PROJECT X AS A WAY TO INTENSITY FRONTIER PHYSICS

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Abstract

We describe the goals and methods of an Intensity Frontier physics program to be pursued at Fermilab in the next decade. After a description of the physics program, we introduce the accelerator methods based on a high intensity 8 GeV Linac aimed at the support of a 2 MW 120 GeV as well as an 800 kW 8 GeV physics programs.

INTRODUCTION

The search for the αρχη, the first principle of the world [1] has permeated the human civilization since the beginning of recorded history. The introduction of the scientific method [2] has modified the investigation process with the introduction of the interplay between experimental and theoretical advances. The questions we can ask nowadays are slightly more specific than those of our presocratic predecessors: what are the most basic building blocks of the universe? What are the forces that enable these elementary constituents to form all that we see around us? What properties of these particles and forces drive the evolution of the universe from the Big Bang to its present state, with its complex structures that support life—including us?

These are the questions that particle physics is trying to answer and for which the Standard Model (SM) has provided a very successful major synthesis [3]. Recently, however, revolutionary discoveries have shown that this Standard Model, while it represents a very good approximation at the energies of existing accelerators, is incomplete. They strongly suggest that new physics discoveries beyond the SM await us at higher energies. For instance, a striking development in neutrino physics was the discovery that the three kinds of neutrinos, which in the SM are mass-less and cannot change from one type to another, do in fact have small masses and "oscillate" from one kind to another [4].

Yet another remarkable discovery in astrophysics was the observation of the accelerating expansion of the universe, implying the existence of a mysterious entity, labeled dark energy [5], which makes up almost three quarters of the energy-matter content of the universe, driving it apart at an ever-increasing rate. In addition, other astrophysical observations [6] have also revealed that about a quarter of the universe consists of an unknown form of matter called dark matter. No SM particle or interaction can account for these strange ingredients of our universe.

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PHYSICS FRONTIERS

As recognized and documented in the report by the Particle Physics Project Prioritization Panel – P5 (Fig. 1), physicists address the basic questions about the nature of the Universe using a range of tools and techniques at three frontiers that together form an interlocking framework of scientific opportunities: the Energy Frontier, the Intensity Frontier and the Astrophysics Frontier.

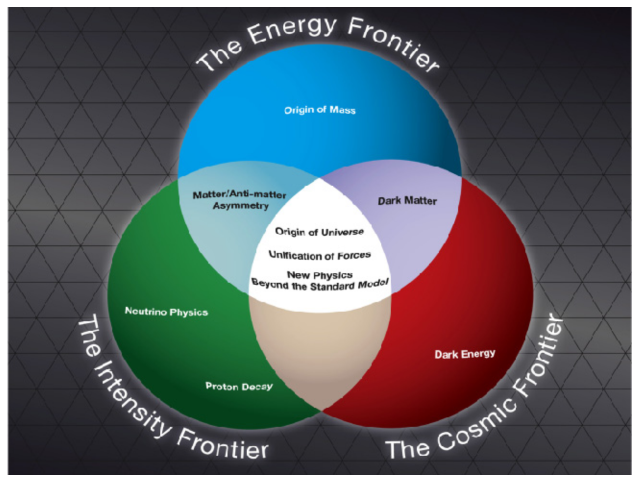

Figure 1: P5 Artistic representation for the interlocking nature of the frontiers of physics investigations [7].

At the Energy Frontier, present and future accelerators (Tevatron, LHC, Lepton Colliders) will make major discoveries leading to an ultimate understanding of particles and their interactions by allowing physicists to directly produce and study the particles that are the messengers of these new phenomena in the laboratory for the first time. At the Intensity Frontier, the goal is to make measurements of the mass and other properties of neutrinos that are fundamental to understanding physics beyond the Standard Model and have profound consequences for the understanding of the evolution of the universe. In addition, incisive experiments using muons, kaons or *B* mesons to measure rare processes can probe the Terascale and beyond.

Finally, at the Cosmic Frontier, the combination of ground and space-based observation of astrophysical objects in the distant cosmos will shed light on the nature of dark energy and dark matter.

