for proper correlation across the complex.

- It shall be possible for applications in the legacy system to acquire data from new linac subsystems. It may not be necessary to support access to all devices and data acquisition protocols however.
- The alarms service shall be able to receive alarms generated by the legacy system.
- Applications that run on the legacy system shall be conveniently accessible to operators.

Detailed requirements for the controls can are documented in Project X Control System Requirements document.
"Project X Control System Requirements"
https://beamdocs.fnal.gov/AD-private/DocDB/ShowDocument?docid=2934

Controls Issues

The issues for controls can be divided into 4 basic parts: the scale, availability, safety, and legacy constraints.

Scale

In broad terms, Project X has a similar scale as the Tevatron considering the linacs, the beam injection line, the main injector recycler, and target station. Each device can have up to five properties, which means the Control System should be designed to control about one million properties. A generous assumption for maximum load is 200 users accessing the control system simultaneously. The average load is probably about 50 users.

Availability

The consequences of failure of a critical part of the control system can be devastating, so the availability of Project X has to be considered in the design for the control system. The ILC control system has a requirement of no more than 2500-hr MTBF (mean time between failures and no less than 5-hr MTTR (meant time to repair) and 15 hours downtime per year. Project X controls will have a similar requirement.

Safety

Project X is targeted for 2.3 MW. At 2.3MW, an accident can cause serious damage to people and equipment. This drives the requirements of a stringent machine protection system (MPS), such as hardware and software interlocks, access control, and alarms.

With high beam power, accidents are not the only concern. Just routine losses can activate components so that they fail more often and become difficult to work on due to residual radioactivity. To prevent this beam trajectories must be well controlled. This will likely require the control system to do fast feedback.

Legacy Constraints

At the time Project X begins operation, the Accelerator NUMI Upgrade will have been completed and the recycler, main injector, NUMI beam line, and 120 GeV fixed target lines operated for some years in that configuration. These elements will be controlled by an evolution of the current ACNET system. This includes field equipment, the timing system, front-end computers, services, and applications. While some changes will be needed in these accelerator components for Project X, the control system hardware and software represents a large investment that could be difficult to completely replace by the start of Project X operation. Hence the Project X control system must interoperate to some degree with the existing system

Controls Plan

The plan for controls is to start with modernizing the software infrastructure to provide a reliable and modern base for prototyping and application development by the Project X contributors. This will be done first so that it is available in time for Project X R&D (see previous sections). The infrastructure consists of low-level systems, central services, application framework, and the software build environment.

With the infrastructure is in place the design of the Machine Protection and Fast Feedback systems R&D begins. This is seen as a high priority and a major change from the current controls.

Once the MPS and Fast Feedback systems are in development the design on high-level applications can start. Examples of high-level applications are the sequencer, alarm displays, save and restore, and data-logger displays.

Controls Schedule

FY08

In the first year, the work will concentrate on the requirements and design to modernize the controls software infrastructure. This includes front-end software, central services, the applications framework, and the software build environment.

FY09

Machine Protection System R&D starts in parallel while the work on the controls software infrastructure begins implementation.

FY10

During the third year the controls software infrastructure design and development is accomplished and system testing becomes the main focus. Development of the Machine Protection System and beam feedback system begins.

FY11

After completion of the infrastructure upgrade, new features as listed in the requirements document are being designed and developed. The Machine Protection and Beam Feedback systems are finishing development and being tested.

III.4 Work Breakdown Structure

A Work Breakdown Structure (WBS) has been created based on the scope of work described above. The WBS is described at level two in Appendix A. The actual WBS goes to level three and is used as the basis of the Resource Loaded Schedule for the R&D Program.

IV. R&D Plan

The R&D plan is assembled from the Plan Elements listed in Chapter III, in a manner that meets the overall program goals outlined in Chapter II. The plan is based on a resource loaded schedule (RLS) and includes:

- Schedule of activities and associated technical and management milestones;
- Organization and management plan;
- Integration with the ILC, SRF, and HINS R&D programs;
- Resource requirements, and yearly profile.

The RLS described here covers the period through CD-2/3a (end of FY11).

IV.1 Schedule

A resource loaded schedule has been developed to capture all activities and associated resources required to execute the program described in this document. The work is organized in terms of the WBS described in Appendix A. The schedule is determined by the pace of funding, the availability of technical resources, and the requirements of DOE 413.3. The Project X R&D Plan Master Schedule is shown in Figure IV.1. A corresponding list of major milestones is presented in Table IV.1. Resource requirements are described in Chapter IV.4

