Project X Initial Configuration Document

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Contents

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 of August 2007 (available on the web through links at http://www.fnal.gov/pub/directorate/steering/index.shtml) and in the Intensity Frontier science described in the P5 report of May 2008 (available on the web at http://www.er.doe.gov/hep/files/pdfs/P5_Report%2006022008.pdf).

The P5 report called out three objectives of the vision which define the mission need. These three objectives are:

- *A neutrino beam for long baseline neutrino oscillation experiments.* A new 2 megawatt proton source with proton energies between 50 and 120 GeV would produce intense neutrino beams, directed toward a large detector located in a distant underground laboratory.
- *Kaon and muon based precision experiments exploiting 8 GeV protons from Fermilab's Recycler, running simultaneously with the neutrino program.* These could include a world leading muon-to-electron conversion experiment and world leading rare kaon decay experiments.
- *A path toward a muon source for a possible future neutrino factory and, potentially, a muon collider at the Energy Frontier.* This path requires that the new 8 GeV proton source have significant upgrade potential.

We have selected a set of parameters and an operational scenario to meet these three objectives.

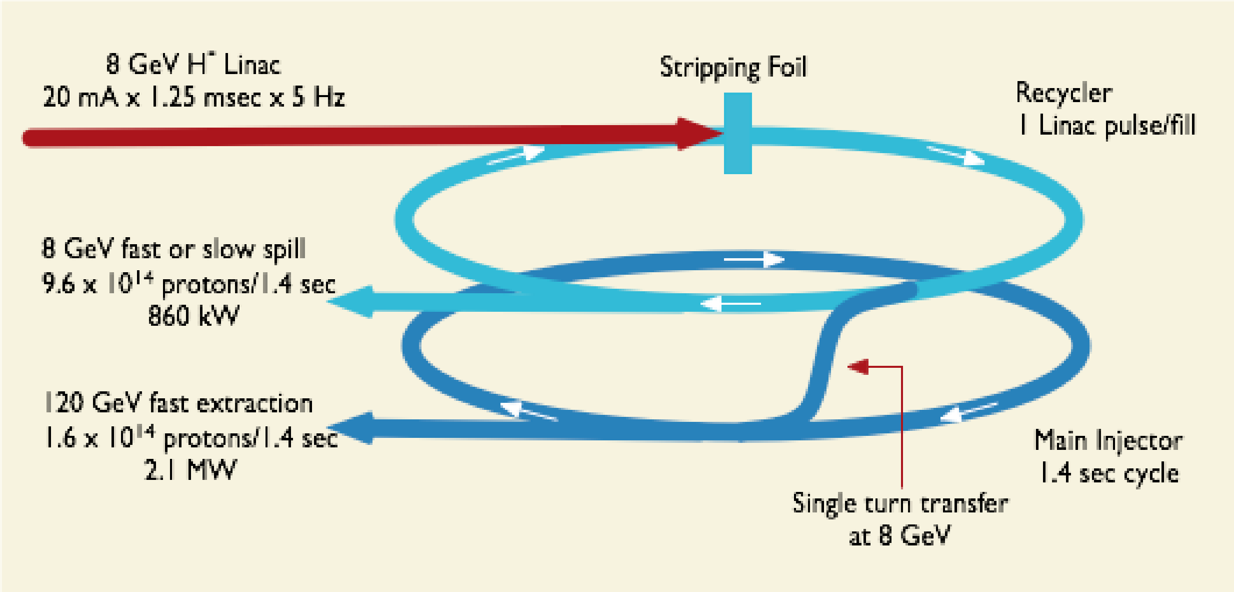

Figure I.1: Schematic view of Project X.

Project X is comprised of an 8 GeV superconducting H^- linac, paired with the existing (but modified) Recycler and Main Injector to provide in excess of 2 MW of beam power throughout the energy range 60 – 120 GeV, simultaneous with greater than 650 kW of beam power at 8 GeV. It is anticipated that the final configuration and operating parameters of the complex will be refined through the R&D program in advance of CD-2. In this document we define the initial configuration.

The linac operates at 5 Hz with a total of 1.6×10^{14} H^- ions delivered per pulse. Total available beam power from the linac at 8 GeV is thus 1.0 MW. The H^- ions are stripped at injection into the Recycler in a manner that "paints" the beam both transversely and longitudinally to reduce space charge forces. Following the 1.25 ms injection, the proton beam is moved off the stripping foil and is transferred in a single turn into the Main Injector. These protons are then accelerated to 120 GeV and fast extracted to a neutrino target. The 120 GeV Main Injector cycle takes 1.4 seconds, producing 2.1 MW of beam power. At lower proton energies Main Injector cycle times can be shorter. Since loading the Recycler requires only one linac beam pulse, the remaining linac cycles (six for a 1.4 sec MI cycle) are available for distribution of 8 GeV protons from the Recycler. Total available 8 GeV beam power can be maintained above 650 kW with Main Injector operations at ~2 MW for energies anywhere within the range 50-120 GeV.

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

The upgrade path for an high intensity beam supporting a possible future neutrino factory or a muon collider is foreseen by doubling the repetition rate and increasing the linac pulse length, with the potential to achieve a beam power of approximately 4 MW at 8 GeV. The linac hardware, conventional facilities, cryogenic plant, and utilities will be designed to accommodate these upgrades.

Chapter II describes the technical goals and assumptions. Chapter III defines the initial configuration of the major subsystems.

II. Technical Goals and Assumptions

The overall goal of the Project X Initial Configuration document is to provide a basis for a cost estimate necessary for a Critical Decision 0 (CD-0) in 2009, the first step in the critical decision tree mandated by DoE order 413.3.

II.1 Technical Goals

High level performance goals associated with Project X Accelerator Facility are listed in Table II.1.

