Report to the Fermilab Director

by the Proton Committee

October 26, 2003

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1. Introduction

The Proton Committee was formed in February 2003 by the Fermilab Director to provide advice on the use of protons at Fermilab through the end of the decade. This report provides the written portion of that advice. This introduction gives background information. The major part of the report is in three sections addressing the short, mid, and long-term parts of the decade. Issues addressing collaboration and organization are reported in their own section. The summary makes use of terminology introduced in the body of the report.

1a. Ground Rules

The Chair set the following ground rules for the committee: 1) Antiprotons will be required for the entire time period considered by the committee, 2) A "New Proton Source" will not be the default solution to increasing proton demands during this time period, 3) Specific on-going activities will be supported as long as they are seen to fit sensibly into an overall view, and 4) This committee leaves physics decisions to the Director.

This committee is aware of another advisory panel for the Director, the Long Range Planning Committee (LRPC) chaired by Hugh Montgomery. This committee will try to hand off to the LRPC gracefully since its horizon extends well beyond that of this committee.

In preparing a report such as this, which addresses the future proton delivery capabilities of Fermilab's Protons Source and Main Injector, it is a challenge to not aim too low nor to aim too high. The intention of this report is to help to start to meet the challenge by blending together input from some of the users who intend to use most of the protons, as well as some of the accelerator experts who have to provide the protons. The authors of this report consider it to be one phase - perhaps best characterized as the "information gathering phase" - of an ongoing process. The numbers in this report are considered to be reasonable given the information available to the committee at this time. The committee used, as much as possible, actual measured performances of the Proton Source and the Main Injector during parts of the last year as benchmarks in estimating the future performance for delivery of protons. And when measurements were not available, the committee used its best judgment to estimate performance.

The second phase of the process is envisioned to make reliable estimates of costs and benefits for the steps being considered from now until FY07 or so. The third phase takes the output of the first two phases and folds them together with the physics priorities and budgets for Fermilab to develop a detailed plan for the work to actually be done. This management process is expected to iterate, as more information is uncovered concerning both the physics to be done, as well as the actual demonstrated performance of the accelerators as improvements are made. And many of the estimates of performance made in this report will be replaced with benchmarks based on measured future performance.

1b. Charge and Membership

The full charge to the committee is given in an Appendix. Its five points are repeated here for convenience, and several words are underlined for emphasis:

1) Identify users of protons over the period 2003-2010 and the demands represented by each.
2) Establish technical goals for delivery of protons, both from the Booster and Main Injector, over the period.
3) Identify major modifications to the Proton Source and Main Injector that will be required to meet these goals assuming availability of Fermilab resources at the few x $10M level over the period.
4) Identify possible resources and opportunities for collaboration by institutions outside Fermilab.
5) Suggest an organization for implementing a program of modifications, including opportunities for integration of collaborators outside Fermilab.

In keeping with the part of the charge that mentions “resources at the few x $10M level”, we have chosen to also remain very general. Thus no cost detail is included in this report. We did this primarily because cost estimates are provided to the Directorate by the Division Heads. It did not seem appropriate to put a second set of costs into the mix. In addition, the committee did not have sufficient time and resources to do the work necessary to bring any new cost information to the table.

The committee is composed of David Finley (Chair), Janet Conrad, Doug Michael, Greg Bock, Shekhar Mishra, Ioanis Kourbanis, Eric Prebys, Chuck Ankenbrandt, Peter Kasper, Alberto Marchionni, and Ray Stefanski.

The Chair requested that one co-spokesperson from MiniBooNE (Janet Conrad) and one from MINOS (Doug Michael) be included on the committee because the needs of these neutrino experiments drive the annual demands for protons. The Chair requested various members of the Beams Division be included because of some combination of their expertise and/or their management position as being responsible for the accelerators that provide protons. One of the Chair’s duties was to cover all aspects not obviously covered by other members. These included proton needs for Run II, users of the Linac, etc. However, the needs for Meson120 were covered by a combination of several members and the Chair.

Subsequent to the June 2003 PAC Meeting, Jeff Appel joined the committee.

1c. Methodology and What Is New

The committee gathered initial information from its own membership and by "interviewing" people either at the direction of the Chair or on their own initiative. A list of people contributing is given in the next section. Team members presented individual reports at the weekly meetings. These reports and other information are presently stored on the Proton Team website http://www-bd.fnal.gov/proton/ProtonTeam/ . We thank Elliott McCrory for creating and maintaining this site. In particular, the presentations by Elliott McCrory [1, 2], Eric Prebys [3], and Peter Kasper [4] outline the issues for the present Proton Source (Linac and Booster) rather well. Also the committee referred to a plan [5] that is driven by the ever-increasing needs of the 120 GeV Neutrino program driven by MINOS.

