Physics at an Upgraded Proton Driver

Hogan Nguyen[a]

[a]Fermi National Accelerator Lab, P.O. Box 500, Batavia, IL 60510, USA

A new 2 MW proton machine, known as the "proton driver", is being considered for Fermilab. It would play a key role in advancing accelerator-based neutrino physics. A workshop was organized in October 2004 at Fermilab to explore this physics case, as well as other physics that could be performed with this machine.

1. Introduction

In the spring of 2003, the Fermilab Long Range Planning Committee concluded an intensive study of the long range future of the lab. The committee recommended that Fermilab aggressively pursues two options for the future: a linear electron-positron collider, and a high-intensity "proton driver".

The proton driver would be a new accelerator complex to replace the existing Fermilab Booster and Linac. It would be the new front-end machine for the Main Injector (MI). The committee's basic recommendation[1] is to elaborate the physics case and to develop technical designs for this complex.

In response, the Fermilab director has requested the staff to prepare document sufficient to establish "mission need" for the proton driver, as defined by the Department of Energy CD0 process. The staff should also develop and document the physics case. The physics documentation is to include support for a forefront neutrino program at Fermilab in the decade 2010, and identification of other opportunities that could be made available with a proton driver facility.

2. Proton Driver Options

The overall goal is to achieve 2 MW of 120 GeV protons out of the MI. To reach this beam power, it is now recognized that the existing Fermilab Linac and Booster are relatively old, and cannot be simply upgraded. The physical size of the beam pipe is too small to accomadate the amount of charge-per-booster-cycle that is required. Other problems include the lack of a beam pipe, which translates to large impedance and beam instabilities[2].

A new front-end complex to the MI is truly needed. In addition, technological advances made since the construction of the original Linac and Booster will greatly improve the machine reliability. To achieve the 2 MW beam power out of the MI, the MI dipole power supplies also need to be upgraded to decrease the magnet ramping cycle time. This would increase the MI cycling rate.

There are two proton driver designs being considered[3]. One is a combination of a new warm linac and a new proton-synchroton. The other is a single 700 meter long super-conducting (SC) linac that feeds directly into the Main Injector. Table 1 shows the design parameters of these two options.

The warm linac and proton-synchroton option has the advantage of being a well-established technology. Its construction and operating cost are believed to be well understood.

The SC linac design has become an extremely attractive option for the following reasons. It is one machine, rather than two machines (as in the warm option), and therefore is potentially simpler to operate. The machine is potentially superior to the warm machine in many characteristics such as power, repetition rate, and beam emittance. The overall cost of SC technology has dropped and is now perceived to be competitive with that of warm technology. With the recent recommendation of SC technology for the International Linear Collider, SC technology has gained wide acceptance, and there will now be a concerted world-

Table 1
Comparisons of parameters for the present accelerator complex and for the two proton driver options.

	Present	Synchroton Option	SC Linac Option
Linac			
Kinetic Energy (MeV)	400	600	8000
Peak Current (μA)	4.0	5.0	2.5
Pulse length (μs)	90	90	1000
Protons/pulse	$2.3 \cdot 10^{13}$	$2.8 \cdot 10^{13}$	$1.6 \cdot 10^{14}$
Repetition Rate (Hz)	15	15	10
Average Beam Power (MW)	0.02	0.04	2.0
Booster			
Kinetic Energy (GeV)	8	8	-
Protons/pulse	$5.0 \cdot 10^{12}$	$2.5 \cdot 10^{13}$	-
Repetition Rate (Hz)	7.5	15	-
Protons/hour	$1.4 \cdot 10^{17}$	$1.4 \cdot 10^{18}$	-
Average Beam Power (MW)	0.05	0.5	-
Main Injector			
Kinetic Energy (GeV)	120	120	120
Protons/pulse	$3.5 \cdot 10^{13}$	$1.5 \cdot 10^{14}$	$1.6 \cdot 10^{14}$
Repetition Rate (Hz)	0.54	0.65	0.67
Protons/hour	$5.8 \cdot 10^{16}$	$3.5 \cdot 10^{17}$	$3.8 \cdot 10^{17}$
Average Beam Power (MW)	0.3	1.9	2.0

wide effort in this front. In addition, the SC Linac design will minimize the research and development by borrowing heavily from work done for TESTLA and the Spallation Neutron Source.

