April 12, 2012

To: LBNE Reconfiguration Steering Committee; Young-Kee Kim, chair

We are writing on behalf of the Project X management team to encourage the LBNE Reconfiguration Steering Committee to take a broad view of the opportunities available for staging a program of continuous improvement in accelerator and detector capabilities that ultimately reaches the goals established within the laboratory's Intensity Frontier Strategy. We will outline in this note the opportunities afforded by a staged approach to Project X and how these might be integrated with staged pieces of other element of our Intensity Frontier Program. Project X staging opportunities were developed last winter in direct response to a request from the Office of High Energy Physics and have been subsequently communicated to that Office.

In developing staging opportunities for Project X specifically, or for the entire Intensity Frontier program more generally, the following principles are applied:

- Each stage should have a cost significantly below $1B
- Each stage should present compelling physics opportunities
- At the completion of the final stage the full vision of a world leading intensity frontier program at Fermilab should be realized

There are very natural opportunities for staging Project X in a manner consistent with these principles, and in a manner that integrates with the other activities contained within the Fermilab Intensity Frontier plan. We outline below a particular multi-stage scenario that has been presented to the Office of High Energy Physics.

Staging Opportunities with Project X

Project X is unique among the world's operating or planned accelerator facilities in its ability to simultaneously deliver high power beams at a variety of energies to multiple experiments, with multiple duty factor requirements. Project X does this by marrying superconducting RF technology to a novel linac configuration, while effectively utilizing accelerator assets already in place at Fermilab. These unique capabilities build upon the investment currently being made in the Fermilab proton facility via the Proton Improvement Plan, and are retained in all stages. A high level summary of the opportunities is described in the attached table.

<u>Stage 1</u>

The scope of Stage 1 encompasses construction of a 1 GeV, CW, H- superconducting linac operating with an average current of 1 mA, and upgrades to the existing 8 GeV Booster to accept beam at a 1 GeV injection energy. This is projected to result in a 50% increase in the per pulse proton intensity delivered from the Booster to the Main Injector complex, relative to current operations. Stage 1 establishes the potential for delivering up to 1200 kW onto a long baseline neutrino target (either NuMI or LBNE). Depending upon the operating energy of the Main Injector, and the fraction of the Main Injector timeline that is diverted from neutrino production, significant power could also be devoted to a rare kaon decay and 8 GeV programs.

Additionally, a new capability is created by the very high power available at 1 GeV. Only about 20 kW (at 1 GeV) is required to support full 15 Hz operations of the Booster. This leaves 980 kW for additional programs. Among those that could be supported are 80 kW to a muon-based program plus an additional 900 kW that could be distributed to any mixture of prospective nuclear edm, ultra-cold neutron, and/or nuclear energy programs.

An additional substantial benefit of Stage 1 is that the existing 400 MeV linac is retired from service, taking a substantial operational risk off the books.

Stages 2-3

Stages 2 and 3 achieve the Project X Reference Design. The scope encompasses extension of the CW linac to 3 GeV and construction of a 3-8 GeV pulsed linac for delivery of beam to the Recycler/Main Injector complex. Upgrades to the Recycler/Main Injector are required to support the increased beam power.

The establishment of a 3 GeV capability will support very high intensity kaon and/or muon experiments, and would also allow full dedication of Main Injector beam power to the neutrino program – it is envisioned that the kaon experiment mounted with the Main Injector in Stage 1 would be associated with the 3 GeV linac following Stage 2, with an increase in power of up to a factor of ten. At the end of Stage 3 the Main Injector has the capability of delivering in excess of 2 MW of beam power onto a neutrino production target at any energy between 60-120 GeV. In addition, with the completion of Stage 3 the existing 8 GeV Booster can be retired from service, taking the second substantial operating risk in the current program along with it.

Stage 4

Stage 4 is a step beyond the Reference Design and is not as well established conceptually as the first three stages. This stage would represent a power upgrade of the Project X complex based on raising the average current in the pulsed linac. The concept is to operate the pulsed linac with a 5 mA peak current and a duty factor of 10%. We know that this is technically achievable and that upgradability can be incorporated into earlier stages at very little cost, but a full concept has yet to be developed. The resultant beam power, 4 MW at 8 GeV, could be used to support any number of neutrino applications (short baseline, long baseline/low energy), or to provide a platform for a muon-based Neutrino Factory or Muon Collider. Additionally, up to 4 MW is potentially available from the Main Injector if accompanied by further upgrades to the Recycler/Main Injector and to the neutrino target facilities.