Jeff Appel, the Head of Program Planning, provided a draft schedule shown in Figures Ia and Ib [6]. The committee used this to divide the decade into three periods: Short Term (present program), Mid Term (MINOS data taking), and Long Term (CKM, E906 and an anticipated large increase in 120 GeV protons for the Neutrino Program). The boundaries of these periods are characterized by major changes in proton user demands. Many of the modifications needed to increase the number of protons provided by the Proton Source and the Main Injector will require beam downtime. Determining whether these schedules allow enough time or not, the committee necessarily leaves to management.

The uncertainties with the Long Term are many, but the committee believes the physics program will eventually demand more protons than reasonable upgrades of the present Linac and Booster can accommodate. At that point it would be prudent to have a New Proton Driver available. There are also uncertainties with the Mid Term. For example, we assume that the Recycler will work with electron cooling by mid-2005 when MINOS is well underway.

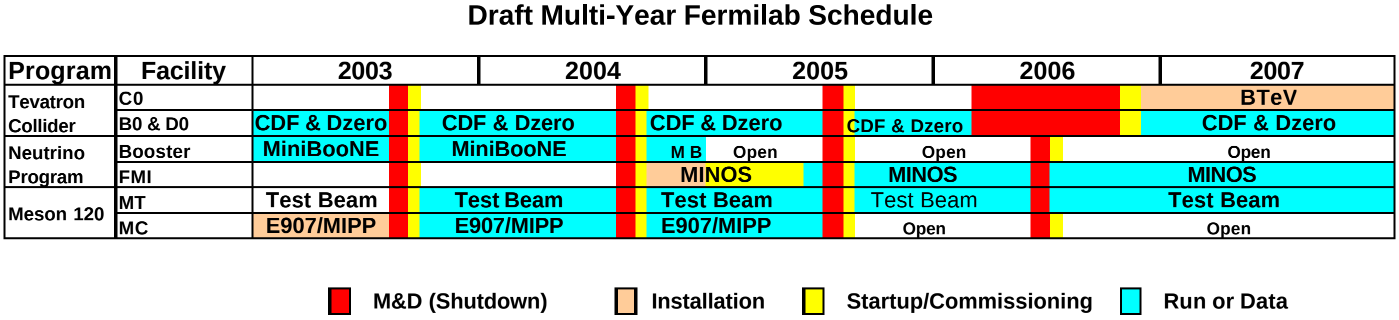
The demands are listed in Tables Ia, Ib and Ic for the Short Term, Mid Term, and Long Term. In order to help the committee evaluate the consequences of the demands on Booster and Main Injector, Peter Kasper developed something new, the "Proton Demands Consequences Spreadsheet". This spreadsheet is explained in detail in an Appendix and is available by sending an email to kasper@fnal.gov. It is hoped this spreadsheet will be of use to those who will evaluate the interrelationships between various parts of the program.

Here we present a very short overview of the needs for protons from now until the end of the decade, and the issues they raise. The intensity demands - from protons per pulse to protons per year - are driven by the neutrino programs led by MiniBooNE and NuMI. On the other hand, Meson120 does not drive intensity demands; rather it primarily needs time for the Main Injector to be at 120 GeV. Run II primarily demands proton intensity for antiproton production. Run II also needs protons directly for the

Tevatron, but these needs no longer drive intensity demands. There is a conflict in the Main Injector between MINOS and Run II antiproton production; namely, MINOS needs the minimum possible Main Injector cycle time, but the Antiproton Source requires a cycle time longer than the minimum possible. This will change once electron cooling works in the Recycler. The Main Injector's largest challenge is the requirement that it serve three programs: Run II, 120 GeV Neutrino, and Meson120. The Booster's performance is now - and will always be - limited by our ability to reduce and control losses. The Linac has a significant single point vulnerability that the Lab must address.

1d. People Contributing

Some of the people contributing to the information gathered by the committee through "interviews" include: Alan Bross, Chuck Brown, Joel Butler, Dave Capista, Weiren Chou, Mike Church, John Cooper, Peter Cooper, Mary Anne Cummings, Paul Czarapata, Roger Dixon, Bill Foster, Nancy Grossman, Steve Holmes, Arlene Lennox, Peter Limon, Elliott McCrory, Dave McGinnis, John Marriner, Bob Mau, Hugh Montgomery, Craig Moore, Bill Ng, Francois Ostiguy, Bill Pellico, Milorad Popovic, Stephen Pordes, Rajendran Raja, Jeff Spalding, Panagiotis Spentzouris, Bob Tschirhart, Bob Webber and Vicky White. We thank these people for their time and input.