Req. No.	Description	Req.	Unit	Reference Requirements
1.0	**General**			
1.1	120 GeV Beam Power	2.1	MW	
1.2	Total Linac Beam Power	1.0	MW	
1.3	Available (outside of MI) Linac Beam Power	0.9	MW	
1.4	Available (outside of MI) Duty Factor	86	%	
1.5	120 GeV Availability	75	%	
1.6	8 GeV Availability	80	%	

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

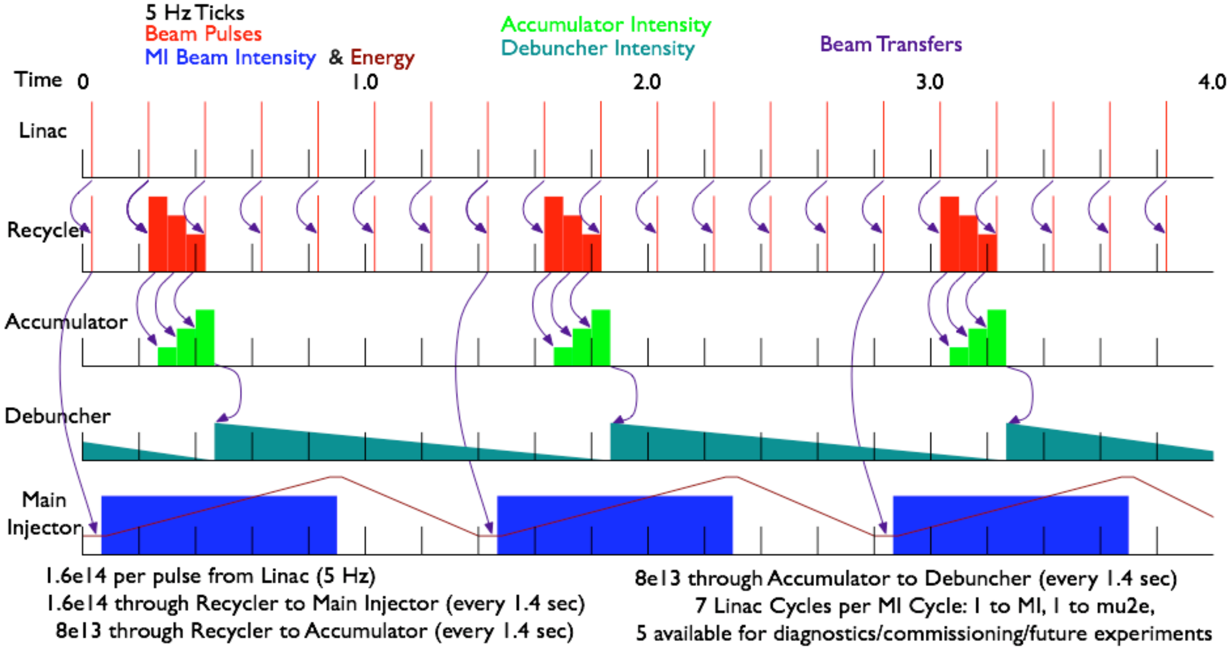

Figure II-1 : Initial Operational Scenario

II.2 Operational Scenario and Assumptions

In the initial operational scenario, the facility provides beam to two end users, a long baseline neutrino oscillation experiment and a muon-to-electron conversion experiment running on the Fermilab site (see Figure II-1). For the long baseline neutrino experiment, a single linac pulse delivers 1.6e14 H^- ions to the Recycler, where they are stripped and stored before a single turn transfer of 1.6e14 protons to the Main Injector. The Main Injector ramps to 120 GeV and delivers the beam through a single turn fast extraction to a transport line (outside the scope of this project). This cycle repeats every 1.4 seconds. For the muon-to-electron (mu2e) conversion experiment, a total of 8e13 protons are delivered from the Recycler to the Accumulator in three 15 Hz pings (each 1.6 μsec long) every 1.4 seconds. The Accumulator stores and momentum stacks the incoming pings and does RF beam manipulations before transfer to the Debuncher for slow extraction. The extraction system will provide the flexibility to vary the delivery scheme to the Accumulator in the event that space-charge limitations arise in that machine. The work required for the Accumulator and Debuncher is outside the scope of this project.

Note that in the initial scenario only two out of every seven linac pulses are used. The unused pulses are available for diagnostic usage, future upgrades, and/or maintaining 8 GeV beam availability while operating the Main Injector at energies below 120 GeV.

For this operating scenario, and to meet the technical goals, the following assumptions are made about the state of operations at Fermilab for the initial configuration:

- The existing Linac and Booster will not be operational once Project X becomes operational.
- The existing Tevatron and supporting utilities will not be operational.

- The existing test beam facility in Meson, based on 120 GeV beam from the Main Injector, will remain available at low duty factor.
- The existing antiproton source will be reconfigured and operating in support of the muon-to-electron conversion experiment when Project X becomes operational.
- A neutrino beamline directed towards DUSEL will be operating with beam power on target of 700 kW, with shielding and infrastructure designed to accommodate up to 3 MW, as Project X becomes operational.
- For the purpose of this document, the interface to the DUSEL beamline is defined as the Main Injector extraction kicker and the interface to the muon-to-electron conversion experiment is the Recycler extraction kicker.

III. Requirements and Initial Configuration of Major Subsystems

III.1 General Configuration

The general requirements for Project X are shown in Table II-1. The major subsystems are:

- A front end linac operating at 325 MHz.
- An 8 GeV linac operating at 1300MHz.
- An 8 GeV transfer line and H^- Injection system.
- The Recycler operating as a stripping ring.
- The Main Injector acting as a rapid cycling accelerator.
- Beam Instrumentation
- Conventional Facilities
- Controls
- Cryogenics

In the following sections, each subsystem documents requirements and configuration.

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 sections. The Low Energy linac is required to deliver 1.25 msec pulses of 1.6E14 H^- ions at 420 MeV and at pulse rates up to 5 Hz. The output beam must conform to transverse emittance and longitudinal bunch parameters required for matching into the 1.3 GHz High Energy linac. Beam halo must be controlled to prevent unacceptable resultant beam losses at high energies. The 1.25 msec 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 (see Figure III-1). Specific requirements are listed in Table III-1.

Req. No.	Description	Req.	Unit	Reference Requirements			
2.0	**325 MHz Linac**						
2.1	Average Beam Current	20	mA	1.2			
2.2	Pulse Length	1.25	mS	1.2			
2.3	Repetition rate	5	Hz	1.2			
2.4	325 MHz Availability	98	%	1.6			
2.5	Peak RF Current	31.86	mA	2.1	2.11	2.13	2.14
2.6	Final Energy	420	MeV	3.7			
2.7	Energy Variation (rms)	1	%	3.11			
2.8	Bunch Phase jitter (rms)	1	degree	3.12			
2.9	Linac Species	H-		4.1			
2.10	Transverse Emittance (95% normalized)	2.5	π-mm-m	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 III-1 : Requirement Table for the 325MHz linac. Requirements that are derived from other requirements have the reference requirement listed in red.

