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PROJECT X: A MULTI-MW PROTON SOURCE AT FERMILAB *

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Abstract

As the Fermilab Tevatron Collider program draws to a close a strategy has emerged of an experimental program built around the high intensity frontier. The centerpiece of this program is a superconducting H^- linac that will support world leading programs in long baseline neutrino experimentation and the study of rare processes. Based on technology shared with the International Linear Collider (ILC), Project X will provide multi-MW beams at 60-120 GeV from the Main Injector, simultaneous with very high intensity beams at lower energies. Project X will also support development of a Muon Collider as a future facility at the energy frontier.

STRATEGY FOR EVOLUTION OF THE FERMILAB COMPLEX

After twenty five years of operations as the highest energy particle collider in the world, the Fermilab Tevatron has now ceded the energy frontier to the Large Hadron Collider (LHC). The current plan is to continue operations of the Tevatron through September 2011. In parallel Fermilab has operated, and will continue to operate, the highest power accelerator based neutrino program in the world since 2005. The Japanese Proton Accelerator Research Complex (J-PARC) has recently initiated operations of a neutrino beam which will become competitive with the Fermilab facility over the next few years.

The above situation has been anticipated for many years and in preparation the Department of Energy's and NSF's High Energy Physics Advisory Panel (HEPAP), in coordination with Fermilab, has outlined a strategy for U.S. elementary particle physics over the coming decades [1, 2]. This strategy establishes a framework for ongoing research in elementary particle physics based on three frontiers – the energy frontier, the intensity frontier, and the cosmic frontier. The first two of these frontiers are heavily reliant on accelerator facilities, and it is recognized that within the U. S. Fermilab will remain the sole laboratory providing such facilities. Within this context Fermilab has established an overall strategy of retaining and expanding our world-leading program on the intensity frontier, while using this program as a bridge to an energy frontier facility beyond LHC in the long term.

A multi-megawatt proton source, known as Project X, is the key to Fermilab's strategy for the future. Project X will provide long term flexibility for adapting to opportunities on both the intensity and energy frontiers, supporting a continuously evolving world leading program in neutrino and rare processes physics, accompanied by applications outside of elementary particle physics. At the same time the technologies deployed within Project X are aligned with the needs of energy frontier facilities including the ILC and muon-based facilities. Project X could evolve into the front end for either a muon-based Neutrino Factory or Muon Collider.

PROJECT X GOALS AND INITIAL CONFIGURATIONS

Project X is being developed to meet the mission need contained in the strategic plans developed by Fermilab and HEPAP [1, 2]. Design goals are based on three mission elements defined within these strategic plans:

- A neutrino beam for long baseline neutrino oscillation experiments. The desired beam power is in excess of 2 MW, available at any energy over the range 60-120 GeV.
- High intensity, low energy proton beams for kaon and muon based precision experiments. The desired beam power is in excess of 100 kW per experiment, at an energy in the range 3-8 GeV, and with a variety of duty factors and bunch configurations. It is essential that this program be operable simultaneous with the neutrino program.
- A path toward a muon source for a possible future Neutrino Factory and/or a Muon Collider. This requires an upgrade potential to approximately 4 MW of beam power in the energy range 5-15 GeV, accompanied by options for delivering this beam power in a modest number of bunches.

Two facility configurations have been developed to date that could meet some or all of these goals. Both configurations feature a superconducting H^- linac paired with the existing Recycler and Main Injector rings to support the neutrino and rare processes programs.

Initial Configuration-1

Initial Configuration-1 (IC-1) is shown schematically in Figure 1. This configuration features very strong alignment with ILC technologies and is described in detail elsewhere [3, 4]. The central features are an 8 GeV superconducting H^- linac that operates with a duty factor of 0.3%.

IC-1 fully meets the long baseline neutrino design goals given above. However, it does not provide a strong platform for mounting the low energy rare processes program. Several problems became evident as this configuration was developed: 1) the Recycler, because of its very large circumference (3300 m), is ill-suited to providing a high intensity slow spilled beam at 8 GeV;

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and 2) the option of utilizing the existing antiproton Debuncher Ring for an 8 GeV slow spill has been examined and it is concluded that the total extracted beam power from this ring cannot be in excess of ~150 kW. In fact, we have concluded there is a fundamental limitation, at 100-200 kW, on the amount of beam that can be delivered from any resonant extraction system due to the losses inherent in the slow extraction process. In addition, a resonant extraction from a single ring does not afford the opportunity for providing different spill structures for multiple users.

These difficulties led to the development of Initial Configuration-2 (IC-2).