Finally, the SC linac design makes better use of the existing Fermilab site. The SC linac layout can be made compatible with the layout for other possible HEP facilities at Fermilab such as a muon collider or a Very Large Hadron Collider, see Fig. 1).

3. Developing the Physics Case

Long baseline neutrino oscillation physics will likely make the most compelling physics case for a 2 MW proton driver. Spectacular discoveries[4] in the neutrino sector have established that neutrinos change flavor and have mass. These discoveries open up profound questions than can be addressed experimentally. Is the picture of 3-generation neutrino mixing correct ? What are the neutrino masses and how are they arranged (i.e. the mass hierarchy) ? Are neutrinos their own anti-particles, and so is lepton number also violated ? Is there CP violation in the neutrino sector ?

In a “superbeam” neutrino complex, the neutrino beam is produced by decays of pions and kaons, which themselves are products of a hadronic interactions of protons on a material target. One can hope to experimentally address three important parameters in the 3-neutrino generation mixing picture: (1) θ_{13}, the least known mixing angle parameter in the 3-generation neutrino mixing matrix, (2) δ, the pa-

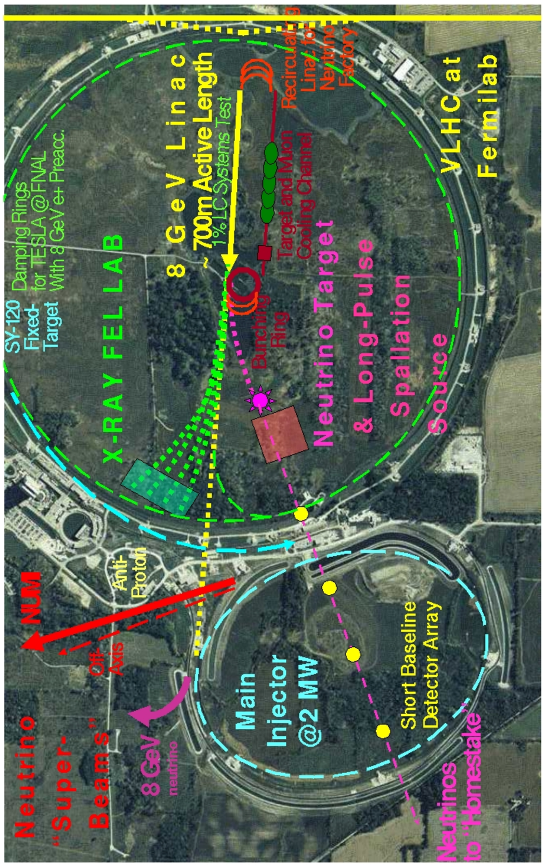

Figure 1. Some possibilities for the SC Linac in relation to other future facilities.

rameter controlling CP violation, and (3) the neutrino mass heirarchy.

Table 2 shows a study of the parameter reach of current and proposed neutrino facilities. As is shown in this table, the higher the beam power, the further one can probe into the neutrino-mixing picture. In addition to beam power, the effectiveness of the neutrino facility depends also on the detector mass, baseline, and neutrino energy. The latter two parameters are important for probing into possible CP violation and the neutrino mass heirarchy. In this realm, the proton driver is perceived to be advantageous over that of JPARC, which is designed for lower energy and a shorter baseline.

The superbeam complex would be a precursor for a "ν-factory" and a "β-beam", which would be the ultimate neutrino study tools. In a ν-factory, muons from pion and kaon decays would be collected into a storage/decay ring. Muon decay is a well-understood phenomenon, and so one has precise knowledge of the neutrino beam flavor and energy content. A ν-factory would be needed if $\sin^2 2\theta_{13}$ were less than 0.001. A ν-factory would require an intense proton beam (> 2 MW). In a β-beam, protons would be used to make short-lived β-unstable isotopes, which are then put into a storage/decay ring. These isototopes are then an ultra-clean source of electron neutrinos.