PHYSICS AT THE INTENSITY FRONTIER

Neutrinos

The most compelling physics program for the Intensity Frontier is one pursuing neutrino studies. One of the primary goals of any neutrino program is to complete our understanding of neutrino mixing and oscillations, in particular to determine the ordering and splitting of the neutrino mass states, to measure the mixing angles and to determine the existence of CP violation in neutrino mixing. The study of CP violation in neutrino oscillations is especially compelling it may help explain the very fundamental problem of the matter-antimatter asymmetry of the universe through the process known as leptogenesis [8]. Discovering the ordering of the neutrino mass states—the mass hierarchy—will help determine whether neutrino mass is related to the unification of the forces and whether neutrino oscillations violate CP symmetry (Fig. 2).

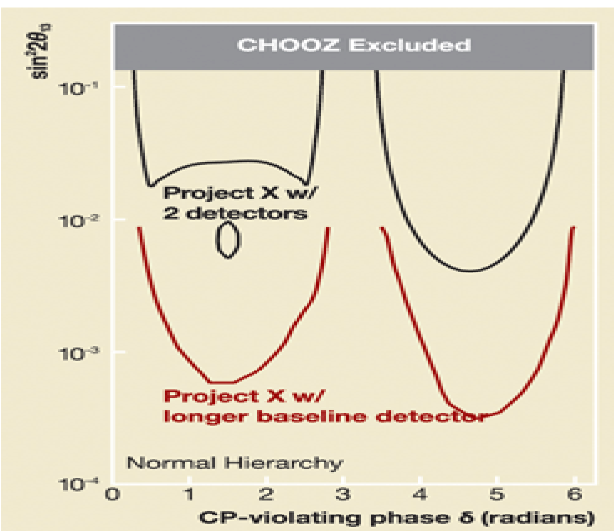

Figure 2: Sensitivity to CP violation at 3σ confidence level of potential future experiments at a high intensity proton source (Project X) at Fermilab.

Experiments to address these neutrino science goals will require both powerful beams and very large detectors, with the product of beam power and detector mass more than an order of magnitude larger than the present-generation experiments. The discovery potential of these experiments will greatly benefit from higher proton beam power (thus higher neutrino flux) and greater flexibility of beam energy than is presently planned.

Muons

Lepton Flavor Violation (LFV) was discovered in neutrino experiments, where the three flavors of neutrinos are observed to oscillate into one another. A key question is whether LFV also occurs with the charged leptons: electron, muon and tau. Theoretical models that incorporate ideas such as unification, supersymmetry or heavy-neutrino mixing predict charged LFV at rates that could be within reach of new experiments [9]. Combined with results from neutrinos and the LHC, these experiments could point the way to leptogenesis or unification.

A new experiment could search for the direct coherent conversion of muons into electrons in the field of a nucleus. This muon-to-electron conversion experiment could detect LFV decays at the 10^{-17} level the rate of standard muon processes. It would probe several distinct LFV processes. If a signal is detected, a $\mu\to e$ conversion experiment could zero in on the new physics by repeated measurements with different nuclear targets. This experiment would have sensitivity to very high energy scales, beyond the direct reach of present and future colliders.

The Muon-to-Electron-Gamma (MEG) experiment at the Paul Scherrer Institute will soon begin to look for the LFV process $\mu\to e\gamma$, with predicted sensitivity at the 10^{-13} level. A $\mu\to e$ conversion experiment at the 10^{-17} level would have greater sensitivity to the $\mu\to e\gamma$ transition than MEG, and orders of magnitude better sensitivity for more general LFV processes (Fig. 3).

