Synchrotron Version of a Proton Driver

W. Chou, June 6, 2003

Outline

0. Making a case for Proton Driver
1. Brief overview of the synchrotron design
2. Cost estimate
3. Respond to different specifications
4. Staging scenario
5. Top 3 technical uncertainties
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7. Comparison of the two options: circular vs. linear

0. Making a Case for Proton Driver

- For long range planning, Fermilab needs a project.
  - CERN: LHC
  - Japan: J-PARC ($1.3B), and wants a LC
  - Germany: DESY FEL (700M euros), GSI future facility (700M euros)
  - SLAC: LCLS ($220M).
  - Fermilab?

- We can't count on the LC – just too many uncertainties.

- Independent of LC, one needs a medium size project.
  - This is a lesson from the SSC. After its demise, the two medium size projects Main Injector and B-factory became the backbone of the U.S. HEP community

- A strong Fermilab program can be built on neutrino physics. The centerpiece is a proton driver.
  - We have two neutrino beam lines: NuMI and MiniBooNE
  - With a proton driver, we'll get two powerful machines, PD and MI
  - 3-1/2 of the 13 facility proposals to the DOE are related to a proton driver: *neutrino superbeam*, *off-axis neutrino experiment*, *neutrino factory*, and possibly also the *underground lab*
  - If we don't ask for it, somebody else will, and they might get it, e.g., BNL

1. Brief Overview of the Synchrotron Design

Charge from the Director

Fermilab

January 10, 2002

To: Bill Foster and Weiren Chou

From: Mike Witherell

SUBJECT: DESIGN STUDY OF PROTON DRIVER OPTIONS FOR THE MAIN INJECTOR

The HEPAP Subpanel report is expected to identify a modest energy, high average power, proton facility as a possible candidate for a construction project in the U.S. starting in the middle of the current decade. Fermilab represents an attractive location for such a facility and we need to identify options that could be presented to the DOE and U.S. community over the next few years if the physics is determined to warrant construction. One such option has been identified, the 8-16 GeV Proton Driver described in Fermilab-TM-2136, and another concept has recently come to light, an 8 GeV superconducting linac.

I would like the two of you to prepare a common document that would outline the two possible approaches to a Proton Driver at Fermilab and required modifications to the Main Injector to accommodate the increased intensity. In both cases I would like you to work with the following parameters:

Peak (Kinetic) Energy	8 GeV
Protons per Main Injector acceleration cycle	1.5×10^{14} (=1.9 MW @ 0.67 Hz)
Protons per second at 8 GeV	3.0×10^{14} (=380 KW)

For each option the report should include a description of the design concept and the technical components, identification of possible siting within Fermilab, and a preliminary cost estimate. In addition I would like you to provide a description and cost estimate for upgrades to the Main Injector, including its existing beamlines, and to the MiniBoone beamline required to support the performance defined above.

To the extent that you have the time and ability to do so I would like you to identify options for subsequent upgrades that could provide enhanced capabilities further into the future, including:

- Higher beam power at 8 GeV

- Higher beam power at energies up to 120 GeV, specifically through the implementation of reduced cycle time in the Main Injector
- An accumulator or compressor ring that could be used to achieve the performance required of the driver for a Neutrino Factory
- Utilization of the linac-based facility as an 8 GeV electron source

In general I would like to see each of these two options brought to a comparable state of development in this report. Because of the significant prior effort expended in the synchrotron-based proton driver, I expect that the development of the linac-based proton driver concept will require the bulk of the effort. Steve Holmes will provide Directorate guidance and support on this, including defining primary reference design parameters.

I would like to receive an interim report on progress prior to the ICFA Workshop at Fermilab on April 8-12 and a final report by May 15, 2002. Preparation of this report will require support of personnel in both the Beams and Technical Division. You should identify required resources and then work with the Divisions/Sections to secure support, consistent with their commitments to Run II. Both the Division/Section heads and Steve Holmes can help you in this task.