325 MHz linac Configuration

Many technologies and components applicable to the Low Energy linac are being developed under the High Intensity Neutrino Source (HINS) R&D program that has been ongoing since FY06. We assume the following for the initial configuration of the 325 MHz linac:

- 50 keV H^- ion source
- 2.5 MeV RFQ
- Medium Energy Beam Transport (MEBT)
- Room Temperature (RT) accelerating cavities to 10 MeV
- β=0.22 single-spoke resonator (SSR-1) superconducting cavities to 30 MeV
- β=0.4 single-spoke resonator (SSR-2) superconducting cavities to 120 MeV
- β=0.6 triple-spoke resonator (TSR) superconducting cavities to 420 MeV

Transverse beam focusing is provided by superconducting (SC) solenoids from the RFQ through the SSR-1 and SSR-2 sections. SC quadrupoles are employed starting in the TSR section.

The MEBT includes two re-buncher RF cavities, three SC solenoids (two with integrated horizontal and vertical steering dipoles), a 325 MHz beam chopper, and appropriate beam instrumentation.

The RT section includes 16 room temperature crossbar-H (RTCH) type cavities, 16 SC solenoids (six with integrated horizontal and vertical steering dipoles), and appropriate beam instrumentation. The 16 RTCH cavities comprise a total of nine individual designs to accommodate the rapidly changing beam velocity through this section. The 19 SC solenoids throughout the MEBT and RT sections have common design parameters, with two cold-mass designs (with and without steering dipoles).

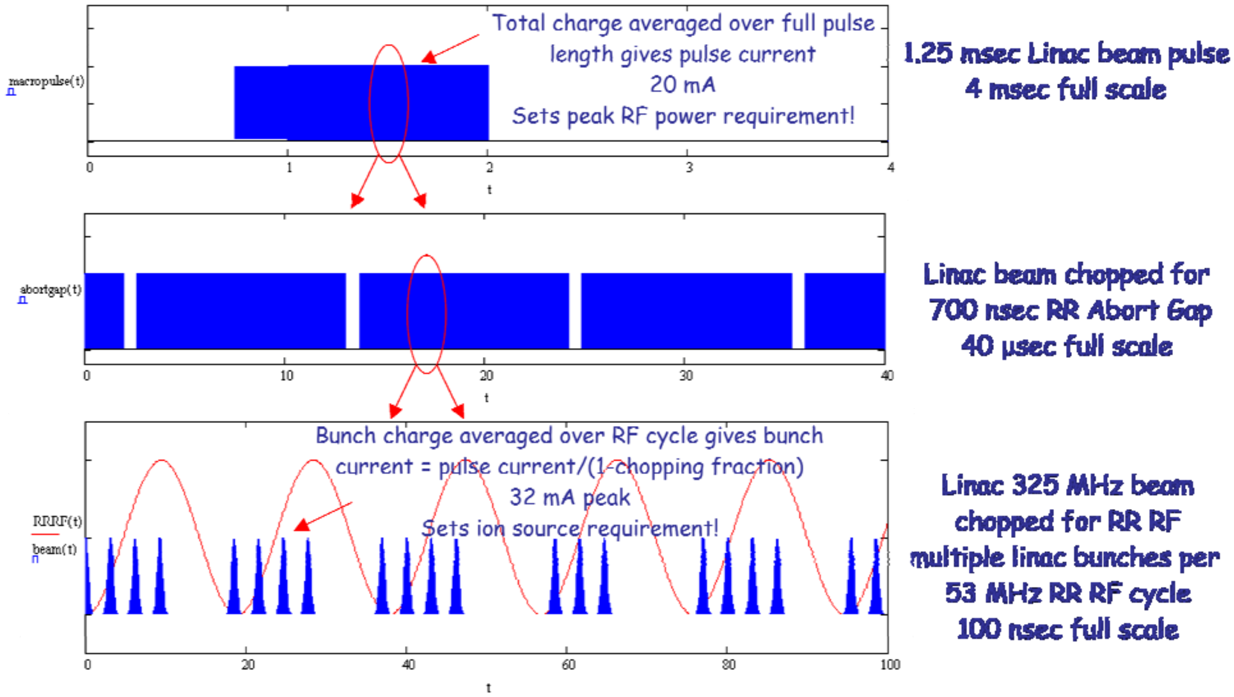

Figure III-1 : Bunch structure from the Linac

The SSR-1 section consists of two cryomodules (CM) each with nine single-spoke β=0.22 SC cavities and nine SC solenoids. Warm beam tube interconnects separate the cryomodules. The SSR-2 section consists of three CMs each containing 11 single-spoke β=0.4 SC cavities and six SC solenoids, with warm beam tube interconnects separating the CMs. The solenoids used in the SSR-1 and SSR-2 sections are similar but different in detail to each other and the design used in the RT section. The TSR section consists of seven CMs each containing six triple-spoke β=0.6 SC cavities and six SC quadrupoles.

RF power for the 325 MHz linac is provided by seven Toshiba E3740A(Fermi) 2.5 MW klystrons, driven by pulse modulators of the Fermilab bouncer-type design. The RF distribution system uses fast ferrite vector modulators for amplitude and phase control of each individual cavity.

In Figure III-2, we show the 325 MHz linac layout including the length and beam energy at several locations.

Figure III-2 : 325 MHz linac layout (Solenoids are indicated by the dark lines)

III.3 1300 MHz linac

1300 MHz linac Requirements

The 1300 MHz linac is a superconducting linac that can support a beam current of 20 mA, a pulse length of 1.25 msec, and a repetition rate of 5 Hz to an energy of 8 GeV. It is designed to accelerate H^- ions and preserve the macro and micro bunch structure created in the 325 MHz linac.

Req. No.	Description	Req.	Unit	Reference Requirements			
3.0	**1300 MHz Linac**						
3.1	Average Gradient (ILC portion)	25	MV/meter				
3.2	Average Gradient (S-ILC portion)	23	MV/meter				
3.3	Average Beam Current	20	mA	1.2			
3.4	Pulse Length	1.25	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	31.9	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 III-2. Requirements for the 1300MHz linac

1300 MHz linac Configuration

The high-energy linac consists of two distinct parts: the energy range (0.42-1.2 GeV) using cavities optimized for $\beta = 0.81$ and the energy range (1.2-8 GeV) using $\beta = 1$ optimized cavities.

The cavities will be variants on those designed for the ILC. The β = 0.81 is called Squeezed ILC (S-ILC) for its "squeezed" ILC cavity shapes. For the β = 1 section, we propose using the Type 4 ILC CM as the prototype, with separate short CMs with quads where needed. The S-ILC CM will have the same physical dimension as the Type 4 ILC CM.