Draft Multi-Year Fermilab Schedule

Program	Facility	2003	2004	2005	2006	2007
Tevatron Collider	C0	🟥 🟨	🟥 🟨	🟥 🟨	🟥 🟨	BTeV
	B0 & D0	CDF & Dzero 🟥 🟨	CDF & Dzero 🟥 🟨	CDF & Dzero 🟥 🟨	CDF & Dzero 🟥 🟨	CDF & Dzero
Neutrino Program	Booster	MiniBooNE 🟥 🟨	MiniBooNE 🟥 🟨	M B Open 🟥 🟨	Open 🟥 🟨	Open
	FMI	🟥 🟨	🟥 🟨	MINOS 🟥 🟨	MINOS 🟥	MINOS
Meson 120	MT	Test Beam 🟥 🟨	Test Beam 🟥 🟨	Test Beam 🟥 🟨	Test Beam 🟥	Test Beam
	MC	E907/MIPP 🟥 🟨	E907/MIPP 🟥 🟨	E907/MIPP 🟥 🟨	Open 🟥 🟨	Open

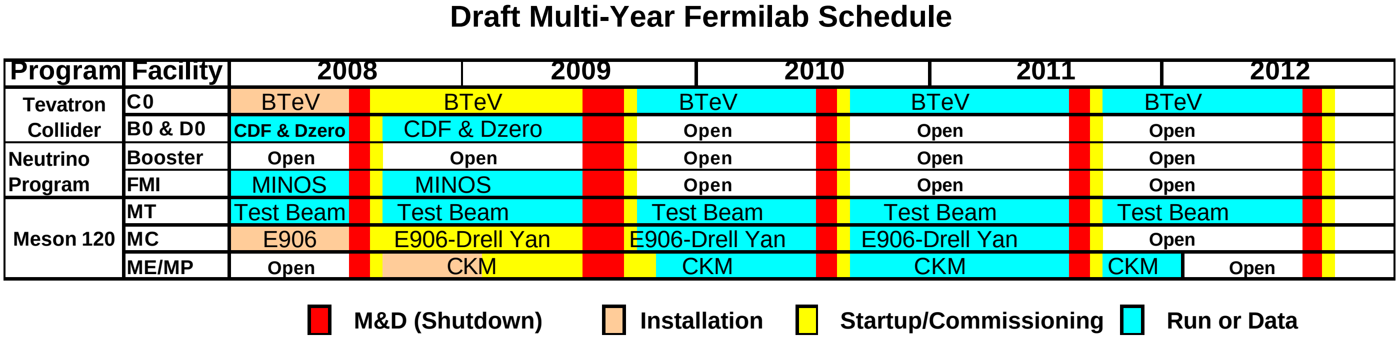
🟥 M&D (Shutdown) 🟧 Installation 🟨 Startup/Commissioning 🟦 Run or Data

This draft is meant to show the general outline of the Fermilab accelerator and experimental schedules.
Major components include:

- 6-8 week shutdown each summer,
- 6-8 week shutdown for the installation of CDF and Dzero detector upgrades in 2006-7
- Starup of the NuMI operation with the MINOS detector.

Additional shutdown periods will be added, typically allowing 40 weeks of accelerator operation per year.
The draft schedule will be updated as more precise information is made available.

Figure Ia. A draft schedule from now until the end of 2007.



Draft Multi-Year Fermilab Schedule

Program	Facility	2008	2009	2010	2011	2012
Tevatron Collider	C0	BTeV 🟥 BTeV	🟥 🟨 BTeV	🟥 🟨 BTeV	🟥 🟨 BTeV	🟥 🟨
	B0 & D0	CDF & Dzero 🟥 🟨 CDF & Dzero	🟥 🟨 Open	🟥 🟨 Open	🟥 🟨 Open	🟥 🟨
Neutrino Program	Booster	Open 🟥 🟨 Open	🟥 🟨 Open	🟥 🟨 Open	🟥 🟨 Open	🟥 🟨
	FMI	MINOS 🟥 🟨 MINOS	🟥 🟨 Open	🟥 🟨 Open	🟥 🟨 Open	🟥 🟨
Meson 120	MT	Test Beam 🟥 🟨 Test Beam	🟥 🟨 Test Beam	🟥 🟨 Test Beam	🟥 🟨 Test Beam	🟥 🟨
	MC	E906 🟥 E906-Drell Yan	🟥 E906-Drell Yan	🟥 🟨 E906-Drell Yan	🟥 🟨 Open	🟥 🟨
	ME/MP	Open 🟥 🟨 CKM	🟥 🟨 CKM	🟥 🟨 CKM	🟥 🟨 CKM	Open 🟥 🟨

🟥 M&D (Shutdown) 🟧 Installation 🟨 Startup/Commissioning 🟦 Run or Data

This draft is meant to show the general outline of the Fermilab accelerator and experimental schedules.
Major components include:

- 6-8 week shutdown each summer,
- 6-8 week shutdown for the installation of CDF and Dzero detector upgrades in 2006-7
- Starup of the NuMI operation with the MINOS detector.