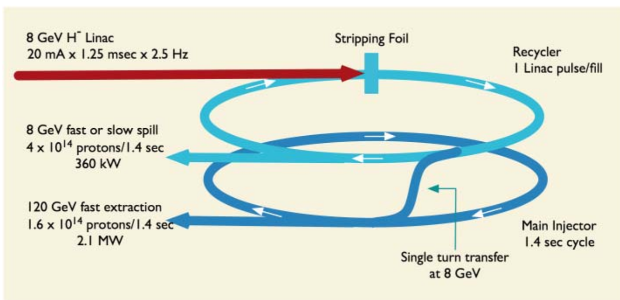

Figure 1: Initial Configuration-1.

Initial Configuration-2

Project X Initial Configuration-2 (IC-2) was developed in recognition of the issues with resonant extraction described above, with parameters based on a low energy/high intensity physics workshop held in the fall of 2009 [5]. That workshop defined an energy range of 2-4 GeV as optimal for a wide range of kaon and muon rare processes experiments, with 8 GeV more ideal for measurement of g-2 of the muon. In addition the workshop defined beam power and beam structure requirements associated with a variety of experiments. The most important requirements are beam powers between 50-500 kW and the ability to deliver high duty factor beams, with differing beam structures to different experiments. The unique feature of IC-2 is its ability to meet these requirements.

IC-2 (Figure 2) is based on a 3 GeV, continuous wave (CW), superconducting H^- linac. The layout is shown schematically in Figure 2. The linac operates with an average current of 1 mA, and with peak currents (sustained for less than the time required to extract <<1% of the cavity stored energy) of 10 mA. A Rapid Cycling Synchrotron supports the neutrino design goals with the roles of the Recycler and Main Injector the same as in IC-1: the accumulation and subsequent acceleration of protons to 60-120 GeV in support of the neutrino program. An alternative, utilization of a pulsed linac to accelerate from 3-8 GeV, is under study. Such an alternative would utilize a 4-5 msec pulse with a 1 mA current. Performance parameters for IC-2 are summarized in Table 1.

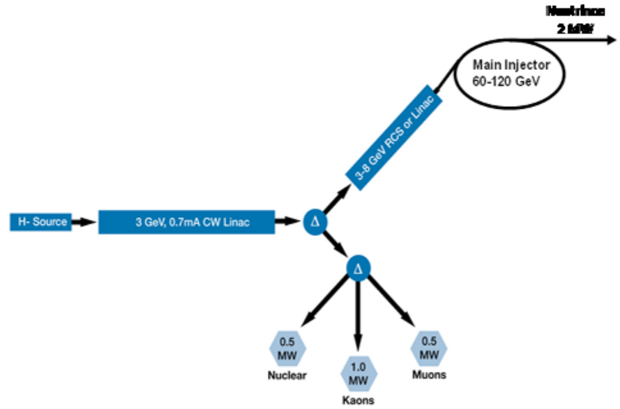

Figure 2: Initial Configuration-2.

Table 1: Project X Performance Parameters (IC-2)

Linac		
Particle Type	H^-	
Kinetic Energy	3.0	GeV
Average Beam Current	1	mA
Pulse Rate	CW	
Beam Power	3000	kW
Beam Power to 3 GeV Program	2870	kW
RCS/Pulsed Linac		
Particle Type	Protons/ H^-	
Kinetic Energy	8.0	GeV
Pulse Rate	10	Hz
Pulse Width	0.002/4.3	msec
Cycles to Recycler	6	
Particles per cycle to Recycler	2.6×10^{13}	
Beam Power to 8 GeV Program	200	kW
Recycler-Main Injector		
Kinetic Energy (maximum)	120	GeV
Cycle Time	1.4	sec
Particles per Pulse	1.6×10^{14}	
Beam Power to 120 GeV	2200	kW

For neutrino operations the 3 GeV linac provides 4.3 msec pulses at 1 mA at a repetition rate of 10 Hz. A total of 2.6×10^{13} H^- ions are delivered per pulse. These beam pulses are stripped and accumulated within the RCS, with six RCS cycles sent on to the Recycler for accumulation followed by transfer to and acceleration to 120 GeV in the Main Injector. Alternatively, the 3 GeV pulses are fed into a 3-8 GeV pulsed linac and then stripped/accumulated in the Recycler. Again six such pulses are required. By either route 1.6×10^{14} protons are delivered to the Main Injector for acceleration to 120 GeV. With a 1.4 second cycle time the total beam power available is 2200 kW. Note that over the 1.4 second period of the Main Injector an additional eight pulses are available for an 8 GeV program. The total beam power available at 8 GeV is thus 200 kW. At proton energies lower than 120 GeV the Main Injector cycle time can be shortened to maintain beam power above 2 MW at energies throughout the range 60-120 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 will require a new RF system, measures to preserve beam stability through transition, and measures to mitigate electron cloud effects.