Figure IV.1: Project X R&D Master Schedule

Project X R&D Plan
WBS Level 2

WBS	Task Name
1	**General - R&D**
1.1	Integration
1.2	**Project Management**
1.4	Cryogenic Plant
1.5	**Milestones**
2	**325 MHz Linac**
2.0	Project Management
2.1	Physics Design
2.2	Ion Source
2.3	Cavities
2.4	RF Systems
2.5	Magnet Systems
2.6	Cryogenics
2.7	Controls
2.8	Instrumentation
3	**1300 MHz Linac**
3.0	Project Management
3.1	**Physics Design**
3.2	**Linac Technical Design**
3.3	**RF Power Systems**
3.4	**Integration**
3.5	**System Tests**
4	**8 GeV Transfer Line**
4.0	Project Management
4.1	**Physics Design**
4.2	**Component Design**
4.3	Power Supply Design
4.4	**Vacuum System Desgin**
4.5	Controls
4.6	Instrumentation
5	**Recycler**
5.0	Project Management
5.1	**Physics Design**
5.2	Magnet and Power Supply Design
5.3	Controls
5.4	Instrumentation
6	**Main Injector**
6.0	Project Management
6.1	**Physics Design**
6.2	**Electron Cloud**
6.3	**RF Systems**
6.4	Controls
6.5	**Instrumentation**
7	**8 GeV Slow Spill**
7.0	Project Management
7.1	**Physics Design**
7.2	**Component Design**
7.3	**Prototypes**
7.4	Controls
7.5	Instrumentation
8	**Neutrino Beamline**
8.0	Project Management
8.1	Primary Beamline
8.2	**Secondary Beamline**
8.3	Remote Handling
8.4	Radiological Issues
8.5	Infrastructure
9	**Civil Construction and Utilities**
9.1	Project Management
9.2	Linac, Gallery, Front End Bldg
9.3	Cryo Plant
9.4	Center Bldg, Transport Line, Linac Absorber
9.5	Transport Line West of Absorber
9.6	MI Connection
9.7	Site Development
9.8	Space Offsets
9.9	MI RF Upgrade Infrastructure
9.10	Cooling Pond Upgrades
10	**Controls**
10.1	Hardware
10.2	Software
10.3	Machine Protection
10.4	Synchronization