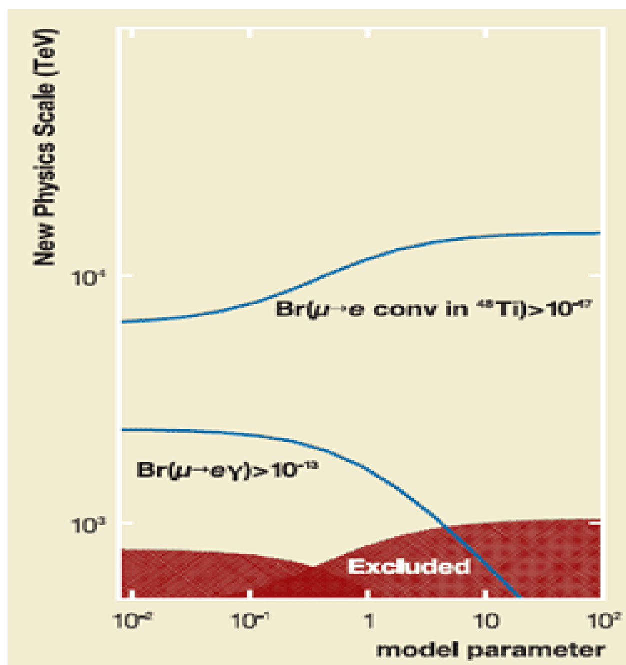

Figure 3: Comparison of the sensitivity to lepton flavor violation of the MEG ($\mu\to e\gamma$) experiment at a transition rate of 10^{-13} and a μ-to-e conversion experiment with the Fermilab Booster that could reach a rate of 10^{-17}. Project X could reach the rate of 10^{-18}. The model parameter interpolates between a flavor transition magnetic moment-type operator (<<1) and a lepton-flavor changing four-fermion operator (>>1).

Kaons

Theories of Terascale physics typically predict new contributions to flavor-violating processes involving quarks. New particles predicted by Terascale physics are expected to have flavor- violating and CP-violating couplings. Experiments at B factories or elsewhere have unexpectedly found no clear signals of such contributions. These results favor theoretical models with minimal flavor violation. The data suggest a strategy of concentrating on rare processes that are as theoretically and experimentally clean as possible, to maximize the sensitivity to small contributions from new physics.

The ultrarare process $K \to \pi\nu\nu$ is the most promising opportunity for implementing this new strategy [10]. The neutral $K \to \pi\nu\nu$ decay is extremely suppressed in the Standard Model and has not yet been observed. It is a clean, purely CP-violating process, with a Standard Model theoretical uncertainty no larger than two percent. A phased program at KEK and then J-PARC may eventually detect about 100 of these rare decays. The physics reviewed above shows the importance of a new experiment with the ultimate capability to detect about 1000 neutral decays, achieving a statistical error that approaches the theoretical uncertainty. Such an experiment would be even more powerful if combined with a precision measurement of charged $K \to \pi\nu\nu$ decays, which are also highly suppressed in the Standard Model and have a modest theoretical uncertainty.

Such experiments would be sensitive to new sources of CP violation involving quarks. They would also be sensitive to flavor-violating effects from new particles, even in cases where the only source of CP violation is the CKM phase of the Standard Model. Either way, rare kaon decays offer a unique window on these phenomena. For example, if superpartner particles are discovered at the LHC, kaon experiments could address such fundamental questions as distinguishing among different mechanisms for the breaking of supersymmetry.

Other rare kaon-decay modes offer opportunities for major surprises. They include possible detection of the lepton-flavor-violating decays $K \to \pi\mu e$ or $K \to \mu e$, and exotic decays of kaons into axions or gravitons.

EXPERIMENTS AT THE INTENSITY FRONTIER AT FERMILAB

With the energy frontier moving to the Large Hadron Collider at CERN in the coming months and the completion of the Tevatron collider program in the next few years, Fermilab's science program will change in a major way toward the Intensity Frontier. This change will require a very high-power proton source. The physics vision for this proton source will have the three main elements described in the previous sections:

- A neutrino beam for long baseline neutrino oscillation experiments based on a new 2 MW proton source with proton energies between 60 and 120 GeV and aimed at the proposed DUSEL underground laboratory in South Dakota.
- Kaon and muon-based precision experiments exploiting 8 GeV protons running simultaneously with the neutrino program and including 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 has significant upgrade potential.

A detector for a neutrino oscillation experiment, if located in the National Science Foundation's DUSEL, would also be a world-class detector for proton decay. This detector could also perform high-statistics studies of atmospheric neutrinos and carry out astrophysical searches including detection of relic-supernova neutrinos and neutrino bursts from supernovae in our galaxy and nearby.

A $\mu \to e$ conversion experiment at Fermilab could be 10,000 times more sensitive than previous experiments. An intense 8 GeV proton beam and the Accumulator and Debuncher rings, available after the end of antiproton production for the Tevatron collider program, would make this LFV search possible. The SNuMI accelerator upgrades would increase the total proton flux at 8 GeV, allowing a modest increase in beam power for the muon program while also increasing the beam power available to the neutrino program. A high intensity proton source could increase the beam power available to the muon program by a factor of 10. Exploiting this increased intensity and a reoptimized muon beam (e.g., decreased energy spread and transverse beam size) has the potential to further improve sensitivity beyond that possible with the SNuMI upgrades.

On the K decay front, experiments based on 1000 Standard Model $K \to \pi\nu\nu$ events could probe Terascale physics with greater than 5 σ sensitivity.