We choose a gradient of 25 MV/m for the initial configuration of the β = 1 section, which is readily achievable with current superconducting RF (SCRF) technology. The RF pulse length is 1.5 msec/pulse at 5 Hz, with a 1.25 msec beam pulse. We plan on using 8 cavities in all CMs as in the ILC design. This choice has the advantage that all CMs are interchangeable.

To handle the increased beam current, we plan on 1 klystron per 2 CMs. The klystron choice is the 10 MW multibeam klystron developed for the DESY XFEL and ILC. The longitudinal dynamics of the non-relativistic H^- beam and possible cavity field variations over time (as seen in the SNS) will require use of IQM vector modulators throughout the linac.

	β=0.81 Section	β=1 Section
Cavity Type	S-ILC	ILC
# Cavities	56	304
# Cryomodules	7	38 (Type 4)
# Klystrons	4	19

Table III-3: Component counts for 1.3 GHz linac

Figure III-3 shows the layout and component counts for the initial configuration of both the 325 MHz and 1300 MHz linacs.

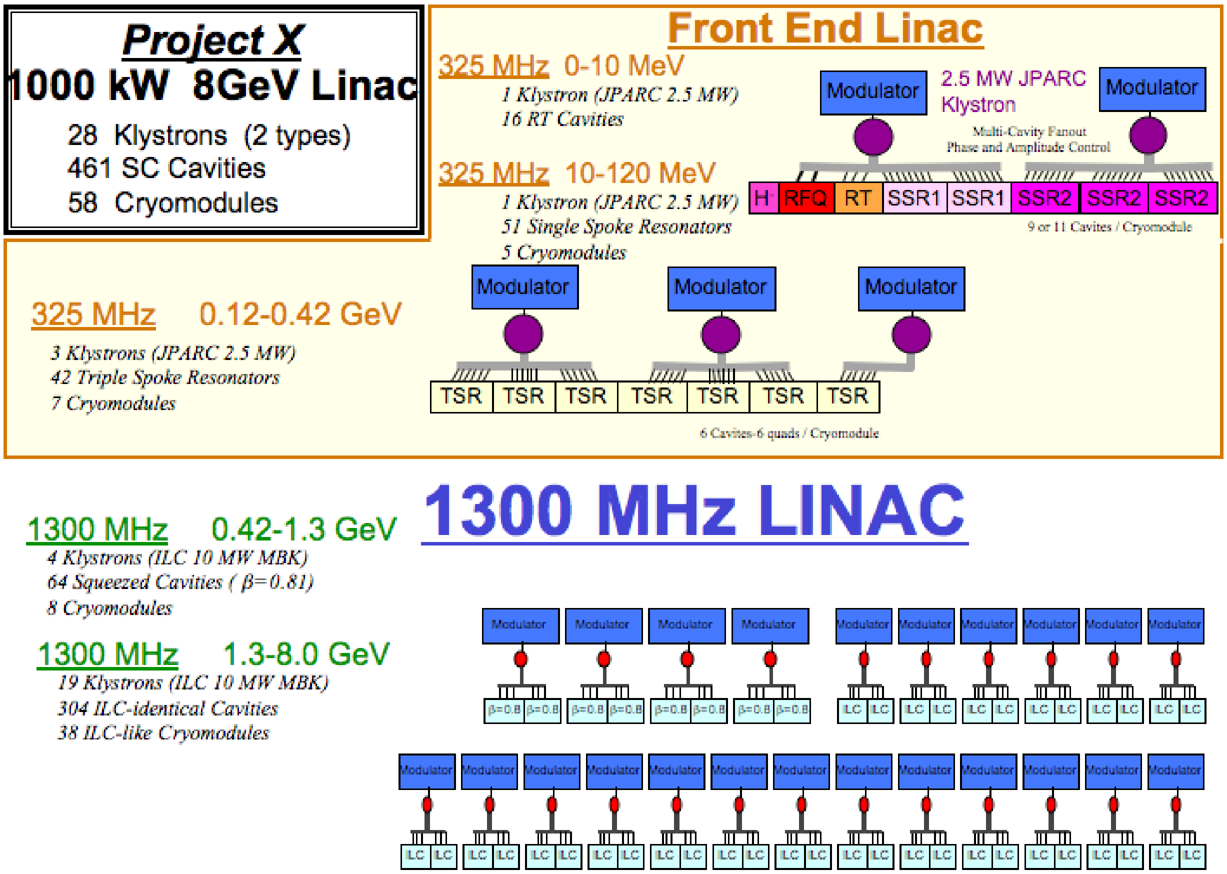

Figure III-3 : Layout and component counts for the initial Project X linac configuration

III.4 Transfer Line

Transfer Line Requirements

The transfer line consists of the beam transport line from the linac to the Main Injector tunnel and the stripping / injection system in the Recycler. It is designed to handle the expected full linac intensity of 20 mA average current and 1.25 msec beam pulse length at a repetition rate of 5 Hz. This translates to an intensity of $8x10^{14}$ particles/sec or an average of 1 MW beam power at 8 GeV. The transfer line includes a phase rotator cavity to reduce the momentum jitter of the linac beam. Specific requirements for the 8 GeV transfer line and injection system are listed in Table III-4.

The activation level is set to minimize unnecessary radition exposure to personnel, which sets a strict limit on transport efficiency of >99.99%. To assure this high efficiency, the transport line should have a large physical (and dynamic) aperture (> $10\varepsilon_T$) 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 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 injection stripping efficiency of 98% implies that 2% of the incident H^- will exit the foil as H^- or H^0 and be sent to the injection absorber. A conservative approach is to design the absorber for 10% full power or 100 kW peak.

Req. No.	Description		Req.	Unit	Reference Requirements	
4.0	**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	+/- 0.75	%	3.11	
4.6		Minimum Transverse Aperture	25	p-mm-mrad	3.14	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 III-4. Requirement table for the 8 GeV transfer line and injection system.

Transfer Line Configuration

The length of the transport line has 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. To mitigate blackbody radiation stripping of the H^-, we include a cryogenic shield around the beam pipe for the full 1 km length. The transport line includes a transverse collimation scheme for capturing large amplitude particles, a momentum collimation system for the protection of off energy particles, and a passive phase rotator cavity to compensate for energy jitter.