The above utilization of the 3 GeV linac to support Recycler and Main Injector operations only requires 4.3% of the beam available from the CW linac (for 120 GeV Main Injector operations). Thus, 2870 kW remain available to support the 3 GeV program. The key elements of IC-2 that allow flexible utilization of this available beam power to support multiple experiments with differing beam requirements are:

- A wide-band chopper just downstream of the 2.5 MeV RFQ that enables filling of rf buckets in the linac with arbitrarily programmed patterns.
- A 10 mA ion source that allows the acceleration of 10 mA peak currents for limited periods of time, while maintaining an average current of 1 mA.
- A deflecting mode rf cavity operating at n±1/4 of the bunch frequency at the downstream end of the linac. (Also referred to as the separator.)

Figure 3 illustrates the functioning of the chopper and deflection cavity to provide tailored bunch patterns to a number of experiments. Buckets are available for occupation at 325 MHz. They are populated in a manner that provides a 10 mA burst for 100 nsec out of each 1 μsec, while maintaining an average current of 1 mA. The color coding of the figure indicates where each bunch arrives in phase at the separator. The blue bunches are not deflected by the cavity, the red bunches are deflected one direction, and the green bunches the other. This particular arrangement results in identical slow spilled beams to the red and green users with a macro-duty factory of 100%, and to the blue user with a macro-duty factor of 10%. The bunch structure going to the blue user is typical of that required for a muon to electron conversion experiment (or any experiment utilizing stopped muons); the green and red patterns are typical of what might be required by any 100% macro-, 10% micro-, duty factor experiment, for example a rare kaon decay experiment. Simple counting of bunches demonstrates that beam power is shared between the red, green, and blue users in the ratio 0.4:0.4:0.2. The price paid for this arrangement is that ~2-3 kW of beam power has to be disposed of at 2.5 MeV where the chopper is situated.

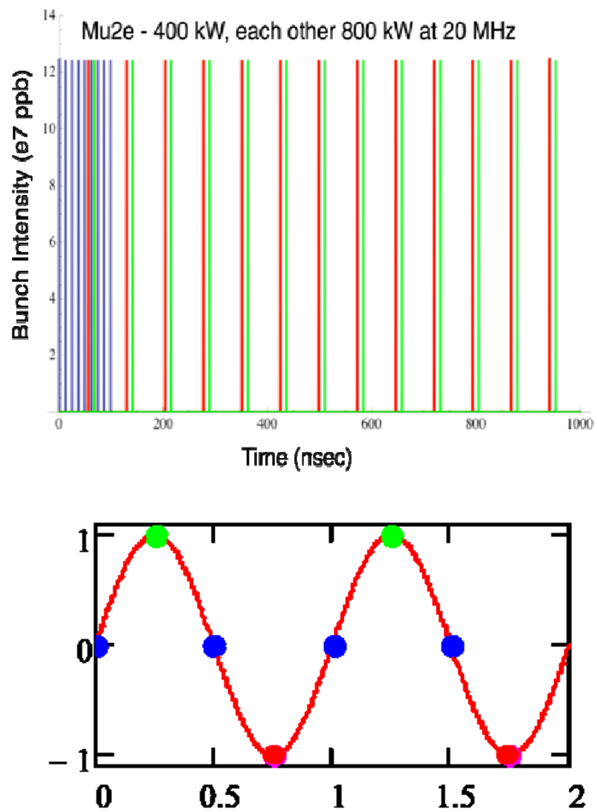

Figure 3: Illustration of the utilization of the 2.5 MeV chopper and 3 GeV separator to provide a particular bunch patter. Top: the loading of 325 MHz buckets to support three distinct experimental users. Bottom: The arrival times of the various buckets at the deflecting mode separator cavity.

SRF Technologies

The entire CW linac downstream of the ion source, RFQ, and MEBT is based on superconducting cavities. Figure 4 shows the deployment of these cavities for IC-2. A total of six cavity types at three different frequencies are utilized. The 325 MHz accelerating structures are of the single spoke resonator type, configured to β's of 0.11, 0.22, and 0.4 respectively. The 650 MHz structures are of (5-cell) elliptical shape with β's of 0.6 and 0.9. The 1.3 GHz structures are elliptical cavities of the ILC configuration, with suitable modifications to operate in CW mode. Approximately 240 cavities of the various types are required in total.