While economic realities will undoubtedly limit the spectrum of financially feasible experiments at the Intensity Frontier , the availability of a flexible intense proton source at Fermilab will be a resource for a wide physics program in the next decade.

PROJECT X DESCRIPTION

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 capitalizing on the laboratory accelerator infrastructure.

The major feature of Project X is a new 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 200 kW of beam power at 8 GeV.

The major elements of the Project X plan are the following:

- A linac operating at 325 MHz (Front-End) and 1300MHz (high-β section).

- 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.

The linac utilizes technology in common with the ILC over the energy range ~0.4 – 8.0 GeV (high-β section operating at 1.3 GHz). 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. However the alignment can also be slightly modified to allow for specific requirements of the Intensity Frontier physics mission.

A first design of Project X, proposed in August 2007, foresaw the injection, stripping and accumulation of 3 Linac pulses in the Recycler Ring, with a subsequent single turn injection into the Main Injector for acceleration to 120 GeV (Table 1 and Fig. 4). Further refinements in September 2008 are considering a departure from the ILC beam parameters to inject a single Linac pulse in the Recycler Ring and Main Injector, with the availability of remaining linac pulses for the 8 GeV physics program (Table 2 and Fig. 5). In the first case the Project X would have a Linac power of 360 kW at 8 GeV. In the second case the Linac power would be approximately 1 MW. The second design allows the possibility of injecting directly into the Main Injector, bypassing the Recycler Ring. Since the Recycler Ring is built with permanent magnets and has a very narrow beam momentum acceptance at 8 GeV, possible shortcomings of the final Linac energy could be avoided by a direct injection in the MI.

The fluid situation of the Project X design parameters reflects the process of optimization presently taking place.

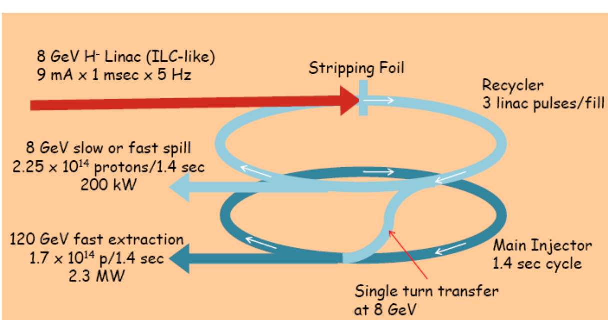

Figure 4: Project X schematic conception for an ILC-identical linac (9 mA x 1 msec x 5 Hz) injecting up to 3 pulses in the Recycler Ring.

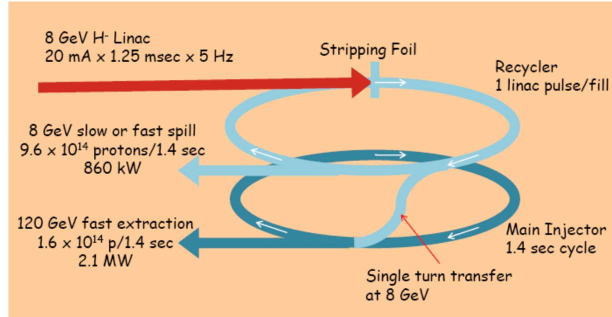

Figure 5: Project X schematic conception for a high-power linac (20 mA x 1.25 msec x 5 Hz) injecting 1 pulse in the Recycler Ring.

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 in the August 2007 design. In this early design, 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 msec 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.

Table 1: Main parameters for various 8 GeV linac designs (the parameters for the HINS program are referenced)

Parameter	360 kW	1 MW	HINS
Current (mA)	9	20	~20
Pulse Length (msec)	1 msec	1.25	3 or 1
Rep. Rate (Hz)	5	5	2.5 or 10
Gradient (MeV/m)	31.5	25	15

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 greater than 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 200 kW range, depending on the energy in the Main Injector.

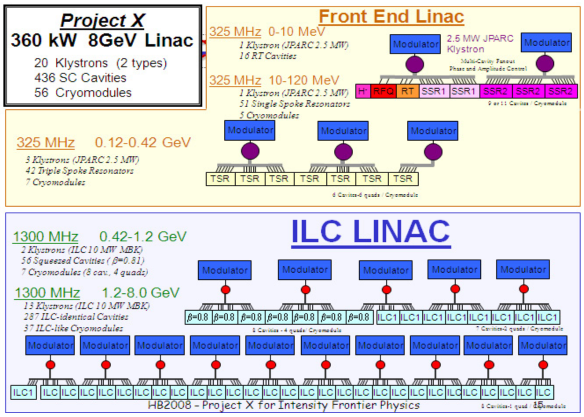

Figure 6: Schematic layout and components count for 8 GeV linac with ILC-identical components.

