**Chapter 5. Facilities for the Intensity Frontier**

The Steering Group considered a variety of accelerator facilities and programs using the following criteria:

* Support for physics research goals,
* effective use of accelerator assets freed up at the end of Tevatron operations,
* Alignment with the ILC R&D program,
* Potential for achievement over the next decade.

Twelve facilities received consideration using some or all of these criteria. Appendix G sorts those facilities not described in this chapter based on relevance to proton- or electron-based programs. This chapter describes the facilities that would support neutrino science and precision physics at the intensity frontier. The facilities include an intense proton source and its injection to the existing rings at Fermilab for a variety of programs.

There are two approaches to making an intense proton source at Fermilab. The first and more powerful approach would replace the present injection complex with Project X, an ILC-like linac capable of accelerating intense beams of either protons or electrons. Project X would use the linac, coupled to the Recycler and Main Injector, to produce much higher proton intensities in the range between 8 GeV and 120 GeV than the present complex. SuperNuMI, the second approach, would reconfigure the existing accelerator complex. Project X would be much more capable than SNuMI, which would leave the 35-year-old proton injection complex in place. SNuMI would provide less flexibility, involve more technical risk and have no alignment with the ILC—but it would also be less expensive and faster to implement than Project X. The Steering Group plan assumes a choice between SNuMI and Project X depending on the scope and longevity of the neutrino program and precision physics program, the desire to develop ILC technology on a real machine and the time available before construction of the ILC.

The table below represents the intensities of the present and future Fermilab accelerator complex using either SNuMI or Project X. The first three columns represent current performance and improvements now underway. The last two columns list SNuMI and Project X parameters. All columns are based on injecting beam from the existing 8 GeV Booster, except for Project X, which eliminates the need for the Booster. While the table does not list any beam power availability at 8 GeV in SNuMI, protons could be made available at this energy at the expense of availability at 120 GeV.



**Possible evolution of proton availability at Fermilab**
\* NOνA column includes a potential upgrade of the Booster repetition rate to support simultaneous delivery of ~2×1020 protons per year at 8 GeV. NOνA itself requires Booster operations at 9 Hz.

## 5.1 SuperNuMI (SNuMI)

SnuMI uses antiproton facilities freed up at completion of the Tevatron collider program to develop a more intense proton source for NuMI. The Antiproton Accumulator would “momentum-stack” protons delivered from the Booster. The momentum-stacking process is inherently more efficient in its use of longitudinal phase space than the “slip-stacking” process that will be used during the NoνA era. This increased efficiency supports the higher proton throughput of SnuMI.

The SnuMI scheme momentum-stacks three Booster batches in the Accumulator and then transfers them to the Recycler. This process repeats six times via “boxcar” stacking in the Recycler. The accumulated 18 batches are transferred from the Recycler to the Main Injector in a single shot. Because the Booster cycles at 15 Hz, the Recycler accumulation process takes 1.33 seconds. The accumulation process takes place while the Main Injector is accelerating, fast-extracting beam to the neutrino target and ramping down for a new load. A 1.33 second cycle time leads to a beam power of 1.2 MW. Since this scheme uses all available Booster cycles, no additional protons are available for an 8 GeV program without diversion from the Main Injector. However, SnuMI is compatible with reconfigurations of the Debuncher ring and/or the Tevatron to support slow-spill programs at 8 or 120 GeV respectively, and with the Tevatron high-energy neutrino facility.

SnuMI could probably be constructed over a two-to-three-year period following completion of Tevatron collider operations. While it would support some of the neutrino- science and precision-physics goals, the SnuMI plan would require continued use of the existing 8 GeV Booster and 400 MeV Linac accelerators, which date from the 1972 start of beam operations at Fermilab. These accelerators’ aging components have led to reliability issues over recent years. Thus, SnuMI entails some risk of operational down time or failures and does not invest in a longer-term program of experiments.