The identification of promising ventures utilizing hadrons and building upon Fermilab infrastructure and expertise is an important part of planning for the future of U.S. HEP. A Proton Driver could represent a strong candidate for a construction project in the intermediate term future with strong potential links to the longer-term future. Both Steve and I look forward to working closely with you and the participating divisions in defining the possibilities.

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FERMILAB-TM-2169

Proton Driver Study II (Part 1)

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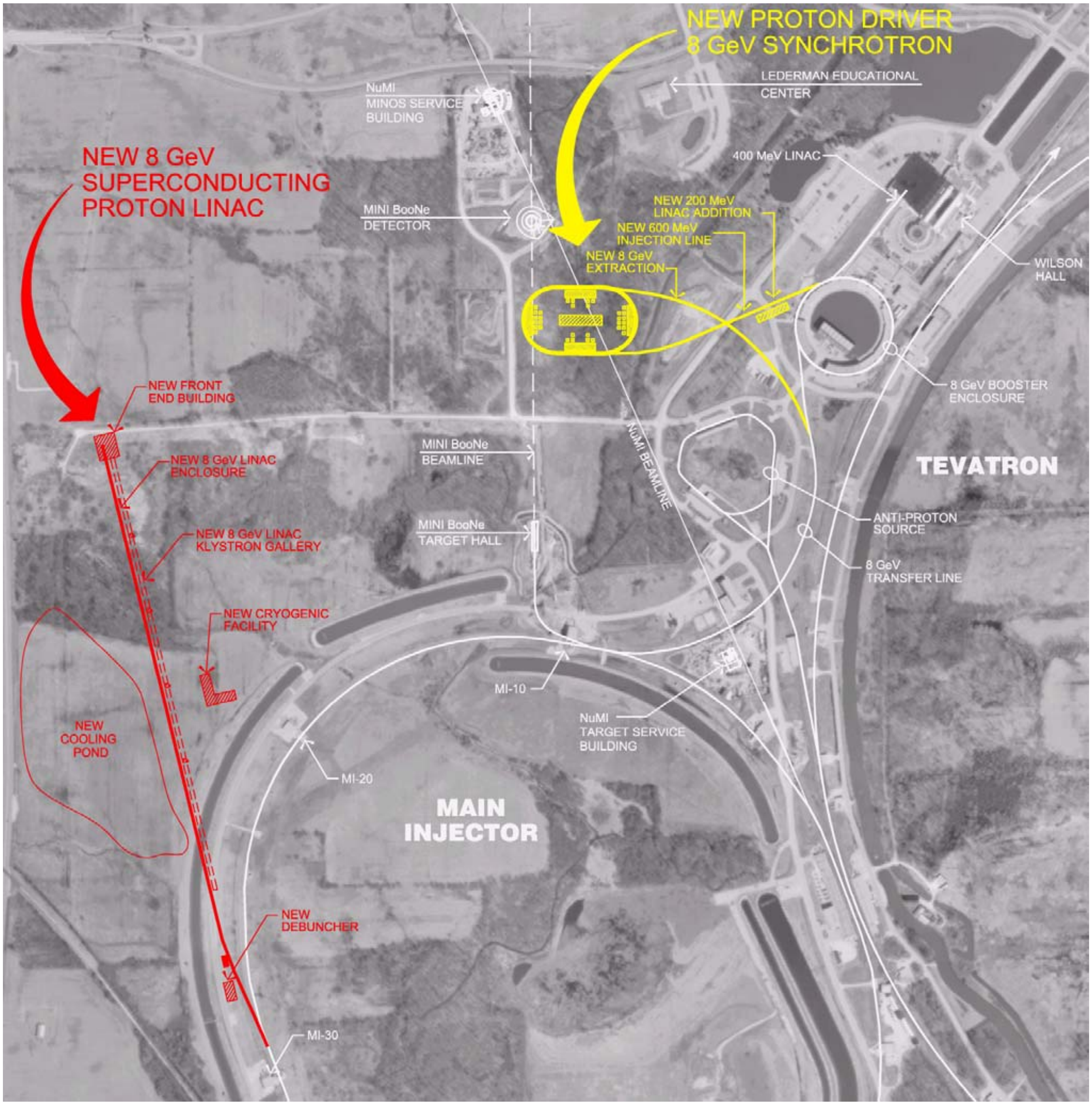
May 2002