With 60° per half cell, the transport line requires ~80 dipoles and ~60 quadrupoles. Since the linac will be injecting into a fixed energy permanent magnet ring, the initial configuration utilizes permanent magnets for the bending and focusing magnetic elements of the transport line. During the development period we plan on investigating the use of powered electromagnets (recycled from the Fermilab Main Ring and/or the SLAC PEP—II High Energy Ring) in this line.

The elevation at the end of the transport line is matched to the elevation of the Recycler Ring at 720.4 ft. The elevation of the transport line enclosure at the interface to the existing 8 GeV line/Main Injector tunnel is matched to the Main Injector tunnel floor elevation at 713.5 ft. Keeping this enclosure elevation throughout the transport line and linac provides adequate shielding and avoids elevation interferences with existing underground enclosures.

We use a thin foil as the default stripping system at injection. We plan on investigating the laser stripping process that has been demonstrated at SNS for 1 GeV H^-.

The injection process itself consists of both transverse and longitudinal phase space painting to create a "KV-like" distribution to minimize the space-charge tune shift in the Recycler. We use 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.

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. For the NOνA program, the Recycler will be converted from an antiproton storage ring to a proton accumulator for single turn injection into the Main Injector. We assume these upgrades are complete.

The Recycler will operate as a stripping ring, taking single pulses from the linac, capturing in 53 MHz RF buckets, and performing a single turn extraction into the Main Injector or elsewhere. The requirements for the Recycler are listed in Table III-5. For the 8 GeV muon-to-electron program, a fast rise and fall time kicker with a 1.6 μsec flattop is necessary.

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	p-mm-mrad	5.6	
5.8	r.m.s. normalized transverse emittance	13	p-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	sec	6.1	
5.12	RF Frequency	53	MHz	6.2	
5.13	Abort Gap Length	700	nsec	6.3	
5.14	Peak Recycler Beam Current	2.356	A	6.5	
5.15	Fast Extraction Rate	15	Hz	0	
5.16	Fast Extraction Pulse Length	1.6	microsec	0	

Table III-5. Requirements for the Recycler

Recycler Configuration

With a new injection insert in the Recycler Ring, we anticipate the need for more flexibility in the lattice design. The Recycler is built with both permanent magnet quadrupoles, permanent magnet combined function devices, powered dipole correctors, and a tune trombone of powered quadrupoles. The installation of new powered quad elements allows for lattice flexibility.

At the specified peak beam current, electron cloud induced instabilities could be an important limitation to the maximum proton flux. We mitigate the generation of secondary electrons (as in the Main Injector, see Section III.6) and upgrade the damper systems to address these instabilities.

A new 53 MHz RF system to capture the injected beam is included in the project. As in the Main Injector, a second harmonic RF system is necessary. The injection kicker being developed for the NOνA program meets the Project X requirements (60 nsec rise time and fall time, 1.6 μsec flattop) for the fast extraction system. As it will no longer be needed for injection, we use it for extraction. The kicker does need to be relocated from the RR10 area to the RR50 area, along with associated controls and power supplies.

At this time, we have not identified a successful approach for slow spill out of the Recycler but will continue to investigate options. 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.

III.6 Main Injector

Main Injector Requirements

The Main Injector will receive 1.6×10^{14} protons from the Recycler in a single turn and will accelerate them to 120 GeV in 1.4 seconds. This intensity is about 3 times the beam intensity the Main Injector will be required to accelerate for the NOνA program. The requirements for the Main Injector are listed in Table III-6.

Req. No.	Description	Req.	Unit	Reference Requirements	
6.0	**Main Injector**				
6.1	120 GeV cycle Time	1.4	sec		
6.2	RF Frequency	53	MHz		
6.3	Abort Gap Length	700	nsec	1.2	
6.4	Acceleration Efficiency	99	%	1.6	
6.5	Main Injector Beam Current	2.356	A	2.3	
6.6	Final Energy	120	GeV	5.2	
6.7	120 GeV Beam Power	2.1	MW	5.6	
6.8	Availability	87	%	5.6	
6.9	Injection Energy	8	GeV	5.6	
6.10	Longitudinal emittance per Bunch	0.5	eV-Sec	5.6	5.12
6.11	Space Charge Tune Shift	0.05	0	6.1	
6.12	95% normalized transverse emittance	25	p-mm-mrad	6.2	
6.13	r.m.s. normalized transverse emittance	13	p-mm-mrad	6.3	
6.14	Bunching factor	2	0	6.5	

Table III-6. Requirements for the Main Injector

Main Injector Configuration

The current Main Injector RF system does not have the power to accelerate the required beam intensity to 120 GeV in 1.4 seconds (even with the addition of a second power tube per station). We include an upgraded RF system capable of handling the required intensity. To achieve the required bunching factor a substantial second harmonic RF system is also needed. An initial design exists for the primary system cavities but not for the second harmonic cavities.

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 Main Injector intensity as in the Recycler. We are investigating the threshold of the instability, and its dependence on various parameters (bunch spacing, bunch length, SEY, etc.) with simulations. Meanwhile we are developing a plan of coating the Main Injector beam pipe in-situ with TiN since there is no easy way of replacing the Main Injector beam pipe without disassembling the magnets. The Ti coating can decrease the secondary emission yield (SEY) of the Main Injector beam pipe by 40%

For high efficiency acceleration through transition, a first order matched γ-t jump system consisting of 8 sets of pulsed quad triplets is used. The system can provide a maximum γ-t jump of 2 units in 0.5 msec, 16 times faster than the normal ramp.

III.7 Beam Instrumentation

Various beam instruments and diagnostics systems are required to characterize the beam parameters and the performance of the Project X accelerators. Several instrumentation systems have to be available during the beam commissioning phase, at a minimum we need to observe:

- Beam intensity
- Beam position
- Transverse beam profiles
- Beam phase / timing

Moreover, a reliable beam loss monitoring system is mandatory, as part of an integrated machine protection system (MPS) to prevent quenches in cryogenic sections or other damage by a high-intensity beam.

New beam instruments need to be designed, tested and finalized for the new accelerator parts of Project X: H^- injector, SCRF main linac and transport line. However, most of the existing beam instrumentation systems in Recycler and Main Injector can be reused with minor modifications.