In the September 2008 design, the loading of the Recycler can be accomplished with one pulse only from the Linac. Figure 6 shows a cartoon of the various elements in the 8 GeV Linac, described in more details in the next sections. Preliminary studies on the location of the Linac have determined that a feasible site within the Fermilab campus may be the south section of Tevatron (Fig. 7).

Figure 7: Proposed site for the 8 GeV linac. The Main Injector ring is visible on the left.

For a project of this size there are many technical issues to be investigated. These issues are outlined in the following sections.

325 MHz Front End Linac

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 high-β system. The initial ~0.4 GeV of the linac draws heavily on technology developed by Argonne National Laboratory for a facility for rare isotope beams [11]. 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.

Many technologies and components applicable to the Front End Energy Linac are expected to be developed under the High Intensity Neutrino Source (HINS) R&D program that has been ongoing since FY06. Within the framework of the HINS program, we plan to build and operate a portion of the Front End (up to energies of 60 MeV) as a technical feasibility proof of the proposal. The 60-MeV HINS proton linear accelerator consists of a normal-conducting and a superconducting section.

The normal-conducting section is composed of an ion source, a 2.5 MeV radio frequency quadrupole (RFQ), a medium energy beam transport, and 16 normal-conducting crossbar H-type cavities that accelerate the beam to 10 MeV. The use of short normal conducting resonators up to ~10 MeV reduces the number of different types of SC cavities and provides adiabatic beam matching.

Each normal conducting cavity consists of 3 or 4 identical cells with geometrical beta corresponding to the relevant beam velocity at the cavity mid plane. Moreover, in order to simplify production, all cavity drift tubes are identical (except for their length) and cross-bars of spokes have the same basic shape. A more detailed RF design and optimization flow is given in [12]. A complete cavity before assembly of the final endplates is shown in Fig. 8.

Figure 8: One normal-conducting resonator after brazing of the spokes and ready for welding of the flanges.

One major innovation of the HINS program is the goal to start beam acceleration using superconducting technology at the low energy of 10 MeV. Superconducting single spoke resonators (SSR1) designed for β=0.2 and operated at 4 K provides acceleration from 10 MeV to 40 MeV. A different family of SSR (SSR2, designed for β=0.4) will provide acceleration to 120 MeV. Figure 9 shows the first SSR1 prototype. The prototype has been tested in the Fermilab Vertical Test System and the typical Q vs. accelerating field curve is shown in Fig. 10.

Figure 9: First 325 MHz SSR1 prototype

Focusing in the RT and SC regions will be provided by superconducting solenoids operating at approximately 300 A [13]. The use of solenoids is intended to maintain an axis-symmetric beam and minimize the halo formation in the Front-End part of the Linac.

The present default scenario is to continue beam acceleration from 120 to 400 MeV by mean of superconducting Triple Spoke Resonators (TSR) designed at β=0.6. In this region, focusing will be provided by quadrupole elements.

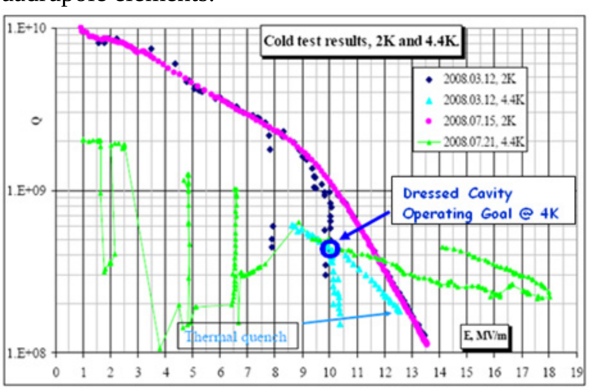

Figure 10: Q vs. Accelerating field plot for the first SSR1 prototype built for the HINS program. The operating goal is also indicated.