Layout of the Two Options



An 8-GeV Synchrotron-based Proton Driver

- Proton Driver Study II (PD2) includes an 8 GeV, 0.5 MW synchrotron, upgradeable to 2 MW. It is smaller than PD1 but also cheaper.

- Design features of the PD2 synchrotron:
  - Same size as the present Booster (474.2 m).
  - Racetrack shape in a new enclosure.
  - Transition-free lattice with zero-dispersion long straights.
  - Reuse of the existing 400 MeV linac, addition of another 200 MeV rf → Total linac energy 600 MeV.

Parameter Comparison: The Present Proton Source vs. the Proton Driver

Parameters	Present Proton Source	Proton Driver
Linac (operating at 15 Hz)		
Kinetic energy (MeV)	400	600
Peak current (mA)	40	50
Pulse length (μs)	25	90
H^- per pulse	6.3×10^{12}	2.8×10^{13}
Average beam current (μA)	15	67
Beam power (kW)	6	40
Booster (operating at 15 Hz)		
Extraction kinetic energy (GeV)	8	8
Protons per bunch	6×10^{10}	3×10^{11}
Number of bunches	84	84
Protons per cycle	5×10^{12}	2.5×10^{13}
Protons per second	7.5×10^{13}	3.75×10^{14}
Normalized transverse emittance (mm-mrad)	15π	40π
Longitudinal emittance (eV-s)	0.1	0.2
RF frequency (MHz)	53	53
Average beam current (μA)	12	60
Beam power (MW)	0.05(*)	0.5

(*) Although originally designed for 15 Hz operations, the present Booster has never delivered beam at 15 Hz continuously. In the past it used to run at 2.5 Hz. In the MiniBooNE era, it will run at 7.5 Hz and deliver 50 kW beams.

2. Cost Estimate

1	**Technical Systems**			98,986
1.1	8 GeV Synchrotron		78,997	
1.1.1	*Magnets*	27,329		
1.1.2	*Power supplies*	25,968		
1.1.3	*RF*	5,115		
1.1.4	*Vacuum*	6,061		
1.1.5	*Collimators*	325		
1.1.6	*Injection system*	938		
1.1.7	*Extraction system*	2,189		
1.1.8	*Instrumentation*	2,393		
1.1.9	*Controls*	2,468		
1.1.10	*Utilities*	4,931		
1.1.11	*Installation*	1,280		
1.2	Linac Improvements and Upgrade		17,500	
1.2.1	*Front end and RFQ*	3,000		
1.2.2	*New drift tube Tank #1*	1,000		
1.2.3	*Transfer line to new CCL*	1,800		
1.2.4	*New CCL modules and klystrons*	11,100		
1.2.5	*Controls and diagnostics*	600		
1.3	600 MeV Transport Line		900	
1.3.1	*Magnets*	720		
1.3.2	*Power supplies*	180		
1.4	8 GeV Transport Line		1,589	
1.4.1	*Magnets*	1,271		
1.4.2	*Power supplies*	318		
2	**Civil Construction**			37,152
2.1	8 GeV Synchrotron		17,500	
2.1.1	*Enclosure*	7,000		
2.1.2	*Service buildings*	7,000		
2.1.3	*Utility support building*	3,500		
2.2	Linac extension		2,500	
2.3	600 MeV Transport Line		1,800	
2.4	8 GeV Transport Line		2,200	
2.5	Site work		4,800	
2.6	Subcontractors OH&P		5,760	
2.8	Environmental controls and permits		2,592	
	Total Direct Cost			136,138
	EDIA (15%)			20,421
	Lab Project Overhead (13%)			20,353
	Contingency (30%)			53,073
	Total Estimated Cost (TEC) ($k) (in FY02 dollars)			**229,984**