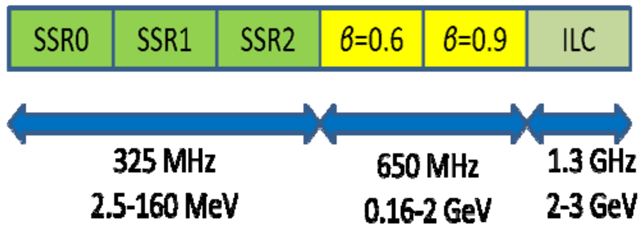

Figure 4: Accelerating module configuration of the 3 GeV CW linac in IC-2.

Preliminary goals for gradient and Q_0 for superconducting accelerating structures have been established based on the following:

- It has been observed [6] that the gradient vs. Q_0 of a cavity operated at 2 K typically shows a "knee", and that this knee corresponds to a (frequency dependent) specific magnetic surface field;
- Once a maximum surface field is established, a cavity shape is selected to maximize the gradient, subject to certain physical constraints;
- A realistic goal for Q_0 is then established based on keeping the cavity losses to <20 W/cavity, again subject to realistic extrapolation from current experience.

Preliminary goals for the IC-2 CW linac cavities are listed in Table 2. Based on these preliminary goals a final optimum configuration in (G, Q_0, T) space will be determined through the R&D program

Table 2: Cavity performance goals for IC-2

Freq (MHz)	B_{surf} (mT)	G (MV/m)	Q_0	T (K)
325	60	15	1.4×10^{10}	2
650	72	16	1.7×10^{10}	2
1300	72	15	1.5×10^{10}	2

The goals listed in Table 2 for the 325 MHz, β=0.22, cavity have already been met with a prototype single spoke resonator cavity in a vertical test at Fermilab. The 1.3 GHz goals are also consistent with cavities being developed for the XFEL project at DESY [7].

Assuming the performance given in Table 2, the energy gain per cavity throughout the linac is given in Figure 5. The discontinuity in moving from the 650 to 1300 MHz section is largely due to the transit time factor and may be significantly reduced by utilizing a beta=0.95 cavity shape. Such a shape will be explored as part of the R&D program.

It is our intention to utilize a pulsed linac for the 3-8 GeV accelerating section of Project X if this proves practical. Such a linac would utilize (approximately 200) ILC-like cavities and (25) cryomodules, and would operate with an ILC-like rf distribution system. The primary difference would be that the linac would operate with a lower current (1 mA), a longer pulse length (4-5 msec), and a lower gradient (25 MV/m).

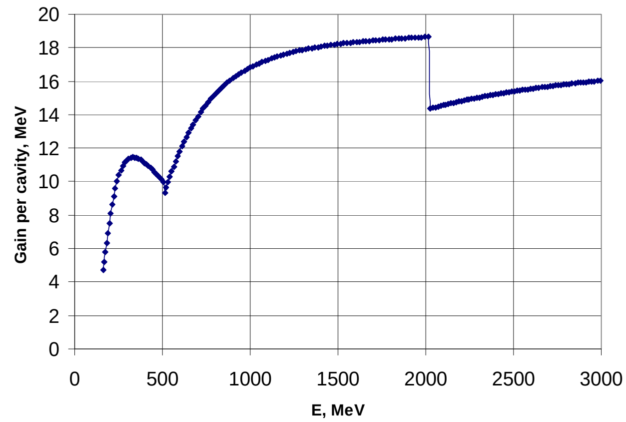

Figure 5: Energy gain per cavity through the CW linac portion of Project X, IC-2

Joint Project X and Muon Facilities Strategy

Project X shares many features in common with the proton driver required for a muon based accelerator facility – either a Neutrino Factory or a Muon Collider. Both require protons directed onto a production target at an energy between 5-15 GeV, with a total beam power of approximately 4 MW. This is well within the upgrade capabilities of Project X. However, the beam delivered from the CW linac (or from the pulsed linac, for that matter) does not carry the correct beam format. The muon facilities generally require the proton beam consolidated into a few very short bunches, repeating at tens of Hz. It appears inevitable the at least two new rings (for accumulation and bunch compression) would be required downstream of Project X to provide the required format. A conceptual design for these two rings will be developed over the next several years. A pre-conceptual layout of a Muon Collider facility on the Fermilab site, including Project X as the front end, is shown in Figure 6.

Project X Collaboration

A multi-institutional collaboration has been formed to undertake the Project X R&D program with Fermilab as the lead laboratory. A collaboration MOU has been established that outlines basic goals and the means of executing the work during the R&D phase. Collaborators generally assume responsibility for components and subsystem design, development, and cost estimating. It is recognized that it would be natural to extend R&D responsibilities into the construction phase. International participation is expected to be via in-kind contributions, established via bi-lateral MOUs, and the first MOU with several Indian institutions is in place. Current members of the Project X Collaboration are listed in Table 3.