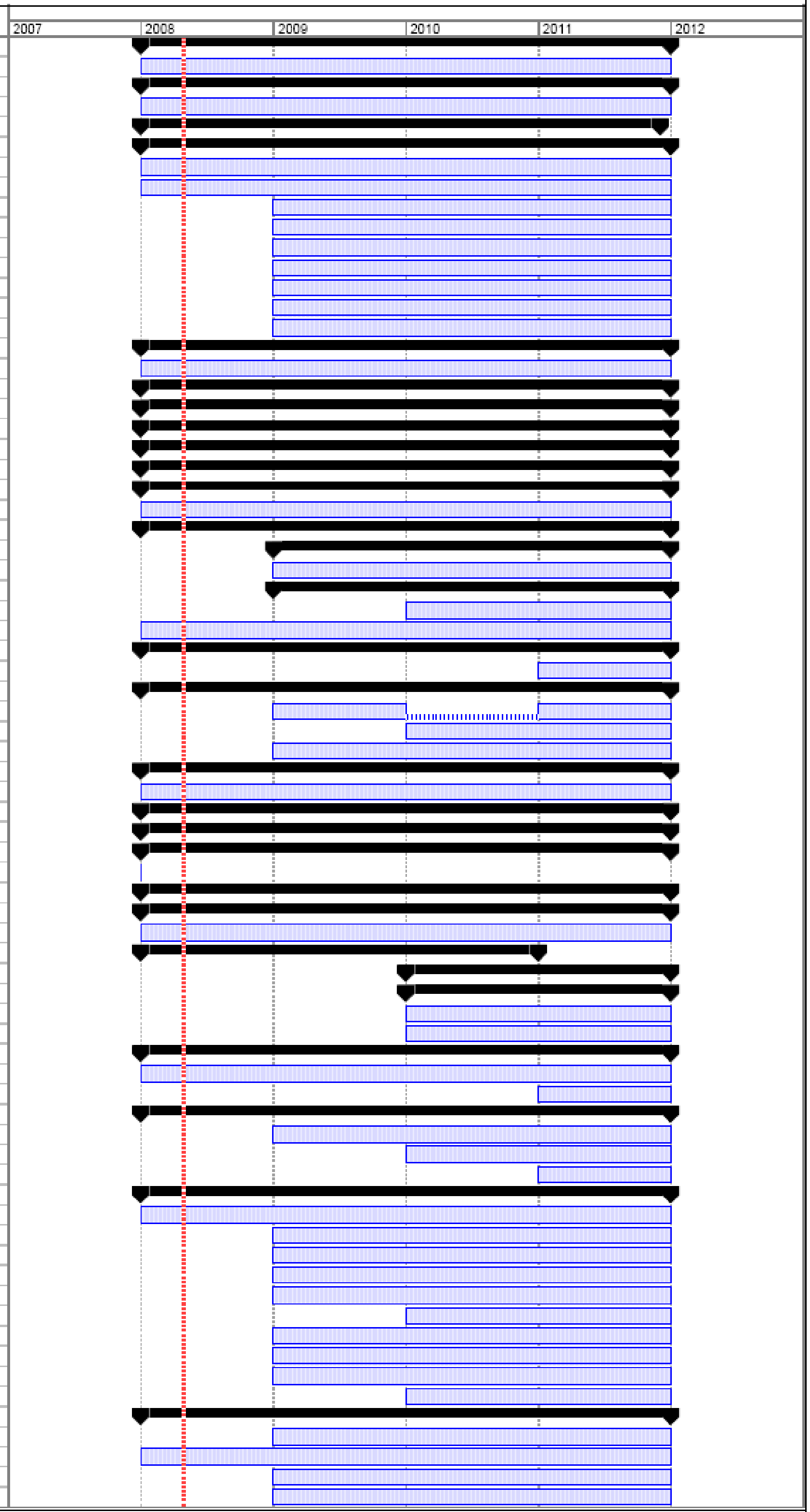


Table IV.1: Project X R&D Major Milestones

CD-0 Approved	8/1/08
Start CD-1 Documentation	9/1/08
Complete CD-1 Documentation	4/1/10
Start CD-2 Documentation	5/3/10
CD-1 DOE Review	6/1/10
CD-1 Approved	8/2/10
Complete CD-2 Documentation	4/1/11
Start CD-3 Documentation	5/2/11
CD-2 DOE Review	6/1/11
CD-2/3a Approved	9/1/11

IV.2 Organization and Management Plan

Fermilab does not have the personnel resources to undertake the Project X R&D Program, or a follow-on construction project, on its own. As such, the intention is to organize and execute the R&D Program via a multi-institutional collaboration, drawing significant participation from outside of Fermilab. The goal is to give collaborators complete and contained sub-projects, meaning they hold responsibility for design, engineering, estimating, and potentially construction if/when Project X proceeds. In parallel with establishing a functional collaboration the full suite of project documentation and project management systems required under DOE 413.3 will have to be completed in support of the various mandated Critical Decisions. The general principles that we foresee being applied to the creation of the collaboration are outlined below.

Collaboration Structure

The Project X R&D Collaboration will be established via a Collaboration Memorandum of Understanding (MOU) that will outline the basic goals of the collaboration, and the means of organizing and executing the work. Organizing principles for the collaboration are expected to include the following:

- Fermilab will hold responsibility for management of the Project X R&D program. This includes appointment of the R&D Program Leader.
- The Project X R&D Program Leader will hold overall responsibility for execution of the R&D Program. This includes: organization and management of the Project X team; development of a reviewable/defensible accelerator physics and engineering design to achieve CD-2/3a, including identification of possible upgrade paths; organization of a supporting R&D program; preparation of periodic progress reports; and development of a reviewable/defensible cost estimate and schedule for a Project X construction project.
- The Program Leader will be assisted in these responsibilities by a Project Team assembled by the Program Leader in consultation with the Fermilab Management and Collaboration Council.
- A Collaboration Council will be established for the primary purpose of advising and assisting the Project Leader in the area of inter-laboratory coordination. The Collaboration Council will consist of representatives of the collaborating institutions.

- The Fermilab Directorate, in consultation with the Collaboration Council, will establish and receive technical advice from a Project X Technical Advisory Committee.
- Interactions between the collaboration members will be governed by a series of bi-lateral (or multi-lateral, where appropriate) MOU's. These MOU's will define specific division of labor between collaboration members, funding mechanisms, and associated deliverables.
- It is anticipated that the Project X R&D Program will be undertaken as a "national project with international participation". From the organizational perspective there is no distinguishing characteristic between national and international institutions, and so the expectation is that the same structure of MOUs described above would establish the participation of international laboratories.

Fermilab Internal Organization

Fermilab has established an internal organization for coordinated management of the Project X and ILC/SRF programs. Program organizations are established with reporting lines within the Fermilab Directorate via the Associate Director for Accelerators for Project X, and the ILC Program Director for ILC and associated SRF infrastructure. Both of these programs are managed and coordinated via a Project Management Group jointly chaired by the Associate Director for Accelerators and the ILC Program Director. Within this organization a single 1.3 GHz program has been created to support the needs of both ILC and Project X.

IV.3 Alignment with the ILC, SRF and HINS Programs

The U.S. is investing significant resources in ongoing ILC, SRF and HINS (High Intensity Neutrino Source) R&D programs. The U.S. effort on ILC is managed by the Americas Regional Team (ART) as part of the larger global effort being coordinated by the ILC/Global Design Effort (GDE). The SRF effort is building superconducting rf infrastructure at Fermilab and other U.S. laboratories that can be used to support the needs of ILC and other superconducting accelerator based efforts. Fermilab is responsible for coordination of the latter program. All of these programs share significant overlap with the technology requirements of Project X. Fermilab has adopted a strategy of maximizing alignment of technology performance parameters among the programs as a means for both providing maximally efficient utilization of existing resources while simultaneously providing maximum flexibility for the future. In particular, and as described in Chapter I, Project X has been configured to allow full overlap with currently defined ILC beam parameters, and as described in Chapter IV.2 the 1.3 GHz program that is common to ILC and Project X activities at Fermilab now has an integrated management structure.