3. Respond to Different Specifications

- Higher energy:
  - There is a complete design for a 16 GeV synchrotron, including a cost estimate
  - Such a machine can first operate at 12 GeV with lower upfront cost (using less powerful but upgradeable power supplies and RF)

- Lower rep rate:
  - For the same beam power and energy, lower rep rate requires higher beam intensity, which means larger emittance (> 40pi). This would cause a mismatch between the PD and the MI acceptance.
  - Or, for the same beam intensity, lower rep rate gives lower beam power, but makes the eddy current problem easier.

- Higher rep rate:
  - For the same beam power and energy, higher rep rate requires lower beam intensity.
  - But to give the same bunch intensity in the MI, one would need a different RF in the PD and a different injection scheme to the MI.
  - Or, for the same beam intensity, higher rep rate gives higher beam power.
  - However, the eddy current loss in the magnets (laminations and coils) and voltage-to-ground will be big issues.
  - Higher rep rate also means one will be unable to reuse the present linac.

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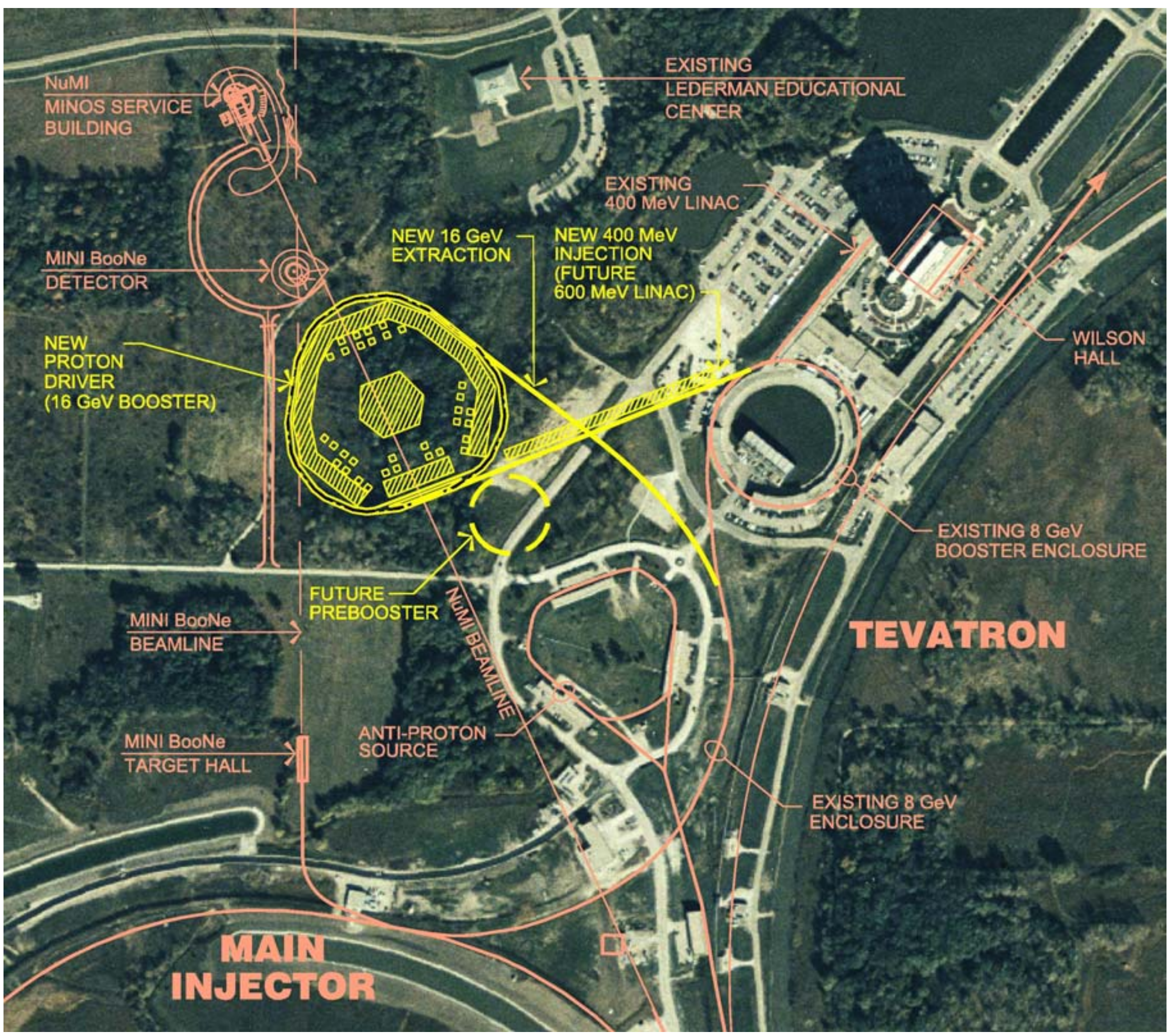
FERMILAB-TM-2136
December 2000