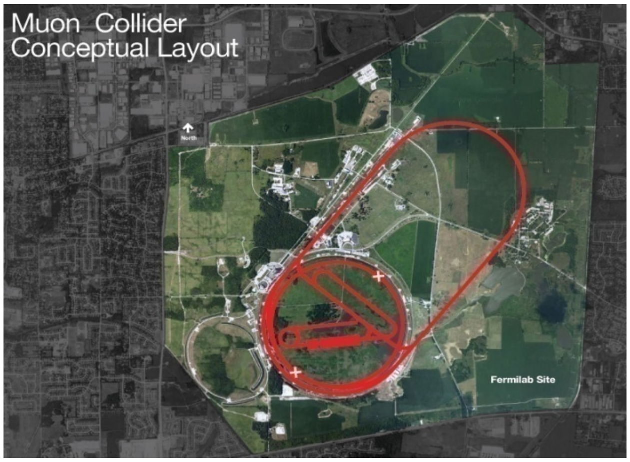

Figure 6: Conceptual layout of a Muon Collider. The Project X linac is situated on the lower half of the Tevatron infield, upstream of the rings needed to prepare the linac beam for targeting.

Table 3: Project X Collaborating Institutions

Project X Collaborating Institutions
Argonne National Laboratory
Brookhaven National Laboratory
Cornell University
Fermilab
Lawrence Berkeley National Laboratory
Michigan State University
Oak Ridge National Laboratory
Stanford Linear Accelerator Center
Thomas Jefferson National Accelerator Facility
ILC/Americas Regional Team
Bhabha Atomic Research Center
Inter-University Accelerator Center
Raja Ramanna Center for Advanced Technology
Variable Energy Cyclotron Center

Strategy and Timeline

The goals for the next six months are to complete documentation, including a preliminary cost estimate, for Initial Configuration-2. In parallel the R&D plan corresponding to this configuration is being updated, and resources are being aligned with this plan.

While the bulk of the R&D will be concentrated in the area of superconducting rf at all relevant frequencies, we will specifically pursue several outstanding technical issues: 1) identifying a baseline concept for the broadband chopper; 2) identifying concepts for pairing a 3-8 GeV pulsed linac with a CW front end; and 3) developing options for multi-turn injection into the RCS or Recycler.

We believe that Project X could be constructed over a five year period, assuming a commensurate funding profile. We have been informed by the U.S. Department of Energy that the earliest possible date for a construction start would be FY2015. If such a scheduled were achieved, Project X could be available to support a physics research program in ~2020.

Summary

Project X is central to Fermilab's strategy for development of the accelerator complex. Construction of Project X would enable a world-leading program in the physics of neutrinos and rare processes. The technology development is aligned with the need of the ILC and various muon accelerators. Potential applications are also available beyond elementary particle physics, e.g. nuclear physics and accelerator driven systems (ADS).

The Project X design concept has evolved over the last year and now provides significantly enhanced physics capabilities as compared to prior concepts. The current configuration supports in excess of 2 MW of beam power at any energy between 60-120 GeV, simultaneous with 3 MW at 3 GeV. Multiple experiments can be supported with varying beam requirements. The CW linac is unique within the world and offers capabilities that will be very difficult to duplicate in a synchrotron.

With adequate support Project X could be constructed over the period 2015-2019, providing a unique facility for physics research starting around 2020.

REFERENCES

[1] Fermilab Steering Group Report, September 2007, http://www.fnal.gov/pub/directorate/steering/index.shtml

[2] Particle Physics Project Prioritization Panel, "U.S. Particle Physics: Scientific Opportunities, A Strategic Plan for the Next Ten Years", May 2008, http://www.science.doe.gov/hep/files/pdfs/P5_Report%2006022008.pdf

[3] Project X Initial Configuration Document-1, http://projectx-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=83&extension=pdf

[4] S.D. Holmes, *Project X at Fermilab; Prospects and Plans*, 2009 Particle Accelerator Conference, Vancouver (2009)

[5] Project X Physics Workshop, Fermilab, Nov. 2009, http://www.fnal.gov/directorate/Longrange/Steering_Public/workshop-physics-4th.html

[6] G. Ciovati, "Review of the frontier workshop and Q-slope results", Physica C 441 (2006) p. 44-50

[7] See for example, L. Lilje, *R&D in RF Superconductivity to Support the International Linear Collider*, 2007 Particle Accelerator Conference, Albuquerque (2007), p 2559