The most compelling physics case for the proton driver will likely be the profound questions raised by the observation of neutrino oscillations. However, it will be important to broaden the opportunities in other areas.

It has been pointed out that if the picture of the seesaw mechanism, lepto-genesis, and supersymmetry are correct, then there is perhaps observable consequences in the charged lepton and quark sectors[8]. For example, some supersymmetrized versions of the see-saw mechanism allow for observable lepton-flavor-violating effects in muon decays[9], and even in rare kaon decays[10].

The charge to develop the physics case is being taken up by Steve Geer of the Fermilab Particle Physics Division. In addition to long-baseline neutrino oscillations, working groups have been established to explore the physics case for neutrino interaction physics, muon physics, antiproton physics, kaons and pions, and physics at the Tevatron.

Fermilab has recently hosted a workshop[11] on October 6-9th, 2004 on the physics case for the proton driver. The summary and recommendations will come at the end of this year.

4. Conclusions

The observation of neutrino oscillation has established that neutrinos have mass and that they

Table 2
Comparisons of physics reach of current and planned future long-baseline neutrino initiatives.

Beam Name	Mass (kton)	Power (MW)	$^a \sin^2 2\theta_{13}$ sensitivity	$^b\delta$ (CP Violation)	Mass Heirarchy
Opera[5]	1.8	0.15	0.04	-	-
ICARUS[5]	2.4	0.15	0.03	-	-
MINOS[6]	5	0.25-0.4	0.05	-	-
CNGS[7]	2.35	0.15	0.02[7]	-	-
T2K	22.5	0.8	0.006	-	-
NOνA	50	0.4	0.004	-	Yes
T2HK	450	4	^{c} 0.001	$\|\delta\| > 20$	-
Super-NOνA	100	2	^{c} 0.001	135 ± 20	Yes
BNL2NUSL	500	1	0.004	45 ± 20	Yes
CERN SPL	400	4	0.0016	90 ± 30	-
β Beam	400	0.04	-	T viol.	-
ν Factory	50	4	$< 10^{-4}$	90 ± 20	Yes

^{a} evaluated at $\Delta^2 m_{32} = 0.003$ eV^2 at 90% CL.
^{b} all evaluated at different parameter space.
^{c} Assume a 5% systematic uncertainty.

mix. This begs further research into profound questions that can be addressed experimentally. The existing MI proton beam power is limited to approximately 0.5 MW, due to various limitations in the existing Fermilab Booster and Linac. A new facility providing 2 MW protons would allow for a deeper probe into the neutrino mixing. The facility would be a precursor to the ultimate neutrino study tools such as a ν-factory or a β-beam facility.

Working groups have been organized to fully document the physics case, and also to explore the physics opportunities in other sectors such as in muons, kaons, antiprotons, and pions. Fermilab has recently concluded a workshop on October 6-9th, 2004 on the physics case for the proton driver. The summary and recommendations will come at the end of this year.

REFERENCES

1. See the web address http://www.fnal.gov/ - directorate/Longrange/ - Long_range_planning.html.
2. See details in http://www-bd.fnal.gov/ - pdriver/booster/reports/22july03.pdf.
3. Proton Driver Study II (Part 1 and 2), Foster, Chou, and Malamud (eds.), Fermilab-TM-2169.
4. For a concise experimental review, see Review of Particle Physics, Alvarez-Gaume et. al (eds.), Phys. Lett. **B** 592 (2004) 451-467.
5. M. Komatsu, P. Migliozzi and F. Terranova, J. Phys. **G29** (2003) 443.
6. Diwan, Messier, Viren, and Wai, NuMI-L-0714.
7. Rubbia and Sala, JHEP **0209** (2002) 004.
8. Ellis and Raidal, Nucl. Phys. **B643** (2002) 229-246.
9. Hisano and Nomura, Phys. Rev. **D59** (1999) 116005.
10. Grossman, Isidori, and Murayama, Phys. Lett. **B588** (2004) 74-80.
11. See the web address http://www-td.fnal.gov/ - projects/PD/PhysicsIncludes/ - Workshop/index.html.