Beam Instrumentation Requirements

A complete “instrumentation requirements” document needs to be developed. Beside the nominal beam parameters and general layout of the sub-accelerators it will list various beam operation modes (e.g. short pulse, low intensity, nominal beam pulse, etc.) and the requirements to characterize the beam parameters (resolution, precision, dynamic range, etc.). We foresee the following general detectors and systems for beam instrumentation and diagnostics:

- Beam Position Monitors

The beam orbit monitoring is the most fundamental measurement, and the most powerful diagnostics tool in an accelerator. Project X requires a large number (~100) of new beam position monitors (BPM), thus makes it a complex and expensive measurement system. BPM pickups need high quality RF cables to transmit their low-power signals to the read-out hardware outside the accelerator tunnel. This may impact the arrangement or layout of some conventional facilities. It is unavoidable to locate BPM pickups in cryogenic SCRF sections of the machine, which needs extra care to meet UHV, cryogenic and clean-room requirements simultaneously.

- Beam Monitoring in the SCRF linac

The beam monitoring within the cryogenic environment is probably limited to beam position detection. As beam profile and other beam monitors with moving parts cannot operate in a cryogenic environment, beam emittance and similar measurement systems would require a “warm” diagnostics section within the SCRF linac.

- Beam Profile Monitors

Profile monitors are required in the transfer line for measuring emittance and matching between the linac and transfer line and the Recycler. Options for transverse profile monitors are the standard multi-wire monitor and the newer laser profile monitor. The choice of technology has not been selected.

- Beam Loss Monitors

Typical fast ionization chambers with a large dynamic range will be utilized for most loss measurements. However, there may be instances where measurements of thermal neutrons or machine activation during cooldown periods are desired. The loss monitors will be incorporated in a machine protection system.

- Beam Current Monitors

Accurate measure of beam current throughout the linac, transfer line, injection straight are required to determine transport and injection efficiency.

- Special Monitors

Several types of special (even "exotic") beam monitors and diagnostic tools are required to verify the beam quality and minimize beam losses. This includes the monitoring of the transverse beam halo (OTR screens with micro-mirrors, vibrating wire, laser wire) and the detection of longitudinal tails using optical sampling techniques with mode-locked laser wires. A list of special beam monitors and diagnostic tools needs to be established.

- Data Acquisition and Timing

Most beam monitoring systems will use digital signal conditioning and processing methods to extract the wanted beam parameter(s). The generated output data needs to be "time stamped" with respect to the beam event, so beam and other recorded data can be cross-correlated throughout the entire Project X complex. This will simplify diagnostics and trouble-shooting on the day-to-day operation.

III.8 Conventional Facilities

Conventional facilities include all above and below grade buildings, enclosures and utilities required to house and support the proposed Project X facility. Civil construction for Project X includes all below-grade beamline enclosures, above-grade buildings, roads, parking, utilities and services to accommodate the equipment for the operation of Project X on the Fermilab site.

Construction of the below-grade linac beam line and beam transport line to the Main Injector as well as the above-grade service buildings are similar to utilized and proven construction methods previously executed at Fermilab. Construction of all below-grade enclosures consists of conventional open-cut type construction techniques. The architectural style of the new buildings will reflect, and will be harmonious with, the existing buildings. The current layout has been optimized for the accelerator requirements. Future layouts will consider existing topography, sustainability, watersheds, vegetation, natural habitat, and wetlands and will be thoroughly addressed in the Environmental Assessment for this project.

<u>Site Construction</u>

1. <u>Site work</u>

   The following topics address the necessary work for construction, independent of the buildings and enclosures.

a. Site Drainage will be controlled by ditches and culverts while preserving the existing watershed characteristics both during construction and subsequent operation.
b. Road Construction includes a new temporary construction road providing access from Butterfield Road. This road will provide direct access for construction traffic during construction only – the roadway will be restored to original condition upon completion of the project. A new service road will provide permanent access to all service buildings and utility corridor via existing lab roadways.
c. Landscaping includes the restoration of disturbed areas. Construction yards and stockpile areas will be removed after completion of the construction phase of the project. All disturbed areas will be returned to a natural state or landscaped in a similar manner as found at other Fermilab experimental sites. Erosion control will be maintained during all phases of construction.
d. Wetlands Mitigation includes the avoidance or minimization of adverse impacts to wetlands in the project area. Wetlands will be delineated by environmental consultants, and a Clean Water Act permit application prepared for submittal to U.S. Army Corps of Engineers for impacts that cannot be completely avoided. Compensatory mitigation will be provided according to terms and conditions of the permit. This may be in the form of purchased wetland bank credits, restoration or enhancement of existing wetlands on site, or creation of new wetland areas. The amount and type of mitigation would be dictated by the permit, which must be in place prior to the initiation of construction. A Floodplain/Wetland Assessment pursuant to 10 CFR 1022 would be incorporated into the Environmental Assessment.
e. Space Management includes providing for a one-for-one replacement of existing for new facilities, both buildings and enclosures, on the Fermilab site. Options for space management include demolishing obsolete on-site facilities or securing replacement square footage from space banks maintained across the DOE laboratories. Some combination of these options will be used for this project.

2. Utilities

The following utilities are required to support the operation of the facility. The list incorporates current assumptions and may require further refinement as the design progresses.

a. Electrical Power includes new duct banks and utilization of existing duct banks from two sources including Kautz Road Substation (KRS) and Master Substation (MSS). Separate high-voltage feeders with backup will be provided for conventional, machine and cryogenic power.
b. Communications include new duct banks tied into the existing communication network along Kautz Road.
c. Chilled Water (CHW & CHWR) for machine and building cooling will be supplied via new supply and return lines from the existing Central Utility Building (CUB).
d. Low Conductivity Water (LCW) for machine cooling will be supplied via new supply and make-up water from the existing Main Injector ring LCW system.

e. Industrial Cooling Water (ICW) for fire protection will be supplied via new supply and return lines from the existing D-0 Utility Corridor.
f. Domestic Water Supply (DWS) for potable water and facilities will be supplied via a new supply line from the existing D-0 Utility Corridor.
g. Sanitary Sewer (SAN) for facilities will be supplied via a new sewer main and lift station to the existing D-0 Utility Corridor.
h. Natural Gas (NGS) for building heating will be supplied via a new supply line from the existing D-0 Utility Corridor.