Goals of the ILC, SRF, and HINS programs

These programs are all aiming for significant deliverables over the period 2010-2012. Goals and research plans for the ILC, SRF, and HINS programs are documented elsewhere, but summarized below. These goals are aligned with the requirements of the strategic decision making process outlined in the Fermilab Steering Committee Report described in Chapter I.

The GDE managed ILC program has developed a set of goals aimed at demonstrating a cost effective cryomodule design that meets ILC performance requirements. Responsibility for ILC cryomodule development is shared between Fermilab, Asian, and European institutions. The XFEL project at DESY, with production at a rate of roughly one/week starting in late 2010, is expected to provide critical input to the cryomodule design.

A goal of the Americas Regional Team (ART) managed U.S. program is to support the development of domestic capabilities for cavity fabrication, processing, and testing and the development of rf sources (centered at SLAC). The ART program directly supports the ILC cryomodule development goal (S1) through the design, construction, and testing, with U.S. industrial participation, of multiple ILC cryomodules, and the operations of three of these cryomodules with beam at the ILCTC_NML test facility at Fermilab. This program is also supported by, and coordinated with, a domestic SRF program aimed at creating infrastructure to enable these goals. In particular, the U.S. SRF program is aimed at developing infrastructure sufficient to achieve a capability of producing cryomodules meeting the ILC operational specification at a rate of 12 cryomodules/year by 2012.

The goal of the HINS program is to demonstrate a new technological approach that could support the acceleration of high intensity, non-relativistic, H^- (and other ions).

The basic Project X development strategy is to carry a 1.3 GHz linac design compatible with an operating accelerating gradient in the range 23.6 MV/m (XFEL design) to 31.5 MV/m (ILC design) through the conceptual design stage, and to select the final design gradient in advance of CD-2 based on the current state of development. In relation to HINS the strategy is to provide coordination between the programs, with a decision on whether to adopt HINS developed technologies for the Project X linac front end in advance of CD-2 based on consideration of cost, risk, and long term upgrade paths.

An important component of the GDE/ILC program over the next several years is development of a cost effective civil construction design. Nearly all utility infrastructure that Project X has in common with ILC (power distribution, HVAC, cooling, cryogenics, etc.) involves Fermilab resident expertise that can be shared between the ILC and Project X efforts. This allows the opportunity for the shared development of cost effective designs in these areas.

Key goals of these programs, and comparison to Project X requirements, are described in Table IV.1. Goals are generally targeted in the 2011-2012 timeframe.

ILC/GDE Goals	Project X Requirements	Comments
Develop a final ILC cryomodule design and produce several cryomodules in each of the three regions.		Project X CM design will be based on ILC design.

Successfully assemble and test a cryomodule operating with an average gradient of 31.5 MV/m.	Operating gradient in the range 23.6-31.5 MV/m	PX gradient decision to be made in advance of CD-2
Successfully test a complete ILC rf unit with beam	Successful high power testing of cryomodules prior to construction	Macroscopic beam properties are same for ILC and Project X, microscopic are different.
Integration of industry within the cryomodule design and development program, leading to a cost effective manufacturing process.		Based on XFEL experience in Europe
Develop 10 MW rf power/distribution source	Requires ~13 ILC power sources	Project X does not require development of alternatives to ILC baseline klylstron and modulator.
ILC/ART Goals		
Qualify at least one US vendor as a reliable source of cavities meeting ILC specification (35 MV/m, 95% yield)	90% yield at an operating gradient in the range 23.6-31.5 MV/m, to be determined prior to CD-2.	Current yield from European vendors ranges from 80% at 28MV/m to 50% at 31.5 MV/m. U.S. vendors are just entering the game.
Production and testing of several cryomodules, including at least one based on the final ILC design	Require at least three CMs for initial systems test.	ILC design is directly applicable to Project X above 1.2 GeV.
SRF Goals		
Create processing, assembly, and test facilities that that will support a US capability of 12 CMs/year by 2013.	Capability of 12 CMs/year at the start of construction	Project X requirement is assembly of forty 1.3 GHz cryomodules over four years.
Test at least three ILC cryomodules by 2012.	Successful high power testing of cryomodules prior to construction	
Test one complete ILC rf unit (3 cryomodules) with beam by 2012		Integrated systems test for Project X; not necessarily required prior to start of construction.
HINS Goals		
Demonstrate 60 MeV acceleration of H^- at 27 mA × 3 msec × 10 Hz with superconducting cavities	9 mA × 1 msec × 5 Hz	Project X requirements are less demanding than HINS; HINS may represent upgrade path.
Demonstrate multiple room temperature and superconducting cavities driven from a single rf	Requires multiple superconducting cavities driven from a single rf	Warm-cold cavity combination from single rf source not required for

source	source	Project X.
Demonstrate high rate beam chopping at 2.5 MeV	Required	

Table IV.1 Comparison of goals of ILC, SRF, and HINS programs with Project X requirements.