## 5.2 Project X

Project X is based on an 8 GeV superconducting H- linac. The downstream 7 GeV would use ILC cryomodules and radio frequency distribution systems, with perhaps some modifications in the transverse focusing arrangement and RF phase adjustment. Project X's front end draws heavily on technology developed by Argonne National Laboratory for a facility for rare isotope beams, the Advanced Exotic Beam Laboratory. Using the Recycler as a stripper and accumulator ring is the key element that allows the linac to run with the same beam parameters as the ILC. The linac operates at 5 Hz with a total of 5.6×1013 H- ions delivered per pulse. They are injected into the Recycler using a standard H- stripping procedure. The total pulse length (1 ms) implies 100-turn injection. The injection process "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 1.7×1014 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 50 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 proton energy in the Main Injector. This is an order of magnitude higher than the proton power currently available. different configurations of the Recycler could distribute this beam in any combination of fast or slow extractions required by the physics program. Project X is also compatible with reconfigurations of the Debuncher ring and the Tevatron to support slow spill programs at 8 or 120 GeV respectively, and with the Tevatron High Energy Neutrino Facility. The Tevatron-based programs would come with a modest cost in protons delivered to the neutrino program at 120 GeV, because of the use of a Main Injector cycle to transfer beam to the Tevatron.



Taking full advantage of the increased beam power available from Project X would require changes to the Recycler, the Main Injector and the neutrino target. The Recycler would need a new H- injection system and probably measures to mitigate electron cloud effects, as well as a new (fast or slow) extraction system, and new RF systems. The Main Injector would need a new RF system and measures to mitigate electron cloud effects. Project X would require design and construction of a new neutrino target station to support 2.3 MW operations. Building a spur off the current NuMI beamline would permit directing a beam toward the DUSEL site.

The engineering design for Project X will produce a detailed cost estimate and construction plan. However, we expect that the accelerator portion of Project X would be comparable in size and scope to the Main Injector. Construction would take four to five years with a few hundred FTEs per year. It would be most effectively achieved as an interlaboratory collaboration centered at Fermilab.

## 5.3 Existing rings

Current operations at Fermilab use six rings: Booster, Accumulator, Debuncher, Recycler, Main Injector and Tevatron. The descriptions of Project X and SNuMI explain how the Main Injector would be used to produce an intense source of neutrinos, with nearly 10 times the intensity of the current source. Besides the Main Injector, the following examples show how an expanded program could use additional existing rings at Fermilab.

### 5.3.1 Debuncher slow extraction

The Antiproton Debuncher ring could provide an 8 GeV slow-extraction facility with parameters appropriate for a muon-to-electron conversion experiment. Protons could be provided either from the Accumulator (SNuMI) or from the Recycler (Project X). An RF system within the Debuncher would confine the protons to a single bunch, and a slow extraction system would spill the beam over the 1.33-1.4 second cycle time. Operating with a single bunch, the circumference of the Debuncher creates a spill structure containing a ~100 ns pulse every 1.6 μs. With the SNuMI configuration, total delivered beam would be 1.35×1013 every 1.33 seconds, with a corresponding 16 percent reduction in available protons at 120 GeV. If Project X were used to deliver protons, any number up to the full complement of 2.2×1014 every 1.4 seconds could be made available with no impact on the 120 GeV program.

### 5.3.2 Tevatron Stretcher

Taking protons at 120 GeV directly from the Main Injector, the Tevatron could be converted to a 120 GeV "stretcher" ring to provide very high (>90 percent) duty factor beams for a variety of precision frontier experiments. The Tevatron Stretcher provides an independent program that could be used with or without the SNuMI or Project X intensity upgrades. However, the program would result in a tax on the Main Injector-based neutrino program.

A possible scenario would use two Main Injector cycles, at 3.75×1013 protons per pulse, providing 7.5×1013 protons in the Tevatron at 120 GeV. This beam is not accelerated, but rather is slow extracted over roughly 60 seconds. The duty factor would approach 95 percent. This scenario would deliver a total of about 3×1019 protons in a year, representing approximately a five percent diversion of protons from the SNuMI or Project X neutrino program. Because the delivered intensity would be about a factor of 2.5 beyond the highest intensity ever stored in the Tevatron, the laboratory would need to address a number of intensity-related issues. In addition, this scheme would require the design and implementation of a 120 GeV resonant extraction system.

The Tevatron Stretcher and associated extracted beam lines would require a one-to-two year construction period at an appropriate time following completion of Tevatron collider operations.

### 5.3.3 Tevatron high-energy neutrino facility

The Tevatron could operate at high intensity and high energy in fixed-target mode. The science program described in Chapter 4 would require a minimum beam energy of roughly 800 GeV, with a delivered intensity of at least 4×1019 protons per year. The minimum cycle time of the Tevatron in fixed-target mode is about 40 seconds, establishing the basic per-pulse intensity requirement.