3. Facilities Construction

Conventional facilities will be constructed with future upgrade capabilities considered in the initial design phase. Equipment galleries, enclosures, and surface buildings will be designed to accommodate future expansion of the technical components of the facility.
(see Figure III-4 for facilities locations)
(see Table III-7 for description of facilities)
Conventional Facilities Major Elements:

a. Below-Grade Construction
Item 1 - Linac Beam Line Enclosure
Item 2 - Beam Transport Line Enclosure
Item 3 - Linac Beam Absorber
Item 4 - Momentum Beam Absorber
b. Above-Grade Construction
Item 5 - Upstream Service Building
Item 6 - Klystron Gallery
Item 7 - Cryogenic Service Building
Item 8 - Typical Service Building
Item 9 - Center Service Building
Item 10 - Arc Service Building
Item 11 - Debuncher Service Building

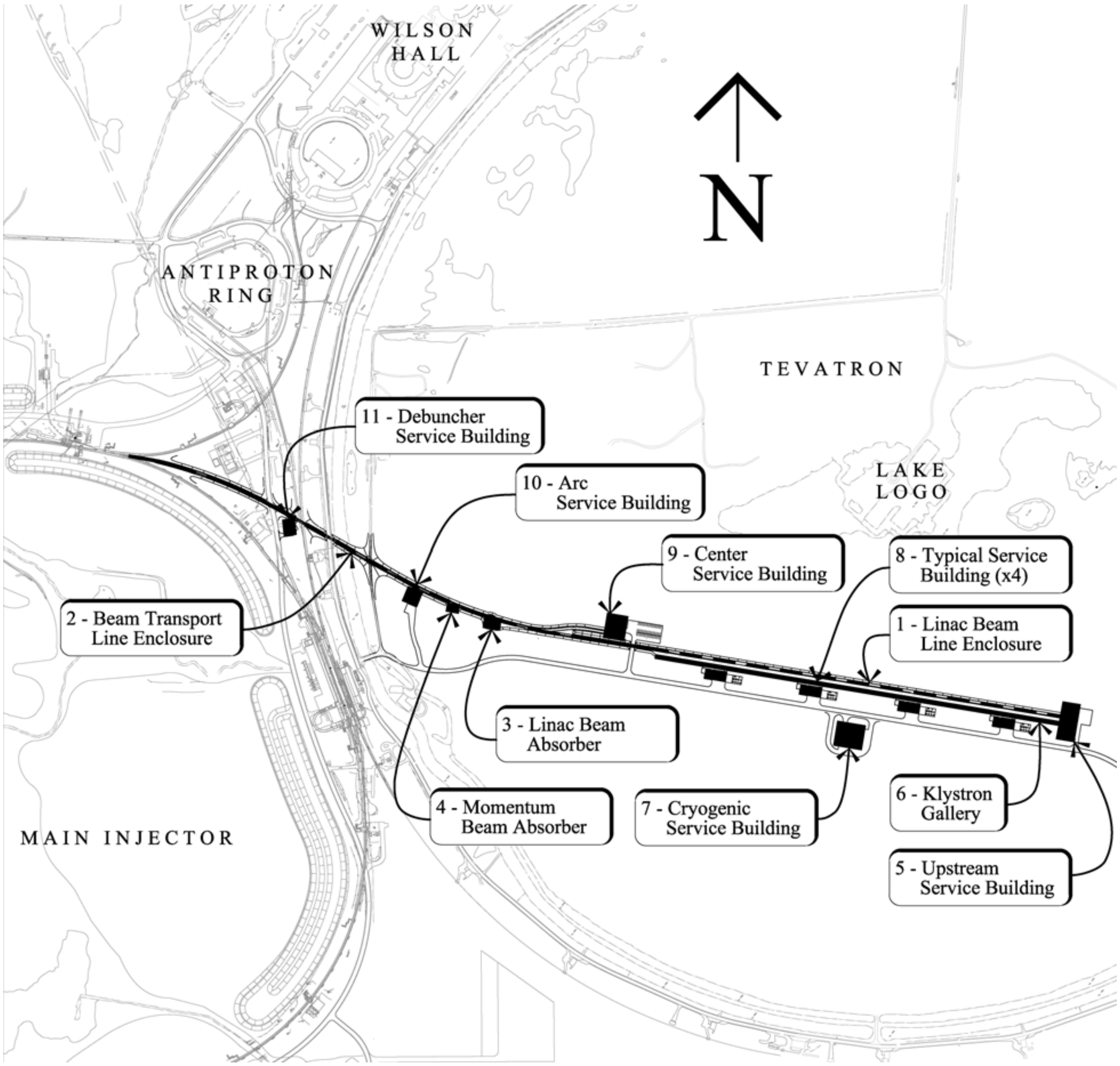

Figure III-4 : Site Plan

Item No.	Facility Name	Function	Contents
1	Linac Beam Line Enclosure	Below-grade enclosure for equipment/controls for linac H- accelerator components	H- source, RF cavities, magnets, beam instrumentation and utilities
2	Beam Transport Line Enclosure	Below-grade enclosure for H- beam transport from Linac Beam Line Enclosure to Main Injector	Beam transport magnets, momentum collimators and utilities
3	Linac Beam Absorber	Below-grade enclosure for equipment/controls for linac H- abort components	Concrete block and steel shielding and utilities for linac abort system
4	Momentum Beam Absorber	Below-grade enclosure for equipment/controls for momentum beam absorber components	Concrete block and steel shielding and utilities for momentum beam absorber components
5	Upstream Service Building	Building for personnel/equipment access for installation and operation of low-energy support equipement and tech space	Electrical equipment and controls, utility services and H- source support equipment
6	Klystron Gallery	Building for equipment for RF power generation	Klystrons, modulators, controls and utility dervices
7	Cryogenic Service Building	Building for equipment for helium refrigerator plant	Compressors and helium cold boxes
8	Typical Service Building	Building for LCW pumps, electrical services, power supplies and controls	Heat exchangers, pumps, electrical equipment, power supplies and controls
9	Center Service Building	Building for personnel/equipment access for installation of linac	Crane bay, hatch and staging area
10	Arc Service Building	Building and enclosure for correction power supplies and controls	Power supplies and controls
11	Debuncher Service Building	Building and enclosure for debuncher RF modulator and klystron magnet power supplies and controls	Klystron modulator, power supplies and controls

Table III-7 : Facilities Description

III.9 Controls

Controls Requirements

The Control System is responsible for control and monitoring of all accelerator equipment, machine configuration, timing and synchronization, diagnostics, data archiving, and machine protection. Its scope covers all hardware and software asociated with interface of equipment to the control system, the timing and machine protection system, and control and monitoring applications.