Strategy for Aligning Project X Requirements with the ILC and SRF Programs

The ILC and SRF programs as currently structured meet the goals established by the ILC GDE in the context of a 2012 completion of the Technical Design. The major components of these programs that are shared with Project X involve the development of a global cryomodule design, construction of infrastructure and test facilities aimed at cryomodule fabrication and testing, and the construction/testing of several cryomodules meeting ILC specifications. The major test facility being constructed is the ILCTA-NML (ILC Test Accelerator at the New Muon Lab), that will support beam operations of a complete ILC rf unit. While there is considerable overlap between the needs of the ILC program and the needs of Project X, there are differences in requirements that affect the scope of the infrastructure and beam tests planned for the ILCTA-NML. The primary differences are that Project X beam structure does not require the very short bunches required for the ILC test and the primary Project X need is for an integrated systems test, not determination of cryogenic heat loads generated by beam driven higher order modes in the cavities (as for ILC). As a result the ILCTA-NML facility could be simplified in a number of ways to accommodate Project X requirements:

- The facility will still be based on an electron source producing ILC/Project X beam parameters as no relativistic H^- source is available. The 9 ma average current, with a 1 msec pulse length will be provided, but not the specific ILC or Project X bunch spacing or duty factor.
- The photoinjector and bunch compressor required for ILC tests can be replaced with a simple thermionic gun. A capture cavity to accelerate the beam to 30 MeV will still be required.
- A new refrigerator system is not required to support operations, which will take place at a more modest (<2 Hz) repetition rate.
- An extension to the NML building is not required.

The total impact of these simplifications is to reduce the cost of the NML facility by roughly 20%.

The configuration described above still supports substantial progress toward ILC (S1 and S2) goals, most notably demonstration of stable high-power operations (9ma × 1 msec) at nominal ILC gradient. The option for subsequent expansion to match the full suite of ILC goals is preserved through this approach.

Resource Requirements for the ILC, SRF and HINS Programs

Table IV.2 displays the ILC, SRF and HINS funding profiles, including only those components that are directly associated with Project X. The ILC Cavities and Cryomodules line, and ILC RF

Power lines are currently unknown due to restructuring of the ILC program taking place following passage of the FY2008 budget. These numbers will be determined following release of the President's FY2009 Budget Request in early February. Integration with Project X could proceed on the schedule shown if ILC were able to produce three complete cryomodules for testing in early FY2011, and a klystron and modulator that could support beam tests at ILCTA_NML in FY2012. The achievement of ILC S1 cromodule goals is more than adequate for supporting Project X goals. (S0 goals are not required). An rf system based on the multi-beam klystron (MBK) and standard PFN modulator with bouncer are also sufficient for Project X. The SRF Infrastructure line includes the modified ICLTA_NML facility supporting some critical ILC S2 goals. All costs are fully burdened and in then-year dollars. Note that the table does not include the Project X R&D Plan funding discussed later in this chapter (section IV.4).

Table IV.2: Funding profiles for those components of ILC, SRF, and HINS programs associated with Project X.

	ILC, SRF, and HINS Program Funding (Dollar amounts in millions, fully burdened)					
	FY08	FY09	FY10	FY11	FY12	FY13
ILC Cavities & Cryomodules	$5.7	TBD	TBD	TBD	TBD	
SRF Infrastructure	$5.0	$23.5	$23.5	$23.5	$23.5	$10.0
ILC RF Power	$0.0	TBD	TBD	TBD		
HINS	$10.8	$10.8	$10.8	$5.7		

This SRF and HINS funding profiles supports the following deliverables:

SRF Infrastructure:

- Facilities capable of assembling 1 cryomodule/month
- Test facility capable of testing a single ILC unit (3 cryomodules) with the ILC/PX beam current and pulse length, at 1 Hz repetition rate. (ILCTA_NML)

HINS:

- A 60 MeV front end H- linac capable of 27 ma x 3 ms operation, based on superconducting spoke resonators and an rf distribution system utilizing ferrite vector modulators.

IV.4 Resource Plan

The Resource Loaded Schedule described in IV.2 is used to produce resources requirements for the Project X R&D Plan. The proposed budget requirements are shown in Table IV.3 and the distribution of cost by WBS (i.e. major system) if Figure IV.2. The table presents costs accounting as would be required for an R&D activity associated with a potential project being developed under the requirements of DOE 413.3: Costs are in escalated per standard DOE rates and include all relevant indirect costs. Scientist salaries are not included in the projected costs (although scientist effort is captured in the RLS). A more detailed breakdown at WBS level three is given in Appendix C.