THE PROTON DRIVER DESIGN STUDY



4. Staging Scenario

1. Linac improvement
    a) A new linac front-end (a new RFQ and a new 10 MeV Tank 1)

    or

    b) A new 116 MeV DTL

    and/or

    c) A replacement of the last two CCL stations (No. 6 an 7, 313.6 – 401 MeV) by the SNS-type beta = 0.81 superconducting RF to raise the linac energy to about 500 MeV

2. Booster RF improvement
    a) Install two large aperture cavities (in progress)
    b) Modify all 18 cavities

3. Build a new 8-GeV synchrotron

5. Top Three Technical Uncertainties

1. Keep the uncontrolled beam loss below 1 W/m
   - The beam loss budget is 10% at injection and 1% at extraction
   - The collimators need to collect about 90% of the lost particles (the controlled beam loss)
   - The collimator section may require remote handling

2. Manufacture large aperture magnets with low ac losses
   - The design calls for either stranded conductors (PD1) or parallel connection of conductors (PD2). R&D is necessary.

3. Build and operate a dual-harmonic resonant power supply
   - This is a new design and requires R&D.

3.5. Reuse the 116 MeV DTL linac
   - The tube supply problem (We will inherit this problem if it remains unresolved and we want to reuse it)

6. Upgrade Path

Chapter 12. Future Upgrade

The baseline design of the PD2 synchrotron provides 0.5 MW proton beams at 8 GeV. Chapters 1 through 11 are a detailed description of the PD2 synchrotron design concepts and technical components. A possible siting within Fermilab is identified. The design and the choice of the site also provide the potential to upgrade the beam power to 2 MW in the future. This can be achieved by a further increase in the linac energy from 600 MeV to 1.9 GeV.

Beam power is the product of beam energy E, number of protons per cycle N, and repetition rate f_{rep}:

$$P_{beam} = E \times N \times f_{rep}$$

Because the peak dipole field in the PD2 design is 1.5 Tesla, it would be difficult to increase the beam energy above 8 GeV. The 15 Hz repetition rate would also be difficult to increase because of eddy current losses in the laminations and coils of the magnets. Therefore, in order to raise the beam power, a logical step is to increase the number of protons per cycle.