1300 MHz Linac

The 1300 MHz Linac is an ILC-like linac that can support a higher beam current (20 mA instead of 9 mA), a longer pulse (1.25 msec instead of a 1 msec) 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 – 8 GeV) and non ILC-like (0.4-1.2 GeV). The non ILC portion is also called Squeezed ILC (S-ILC) for its "squeezed" ILC cavity shapes, optimized for β = 0.81. While the ILC-like cavities and cryomodules are being developed by the ILC effort [14], the S-ILC R&D is Project X specific.

The requirements for cavity gradient for Project X are less stringent than the ILC. While the ILC target gradient is 31 MV/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 technology.

An alternative to the triple spoke SC cavities described previously in the 0.12 – 0.4 GeV region are the β = 0.47 and 0.61 elliptical options**.** At our present level of understanding the beam dynamics of either choice appear workable. One technical area of investigation is the mechanical behavior of spoke and elliptical cavities under high-power RF operation, with emphasis on the performance under Lorents detuning forces. The final choice will be based on these technical as well as economic considerations.

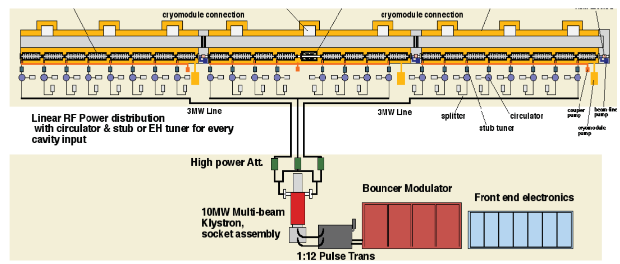

Figure 11: RF unit schematic.

The linac is composed of RF units, each of which is formed by contiguous cryomodules containing nine-cell elliptical cavities. The number of cryomodules in one unit will be determined according to the beam power needed at 8 GeV. The layout of one RF unit for the 360 kW 8 GeV Linac is identical to the ILC and is shown in Fig. 11.

For the ILC-identical portion of the linac, each RF unit has a stand-alone RF source, which includes a conventional pulse-transformer type high-voltage (120 kV) modulator, a 10 MW multi-beam klystron, and a waveguide system that distributes the RF power to the cavities. Simple modifications to this scheme will be needed for the 1 MW linac design.

The cryomodule design is a modification of the Type-3 1.3 GHz version developed and used at DESY. Within the cryomodules, a 300 mm diameter helium gas return pipe serves as a strongback to support the cavities and other beam line components. The middle cryomodule in each RF unit contains a quad package that includes a superconducting quadrupole magnet, a cavity BPM, and superconducting horizontal and vertical corrector magnets. The quadrupoles establish the main linac magnetic lattice. At low energies (1-2 GeV) additional quadrupoles will be needed for full beam control.

The cavities operate at 2 K, they are immersed in a saturated He II bath, and helium gas-cooled shields intercept thermal radiation and thermal conduction at several intermediate temperatures.

The basic issue in the development of the technology for Project X is the production rate of cryomodules. The high energy end of the Project X linac requires about 40 ILC-like cryo-modules. The present ILC cryo-module production rate in the US is about one cryo-module per year. To support a timely construction of Project X, the cryomodule production rate should be about one cryomodule per month. This goal is in line with the goal of developing ILC superconducting RF infrastructure at Fermilab. Figure 12 shows the first 1.3 GHz cryomodule build in the US being installed in the New Muon Lab testing facility at Fermilab.

Figure 12: Installation of a US-assembled 8 cavity TESLA cryomodule in the New Muon Laboratory facility at Fermilab.

Linac RF Power Distribution

In order to control individual amplitude and phase of the RF power distributed to each cavity, the linac design uses fast, high power Ferrite Vector Modulators (FVMs) up to approximately 1.5 GeV as a less expensive alternative to the one-klystron-per-cavity approach adopted by SNS.

The FVMs are high-powered versions of devices which are commonly used in microwave work [15]. The basic concept of the FVM is to split incoming RF power into two equal branches, independently phase shift each branch under electronic control, then recombine each branch in a 4-port hybrid junction. Depending on the relative phase shift of the two branches, the hybrid junction will cause a fraction of the recombined power to be sent forward to the cavity, with the remainder of the power being rejected to RF loads. Figure 13 shows the principle of operation.