Table IV.3: Budget profile for the Project X R&D Plan as derived from the resource loaded schedule.

	Project X R&D Plan Budget Profile (Dollar amounts in millions, fully burdened)					
	FY08	FY09	FY10	FY11	FY12	TOTAL
SWF	$6.7	$10.5	$19.1	$26.3		$62.6
M&S	$1.5	$4.9	$6.2	$13.7		$26.3
TOTAL	$8.1	$15.5	$25.4	$40.0		$88.9
	CD-0		CD-1	CD-2/3a		

As noted in the table, R&D effort extends through 2011. It is anticipated that Preliminary Engineering Design (PED) funds will be utilized in FY2011, assuming receipt of CD-1 in mid-2010. While the budget displayed in the table is based on current Fermilab labor rates, this encompasses the entire effort required to support the R&D program through CD-2/3a, and will be distributed over the Project X R&D Collaboration in a manner to be determined by the collaboration.

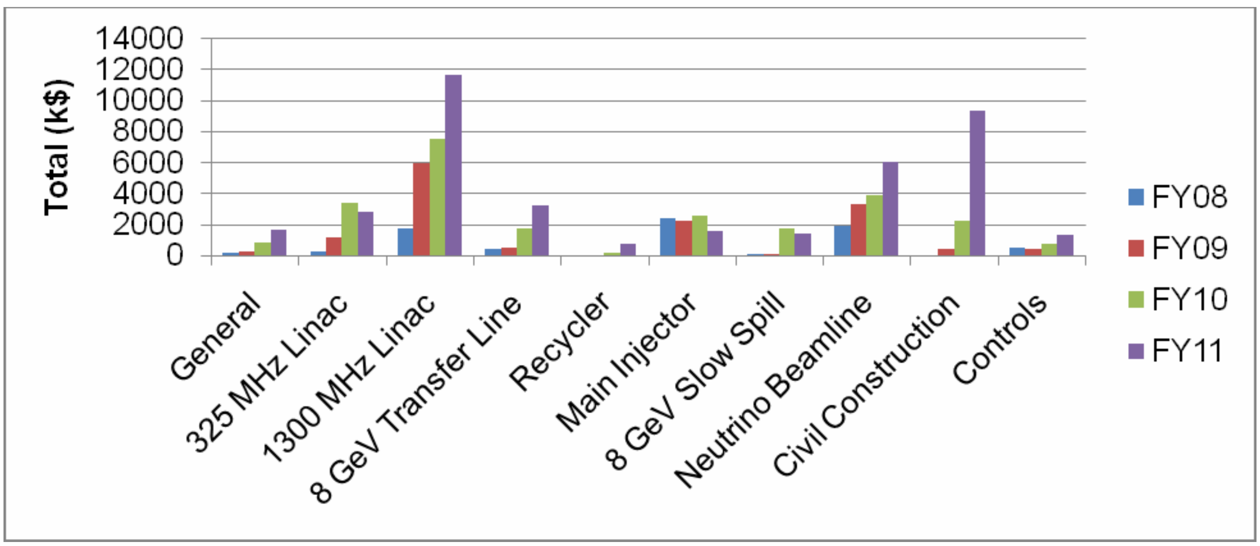
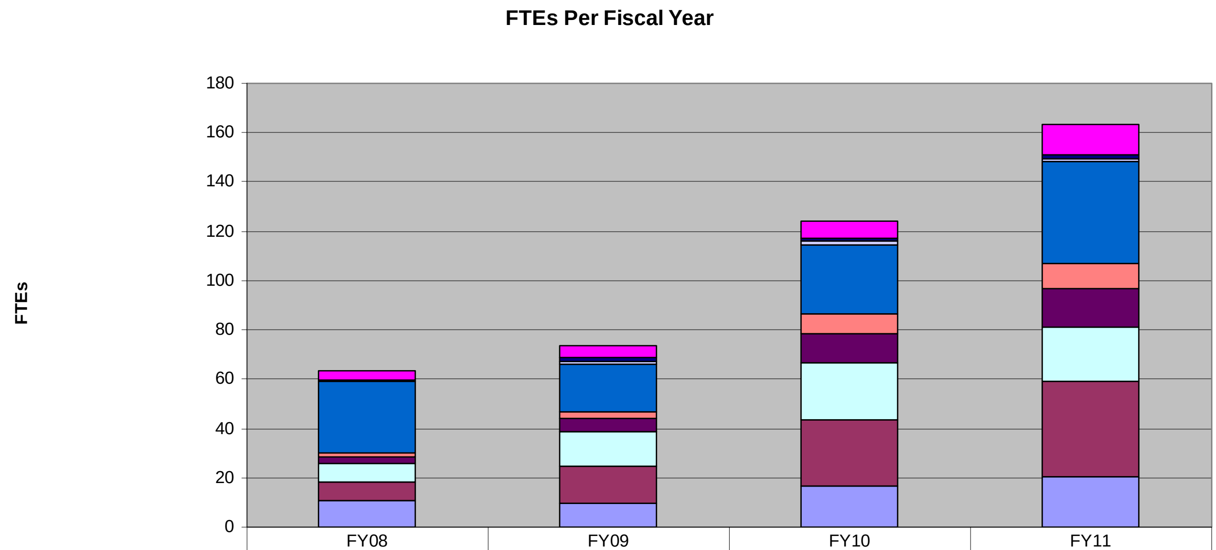


Figure IV.2: Distribution of the Project X R&D Plan budget by major system.