Space charge is a major concern in high intensity proton machines. The effect scales as $\beta\gamma^2$, the relativistic factor. When the linac energy is increased from 600 MeV to 1.9 GeV, this scaling factor increases by a factor of 4. Therefore, for the same space charge effect, the beam intensity can be increased by a factor of 4. The number of protons per bunch increases from 3×10^{11} to 1.2×10^{12} and the number of protons per cycle increases from 2.5×10^{13} to 1×10^{14}. Consequently, the beam power increases from 0.5 MW to 2 MW. Table 12.1 lists these parameters.

Table 12.1. Parameters of PD2 Upgrade

Parameters	PD2 Baseline	PD2 Upgrade
Linac energy (MeV)	600	1900
Synchrotron peak energy (GeV)	8	8
Protons per cycle	2.5×10^{13}	1×10^{14}
Protons per bunch	3×10^{11}	1.2×10^{12}
Repetition rate (Hz)	15	15
Beam power (MW)	0.5	2

In the PD2 design, the 600-MeV beam transport line is about 254-m long. This leaves enough room for another 1.3 GeV accelerating structure to bring the linac energy up to 1.9 GeV. When one takes this upgrade path, one should consider using superconducting (sc) rf cavities for the additional 1.3 GeV acceleration. This technology is making rapid progresses thanks to the SNS Project and R&D work at other labs (DESY, CERN, CEA/Saclay, ANL, JLab, etc.). Compared to room temperature rf linacs (e.g., the 800 MeV linac at LANL), sc rf linacs have higher accelerating gradient and probably also cost less. One issue that needs to be addressed when adopting an sc linac is the proton beam pulse length. An sc linac works well for long pulses (1 msec or longer). Whether it is an appropriate choice for short pulse operations (e.g., 360 μsec in the PD2 upgrade) need further investigations.

In the PD2 upgrade, the existing normal conducting CCL rf system will be reused, because this is a relatively new system in the Fermilab accelerator complex, built about 10 years ago. However, the pulse length of this system must be raised. When the beam intensity is increased by a factor of 4, the number of protons injected from the linac also increases by the same factor. Assuming the linac peak current remains the same as in the PD2 design (50 mA), the pulse length needs to be quadrupled, from 90 μsec to 360 μsec. The existing CCL structures (from 110 MeV to 400 MeV) can only give a maximum pulse length of about 100 μsec (see Ch. 8). These structures need to be modified. Although the klystrons may be able to operate at longer pulses, the modulators and pulse transformers must be replaced. Moreover, the CCL cavity-sparking rate has a strong dependence on the pulse length. This also needs to be studied.

7. Comparison of the Two Options

In summary:

Synchrotron – cheaper, more secure
Linac – better, more challenging

Synchrotron

- Strengths
  - A lot of the work completed - Three design iterations, all documented
  - More matured technology (*"Boring is good"*)
  - Less expensive (TEC $230M, including 15% EDIA, 13% overhead, 30% contingency)
  - Fit the existing complex better
  - Better use of Fermilab's expertise
  - R&D helps improve the performance of existing machines
- Weaknesses
  - (See the strengths of linac)
  - Less innovative (less attractive to universities)
  - Longer injection time to the MI
- Possible improvement
  - To investigate ac superconducting magnet technology

Linac

- Strengths
  - Natural connection to a TESLA type LC
  - More intense beam intensity (longer pulse) possible
  - More versatile physics (p, e, X-FEL)
- Weaknesses
  - More expensive: Cost estimate must be compared with other estimates for a similar machine, e.g.
    - BNL: 1 GeV sc linac TEC $170M
    - CERN: 2.2 GeV sc linac SF350M

- Several critical technical issues:
  - 1 klystron driving multiple cavities
  - 8 GeV H^- injection into the MI
  - Beam loss at high energy sections
- Difficult to use the MiniBooNE beam line
- To be a true "proton driver" (i.e., serving a neutrino factory), the linac needs a compressor ring.

- Possible improvement
  - To have a cost review
  - To carefully investigate these technical issues