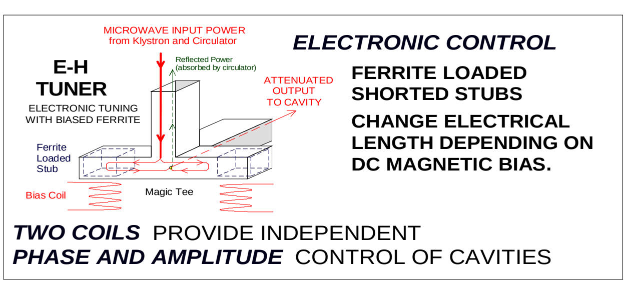

Figure 13: Conceptual principle of operation for a FVM controlling phase and amplitude of RF power

Figure 14a and Fig. 14b show the results on the measured phase shift and amplitude in a prototype 325 MHz FVM. The usable range of the ferrite stub tuner, corresponding to the region where RF losses are below 0.2 dB, is about 120 degrees.

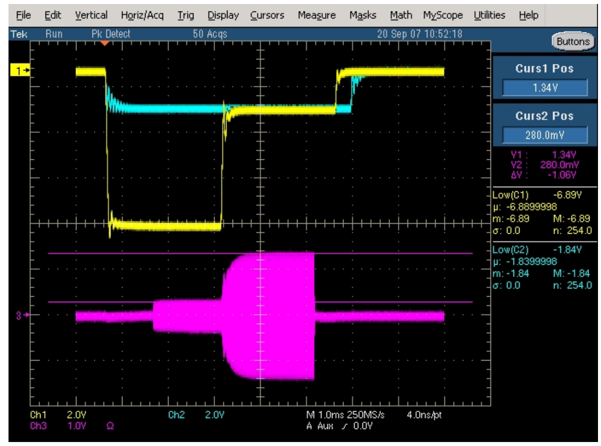

Figure 14a: 13 dB Amplitude Control with Vector Modulator for a 6 kW, 3.5 msec RF Pulse. The purple trace is cavity RF amplitude; the blue and yellow are the vector modulator coils bias currents

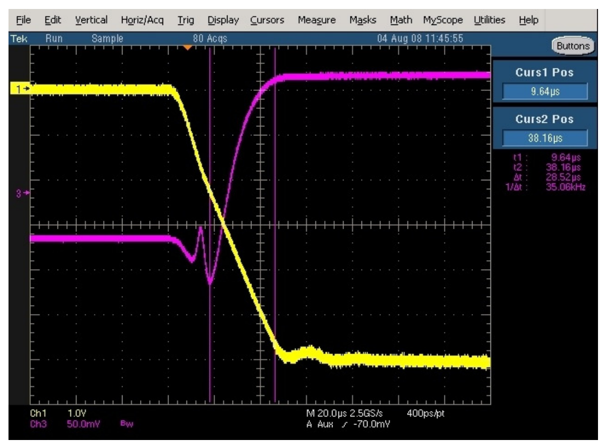

Figure 14b: 120 Degree Phase Control with Vector Modulator for a 300A current change in Vector Modulator coils bias current. The purple trace is the cavity RF phase signal (changing by 120^0 between the 2 vertical purple lines), the yellow trace is the bias currents.

8 GeV Transfer Line

The beam power handling requirements of the transport and injection system is designed to handle the expected full linac. To minimize unnecessary radiation exposure to personnel, a level of 100 mrem/hr at 30 cm is considered the maximum localized activation level. This translates into an average beam power loss of 50 mW/m or an average uncontrolled loss rate of 10^{-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 for the low-intensity design of the Linac. 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. 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.

Recycler Ring

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 NOνA program, the Recycler will be converted from an antiproton storage ring to a proton accumulator for single turn injection into the Main Injector.

The Recycler will operate as a stripping ring and a proton accumulator, taking 1 or 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 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.

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 will be needed to allow this flexibility.

Main Injector

The Main Injector will receive 1.6-1.7x10^{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 times the beam intensity Main Injector will be required to accelerate for the NOvA program.

Electron cloud instabilities could be a limitation to the maximum MI intensity as in the Recycler. Currently in MI with 10^{11} particles per 53 MHz bunch electron cloud is not a problem because the bunch intensity is below the threshold.

Upgrades to the RF distribution system will be needed to accelerate the required beam intensity to 120 GeV in 1.4 sec. There is also the 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.

CONCLUSIONS

Exploration of the Intensity Frontier is actively happening in several facilities around the world. We described an upgrade of the Fermilab accelerator infrastructure based on an 8 GeV Linac and a 2 MW proton source in the 60-120 GeV range that would allow a full range of experiments and measurements at the Intensity Frontier. The R&D program to support this facility is being actively pursued.

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