The total effort on the Project X R&D Plan is estimated to be 424 person-years. The RLS captures effort by skill type and by year. The distribution in effort by labor type by year is shown in Figure IV.3. Total effort rises to 160 FTE in FY11. It is anticipated that somewhat more than half of this effort will involve Fermilab staff, with the balance coming from outside collaborators. This amount of effort is consistent with the anticipated evolution of the Fermilab staff as Collider Run II comes to an end. We believe the balance can be provided by collaborating institutions outside of Fermilab.



	FY08	FY09	FY10	FY11
Computing Professional	3.7	4.9	6.5	12.2
Manager	0.5	1.5	1.5	1.5
Administrative Support	0.3	1.0	1.2	1.5
Physicist	29.2	19.5	28.0	41.3
Electrical Tech	1.6	2.9	8.0	10.2
Mechanical Tech	2.3	5.4	11.9	15.3
Drafter	7.5	13.8	23.5	22.4
Mechanical Engineer	7.7	14.9	26.6	38.7
Electrical Engineer	10.8	9.9	16.7	20.2

Fiscal Year

Figure IV.3: Manpower requirements for th Project X R&D Plan.

Institutional Expressions of Interest

A Project X Accelerator Workshop was held over November 12-13, 2007 at Fermilab (http://projectx.fnal.gov/Workshop/Index.htm). The purpose of the workshop was to discuss accelerator physics and technology issues of Project X and explore possible areas of overlap and interest between potentially interested institutions, in reference to the R&D phase Participation in the workshop included 172 individuals from 27 institutions in the U.S., Europe, and Asia.

A report from the Workshop has been produced and may be found linked to the above website. The report contains a compilation of “expressions of interest” from the participating institutions. The purpose of these EOIs is to provide an assessment of capabilities that could be brought to bear in the R&D phase of Project X. The EOI’s are not regarded as binding in any manner, but they do provide the initial step in understanding how the various interested institutions could be brought into an R&D collaboration in a manner that covered all critical technology items. The EOIs from the Workshop Report, grouped by major system, are summarized in Appendix B.

Appendix A: Project X R&D Plan Work Breakdown Structure

1	General
1.1	Integration
1.2	Project Management
1.3	Civil Construction & Utilities
1.4	Cryogenic Plant
1.5	Controls
2	325 MHz Linac
2.1	Physics Design
2.2	Ion Source
2.3	Cavities
2.4	RF Systems
2.5	Magnet systems
2.6	Cryogenics
2.7	Controls
2.8	Instrumentation
2.9	Project Management
3	1300 MHz Linac
3.1	Physics Design
3.2	Linac technical design
3.3	RF Power systems
3.4	Integration
3.5	System tests
3.6	Project Management
4	8 GeV Transfer Line
4.1	Physics Design
4.2	Component Design
4.3	Power Supply Design
4.4	Vacuum System Design
4.5	Controls
4.6	Instrumentation
4.7	Project Management
5	Recycler
5.1	Physics Design
5.2	Magnet and Power Supply Design
5.3	Controls
5.4	Instrumentation
5.5	Project Management
6	Main Injector
6.1	Physics design
6.2	Electron cloud
6.3	RF systems
6.4	Controls
6.5	Instrumentation

6.6 Project Management
7 8 GeV Slow Spill
7.1 Physics Design
7.2 Component Design
7.3 Prototypes
7.4 Controls
7.5 Instrumentation
7.6 Project Management
8 Neutrino Beamline
8.1 Primary Beamline
8.2 Secondary Beamline
8.3 Remote Handling
8.4 Radiological Issues
8.5 Infrastructure
8.6 Project Management

Appendix B: Institutional Expressions of Interest for Participation in the Project X R&D Program

Low energy Linac

- ANL
  - Accelerator physics design, simulation, and modeling
  - Superconducting RF cavity design, production, and testing
  - Integrated superconducting triple-spoke segment of Linac
- BNL
  - Beam Instrumentation
- JLab
  - Superconducting RF cavity development, production, cleaning, testing, and industrialization
  - Cryomodule assembly
  - Low level RF work
  - Cryogenics design
  - SRF system integration and industrialization
- LBNL
  - Front-end Linac design, fabrication, and integration (up to ~100 MeV)
  - Low level RF system design and construction
  - High voltage modulator design
  - H- stripping
  - Laser profile measurement
- University of Maryland
  - Modeling of solenoid lattice optics
  - Emittance growth and halo formation simulation studies (WARP code)