The Stage-1 Research Roadmap

Long-baseline neutrino program

Stage 1 increases the proton throughput of the Booster and Main Injector by ~50% relative to the NOvA era. This means the beam power available to neutrino production targets could be as high as 1100-1200 kW (at 120 GeV). It is plausible that the existing NuMI target could be upgraded to handle this beam power, opening the possibility of sending neutrinos generated by this beam either to northern Minnesota or to South Dakota, if the LBNE beamline were constructed. As a first step toward the exploration of CP violation in the neutrino sector one could imagine the construction of a LAr detector of many kilotons driven by this beam. Establishing Stage 1 of Project X in all LBNE scenarios will advance US long-baseline neutrino science and the joint sensitivity of laboratories world-wide to neutrino parameters.

Mu2e

The Mu2e experiment is based on delivered beam power to the production target of 8 kW. At this level the experiment represents a major extension in sensitivity to muon-electron conversion. In discussion with the Mu2e team it appears plausible that the detector as designed could accommodate up to 80 kW of beam power – a factor of ten increase in sensitivity that could be realized with the Stage 1 linac. Several secondary benefits also increase the sensitivity when operated in this manner: 1) the 1 GeV linac can provide a lower duty factory beam than the current scheme, which reduces prompt pion backgrounds; and 2) the 1 GeV linac is incapable of producing antiprotons, which are a serious background concern for the experiment. In developing the Project X Stage 1 concept we are looking at siting locations that would allow us to deliver 80 kW at1 GeV to the muon campus that will be established as part of the Mu2e and g-2 efforts.

ORKA

"ORKA: the Golden Kaon Experiment" is an intensity frontier/rare kaon decay experiment that was recently granted scientific approval by the Fermilab PAC. The higher Main Injector intensity enabled by Stage 1 of Project X allows the diversion of additional beam power to ORKA, while minimizing the penalty to the ongoing long baseline program. For example, if one were to devote 45% of the Main Injector timeline to ORKA one could provide 75 kW of beam power to ORKA while maintaining in excess of 500 kW onto the long baseline neutrino target. Ultimately the disposition of the Main Injector timeline between ORKA and the long baseline program would be a program planning decision.

Next Generation Short Baseline neutrino experiments

There are several intriguing hints of new physics scenarios, such as sterile neutrinos, that can be further explored with new short-baseline neutrino experiments at Fermilab. These experiments could be mounted with core LBNE technologies such as liquid argon time projection chamber technology or other fine-grained tracking technologies. Stage 1 of Project X would triple the beam power to these experiments as compared to the MiniBooNE era, significantly amplifying the reach of next generation fine-grained neutrino tracking technologies which will be a key element of the LBNE campaign.

New and Unique Research Opportunities Enabled in Stage 1

The beam power of Stage 1 provides a facility that is unique in the world in a number of areas outside the current scope of US high energy physics, but which are of great interest to particle physicists as evidenced by the recent enthusiasm at the Intensity Frontier Workshop. These include world-leading sensitivity to electric dipole moments of neutrons and exotic atoms, and neutron-antineutron oscillation sensitivity far beyond the reach of next generation nucleon decay detectors. In addition the 1 GeV beam power could be very important to exploration of material properties of relevance to the nuclear energy enterprise based on a high-flux, high duty factor, source of fast neutrons. We are currently exploring these opportunities with the particle physics community broadly and colleagues in the nuclear energy community.

In summary we are convinced that it is possible to develop a compelling integrated strategy consistent with the principles outlined at the beginning of this note. This is not simply an issue of two initiatives vying for the same set of constrained resources. The physics reach of the LBNE and the Project X campaigns are inextricably linked since the potential of long-baseline neutrino experiments is ultimately limited by beam power. Hence consideration of LBNE in the context of a campaign *must* incorporate consideration of the Project X campaign.

We are available for any further discussions or clarifications the steering committee or working group might require, and look forward to further exploring these opportunities with the particle physics community. Thank you for your consideration.

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Power Profile for the Fermilab Proton Research Program

← *Project X Campaign* →

Program:	Stage-0: Proton Improvement Plan	Stage-1: 1 GeV CW Linac driving Booster & Muon Campus	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR (MI>60GeV)	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2300 kW	2300-4000 kW
8 GeV Neutrinos	15 kW + 0-50 kW**	0-40 kW* + 0-90 kW**	0-40 kW*	85 kW	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	85 kW	1000 kW
1-3 GeV Muon program	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1100 kW	1100 kW
Nuclear edm ISOL program	none	300 kW	300 kW	300 kW	300 kW
Ultra-cold neutron program	none	300 kW	300 kW	300 kW	300 kW
Nuclear technology applications	none	300 kW	300 kW	300 kW	300 kW
# Programs:	4	8	8	8	8
Total* power (mean):	585-735 kW	1660-2240 kW	4230 kW	5490 kW	11300kW

* Operating point in range depends on MI energy for neutrinos.
** Operating point in range is depends on MI injector slow-spill duty factor (df) for kaon program.