The scale of the control system is expected to be similar to that of the existing complex but with the Project X linac rather than the Tevatron. The system should support up to 1M device properties. Time stamping must be provided so that all data from a single linac pulse can be properly correlated. The control system should contribute less than 1% to the unavailability of the accelerator complex. The high beam power implies the need for a sophisticated machine protection system to avoid damage to the accelerator due to errant beam pulses. Furthermore, to minimize routine losses and minimize activation of accelerator components a fast feedback system will be required to stabilize beam trajectories.

Controls Configuration

At the time the Project X linac begins operation, the NOνA Upgrade will have been completed and the Recycler, Main Injector, and NUMI beam line operated for some years in that configuration. These elements will be controlled by an evolution of the current Fermilab Control 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 replace by the start of Project X operation.

It is highly desirable to have a single control system operating the entire complex rather than separate systems for the new linac and older parts of the system. There should only be a single copy of core services such as alarms and data archiving. Software applications should be able to access any device in the system. This simplifies development and operation and reduces long term maintenance costs of the complex. The Fermilab control system will be updated for the NOνA upgrade and to support the HINS and NML test facilities for Project X. This will include modernizing the application software environment as well as replacing obsolete hardware. Upgraded timing and machine protection systems will be developed for the Project X linac that will accomodate legacy hardware in the existing parts of the complex. These systems as well as linac control software will be prototyped at HINS and NML.

It is recognized that some equipment will be developed outside of Fermilab by institutions with expertise in the EPICS control system. Also it may be appropriate in some cases to use commercial hardware that comes with EPICS software. It is planned to support integration of EPICS front-ends and some core applications into the Fermilab control system.

The control system will specify standard interfaces between its internal components as well as with technical equipment. This will make integration, testing, and software development easier and more reliable and reduce the long term maintenance load. Also, standard interfaces allow parts of the system to be more easily upgraded if required for either improved performance or to replace obsolete technologies. Only portions of the system need be changed while the core architecture of the control system remains the same.

III.10 Cryogenics

Cryogenics Requirements

The cryogenic system scope for Project X includes a new cryogenic plant, a cryogenic distribution system, and the necessary ancillary systems (purification system, cryogenic storage, etc.) to support the plant. A conceptual layout for the cryogenic system is shown in Figure III-5.

The cryogenic distribution system accommodates a range of steady state and transient operating modes including RF on/RF off, cooldown, and warm-up and fault scenarios. The system includes feed boxes, cryogenic transfer lines, bayonet cans, feed and end caps, string connecting and segmentation boxes, gas headers, etc. It will be capable of supporting operation of the linac within cooldown and warm-up rate limits and other constraints imposed by accelerating SRF components. It will protect superconducting RF cavities from over pressurization beyond the component's maximum allowable working pressure during fault conditions. It will provide liquid nitrogen for cooling of the beam pipe in the 8 GeV transport line. Components of the cryogenic distribution system contain cryogenic control and isolation valves, cryogenic instrumentation, safety valves, etc.

It is assumed that on the time scale of the Project X, a large portion of the Tevatron ancillary cryogenic components will be available to use by the project. These components include cryogenic dewars, gas storage tanks, purifier compressors, and parts of the inventory management system.

Cryogenics Configuration

The 325 MHz linac (Low Energy Cryogenic Unit) components are cooled by two-phase liquid Helium at 4.5 K. There are at least two cryogenic strings, one for the 19 solenoids in the warm RF (WRF) section and one for the cryomodules containing spoke resonators. For the spoke resonators, the static heat load (due to conduction and radiation) at 4.5 K dominates the dynamic heat load (due to RF power dissipation).

The 1300 MHz linac (High Energy Cryogenic Unit) components consist of saturated He II cooled cavities to 2 K with two He gas thermal shields in the ranges of 5-8 K and 40-80 K. The dynamic heat load at 2 K is of the same magnitude as the static heat load. There will be several cryogenic strings and segments in this section.

A preliminary heat load estimate has been performed and the estimated uncertainty of the calculations is 30%. For the design study, an additional 50% is applied to the estimated heat loads to ensure the system could meet all operational requirements. With these two factors, the design capacity at 4.5 K equivalent for the entire linac is approximately 6 kW.

A wide range of possible cryogenic plant design solutions that satisfy all requirements and constraints for Project X will be studied further. Combining effective use of the existing Fermilab infrastructure with commercially available components will lead to the most cost-effective solution. This solution will be based on cycles with pure ambient–temperature compressors, cycles with cold compression, or hybrid – cold and ambient temperature compression. Ease of operation, reliability, ability to operate efficiently over a wide range of loads, capital and operational costs, and other factors will be considered in selecting technology for the Project X cryogenic plant.

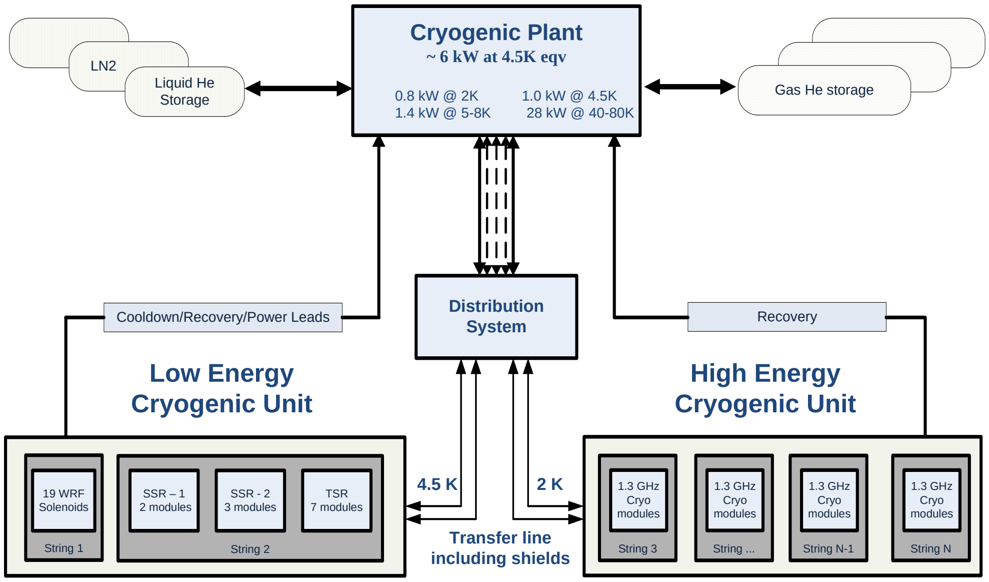

Fig. III-5: Project X cryogenic system simplified flow schematic