High energy Linac

- ANL
  - Design optimization, integration
  - Linac beta<1 section
  - ILC-like linac sections
  - Controls system
  - Electron source
- JLab
  - Design optimization, integration
  - Linac beta<1 section
  - ILC-like linac sections
  - Cryogenics design
  - LLRF system
  - Electron source
- LBNL
  - Design optimization, integration

    - LLRF system
- MIT-Bates
    - Electron source
    - Instrumentation
- MSU
    - Design optimization, integration
    - Beam dynamics, lattice, interfaces
    - Linac beta<1 section
- NIU
    - Electron source
- SLAC
    - Design optimization, integration
    - RF power systems
    - Fast phase/amplitude shifters
    - Controls
    - Instrumentation
    - High availability, dc power
- SNS
    - Design optimization, integration
    - Beam dynamics, lattice, interfaces
    - ILC-like linac sections
    - RF power systems
    - Fast phase/ampl shifters
    - Cryogenics design
    - LLRF system
    - Instrumentation
    - Servicing "hot" cryomodules

Recycler and Main Injector

- BNL
    - Electron cloud issues: Possible experiments in RHIC with bunch trains of 3e11 ppb (instrumentation in place).
    - Impedance and Instabilities: Study of beam break-up instability at transition (experience from AGS and RHIC)
    - H- Injection into recycler ring: Design of H- transport and injection systems (based experience from SNS effort)
    - RF & feedback systems: Design of high intensity RF systems for MI/RR (based experience from AGS and SNS effort)
    - Beam line and ring components: H- transport line and injection system
    - Extraction: Design of 3rd integer slow extraction system (experience from slow extraction from AGS and AGS Booster)
    - Transition crossing: Experience with bipolar gamma-t jump and chromaticity jump.
    - Transition crossing: Test of "duck under" crossing
- Cornell

  - Electron cloud issues: CESR available for e-cloud investigations starting in Spring 2008 for three years.
- LBNL
  - Electron cloud issues: e-cloud physics, mitigation, and instrumentation
  - Impedance and Instabilities: Characterize and understand limitations in recycler ring and main injector
  - Simulations and general beam dynamics: Beam simulations and modeling, halo & beam loss, space-charge tune shift.
  - H- Injection into recycler ring: Laser stripping, foil engineering issues, injection losses and absorber
  - RF & feedback systems: Broadband feedback systems, main RF upgrades, 2nd harmonic RF systems
  - Beam line and ring components: Vacuum systems, beam transport lines
- SLAC
  - Quantify instability thresholds due to electron cloud in the Main Injector and Recycler using the simulation codes being benchmarked against the experiments at PEP-II.
  - Suggest modifications to the vacuum chamber design to mitigate the effects of electron cloud, if necessary.
  - Develop an accurate impedance budget for the rings and estimate the threshold of impedance driven instabilities, in particular, simulating the microwave instabilities with a Vlasov solver.
  - Study beam dynamics and beam losses including full machine nonlinearity, space charge, and realistic collimators.
- SNS
  - Impedance and Instabilities: 2 types of SNS ring-present instabilities (ep and resistive wall) will be main issues for the recycler – SNS instability mitigation approach (chamber TiN coatings, electron collection, impedance reductions, feedback (under development)) could be useful for Project X
  - H- Injection into recycler ring: Foil scattering – one of main problems for both projects. Laser stripping development is of mutual interest (is a must for Project X).
  - H- Injection into recycler ring: Painting self consistent space charge distributions could be extremely beneficial to SNS (and Project X as well)
  - Beam line and ring components: Collimation design has to rely on most realistic mechanisms for particle loss

120 GeV Targeting

- ANL
  - Target Thermal Shock Simulations and Testing
  - Thermal Analysis and Cooling
  - Target Hall Remote Handling. Investigate Work Cell Modification, Telemanipulators
- BNL
  - Irradiation Investigations of Project-X target, Window, and Horn Materials

  - Prototyping of Project-X Target System Design Options
  - Target Thermal Shock Simulations and Testing
  - Testing of Materials in Target Hall Type Environment
- FNAL
  - Irradiation Investigations of Project-X target, Window, and Horn Materials
  - Remote Handling Facility at C0 Assembly Hall
  - Upstream Decay Pipe Window Replacement
- IHEP
  - Prototyping of Project-X Target System Design Options
- UCB
  - Characterization of Target Hall Environment
  - Testing of Materials in Target Hall Type Environment
- ORNL
  - Target Thermal Shock Simulations and Testing
  - Target Hall Remote Handling. Investigate Work Cell Modification, Tele-manipulators
- Princeton
  - Irradiation Investigations of Project-X target, Window, and Horn Materials
- University of Texas at Austin
  - Prototyping of Project-X Target System Design Options
  - Instrumentation
  - Focusing Systems