A possible scenario would resemble the Stretcher scheme described above. Two Main Injector cycles, at 3.75×1013 protons per pulse, are transferred to the Tevatron at 120 GeV. This beam is accelerated and delivered to a neutrino target via a fast-spill mechanism. Based on a minimum Tevatron cycle time of 40 seconds, the scheme would deliver a total of about 4×1019 protons per year, approximately a five percent diversion of protons from the SNuMI or Project X neutrino program. The same intensity issues associated with the Tevatron Stretcher would apply. Several other technical issues would also require resolution, including development of the fast-extraction scheme, mechanisms for loss control and collimation, recommissioning of the CZero high-intensity abort, and a reliability analysis.

Tevatron fixed-target operations would require one to two years to implement at an appropriate time following completion of Tevatron collider operations.

## 5.4 Project X and the ILC

Among the proton facilities that the Steering Group considered, Project X is unique in supporting ILC development at Fermilab. It would drive the initial stage of industrialization of cryomodules and provide experience with operating the linac as a system, advancing the ILC if a delay in a decision to construct slowed progress in industrialization.

### 5.4.1 Industrialization

The superconducting radio-frequency cryomodules are the most complex and expensive technical element of the ILC. Development of the national and institutional capability to build and test cryomodules with ILC specifications is a high priority of the GDE Americas Regional Team and of Fermilab in its bid to host the ILC. The DESY experience has shown that mastery of this technology requires significant infrastructure investments and a long learning curve for personnel.

Project X requires approximately 33 ILC-style cryomodules. In the current design, nine are “ILC-like” and 24 are “ILC-identical.” These cryomodules provide acceleration between 1.0 and 8.0 GeV. Production over a three-year period represents a significant advance over currently anticipated capabilities. However, such a production rate is below ILC requirements, so Project X would represent the initial phase of industrialization for ILC in the U.S. Full integration within an ILC industrialization plan requires more study.

### 5.4.2 Operational experience and systems testing

Project X could be configured to use the same beam parameters as the ILC (9 mA×1 ms ×5 Hz). The linac design calls for 31.5 MV/m but could operate successfully at lower gradients. The RF generation and distribution system would be the same as the ILC’s, giving valuable experience with the klystrons, modulators, couplers, and cryomodules under operational conditions. The focusing arrangement, i.e. distribution of quadrupoles through the cryomodules, is somewhat different from the ILC’s between 1 GeV and 5 GeV.

Operation of the linac with electrons is also under study. It would require a mechanism to provide appropriate phasing of the cavities to compensate for the fully relativistic state of the electrons. Ferrite-based vector modulators, currently under development, could provide this capability. Operation with electrons at the full ILC specification would provide important understanding of higher-order modes and associated loads on the cryogenic system.

### 5.4.3 Test beam for detector development

Project X would substantially increase the capabilities of the 120 GeV test-beam program and would support the laboratory’s test-beam infrastructure through the construction of new beamlines driven by the 8 GeV linac. These new test beams could provide 8 GeV protons and electrons with the exact ILC beam-time structure, of interest to the ILC detector community for evaluation of readout strategies and low-energy calorimeter performance.

## 5.5 Project X and longer term facilities

The high-power 8 GeV beam of Project X would support a program aimed at the development and demonstration of technologies required for muon-based storage rings such as a neutrino factory or muon collider.

## 5.6 Summary

The Steering Group identified two options that would provide significant enhancements to proton intensity in support of neutrino-science and precision-physics programs at Fermilab. Both options allow use of the Debuncher ring and/or the Tevatron to deliver beams in the range between 8 GeV and 800 GeV. The SNuMI project is based on reusing existing antiproton rings for proton accumulation. SNuMI would support the delivery of about 1.2 MW of 120 GeV proton beam power onto a neutrino target and could provide 8, 120 or 800 GeV beams for precision physics programs via modest diversion of protons from the neutrino program. Project X is based on a new superconducting 8 GeV linac. Project X would support more than 2 MW of protons between 50 GeV and 120 GeV on the neutrino target, simultaneous with 200 kW of beam power at 8 GeV. The 8 GeV beams could support a variety of precision physics experiments at 8, 120 or 800 GeV. Fermilab could implement SNuMI within a couple of years and Project X in four to five years. Project X features significant technology alignment with ILC which would continue to develop U.S. industrial capabilities.