Additional shutdown periods will be added, typically allowing 40 weeks of accelerator operation per year.
The draft schedule will be updated as more precise information is made available.

Figure Ib. A draft schedule from 2008 to beyond the end of the decade.

Table Ia. Proton Demands for the Short Term.

Short Term Time Frame: Program / Experiment Demands

Program -->>	Collider	Neutrino	Meson120	Meson120
Experiment -->>	Pbar (1)	MiniBooNE	E907	Test Beam
Run dates (time frame)	2003-10 (all)	2003-5 (short)	2003-5 (short)	2003-10 (all)
Proton demands in this time frame	03: 5E12/2 sec >03: 8E12/2 sec	1E21 total	1E10 ppp (2)	TBD (3)
Protons per year (4)	5E19/year 8E19/year	5E20/year	1.4E16/year	TBD (3)
MI Flattop time	<<1 sec	NA	1 sec	1 sec

Notes:
(1) The Tevatron also receives 36 bunches of 3E11 each for shot setup.
(2) 1E10 ppp requires one low intensity Booster batch that is further collimated.
(3) Day to day scheduling to be determined by Program Planning.
(4) Calculated using 2E7 seconds per year

Table Ib. Proton Demands for the Mid Term.

Mid Term Time Frame: Program / Experiment Demands

Program -->>	Collider	Neutrino	Meson120	Neutrino
Experiment -->>	Pbar (1)	MINOS (2)	Test Beam	B Open (3)
Run dates (time frame)	2003-10 (all)	2005-07 (mid)	2003-10 (all)	2005-7 (mid)
Proton demands in this time frame	8E12/2 sec	2.5E13/2 sec 11E20 total	TBD (4)	1E21 total
Protons per year (5)	8E19/year	05: 2.5E20 07: 5E20	TBD (4)	5E20/year
MI Flattop time	<<1 sec	<<1 sec	1 sec	NA

Notes:
(1) The Tevatron also receives 36 bunches of 3E11 each for shot setup.
(2) MINOS protons on target demands listed for beginning and end of time frame.
(3) Listed as Open on the schedule.
Numbers are estimates and require PAC considerations, Director approval etc.
(4) Day to day scheduling to be determined by Program Planning.
(5) Calculated using 2E7 seconds per year

Table Ic. Proton Demands for the Long Term.

Long Term Time Frame: Program / Experiment Demands

Program -->> Experiment -->>	Collider Pbar (1)	Neutrino MINOS (2)	Meson120 CKM	Meson120 E906	Meson120 Test Beam	Neutrino B Open (3)	Neutrino MI Open (3)
Run dates (time frame)	2003-10 (all)	2008-09 (long)	2008-10 (long)	2008-10 (long)	2003-10 (all)	2008-10 (long)	2009-10 (long)
Proton demands in this time frame	8E12/2 sec	5.8E13/1.8 sec 6.2E13/1.7 sec	3.33E19 total	1E12 ppp	TBD (4)	TBD	6.2E13/1.7 sec
Protons per year (5)	8E19/year	08: 6E20 >08: 7.2E20	1.67E19/year	TBD (4)	TBD (4)	TBD	7.2E20 .
MI Flattop time	<<1 sec	<<1 sec	6 sec (6)	<= 6 sec (6)	1 sec	NA	<<1 sec

Notes:
(1) The Tevatron also receives 36 bunches of 3E11 each for shot setup.
(2) MINOS protons on target demands listed for beginning and end of time frame.
(3) Listed as Open on the schedule.
Numbers are estimates and require PAC considerations, Director approval etc.
(4) Day to day scheduling to be determined by Program Planning.
(5) Calculated using 2E7 seconds per year
(6) CKM requires debunched beam, E906 can use either bunched or debunched beam

2. Short Term: From Now Through NuMI Turn On

This period starts in April 2003 and extends until NuMI/MINOS has begun to take data as shown in Figure Ia.

First, the committee notes that the reliance of the Linac on a single vendor for the 5MW 7835 power tubes represents a significant vulnerability. Failure may result in no protons at all for Fermilab for an unacceptably long period. The Lab obviously has to mitigate this vulnerability.

Because the demands for “Linac only” beam are small compared to the demands of other parts of the Fermilab experimental program, we only mention them here. (The reader may refer to [7] for further details.) These demands are best expressed as a percentage of time per week for which beam is required. MUCOOL is expected to require about 3% of a week, and to be scheduled by Program Planning. Beam maintenance and beam studies are expected to continue to require about 1.0% of a week. The Neutron Therapy Facility (NTF) requires beam parasitically to the HEP program about 1.8% of the time, and the successful arrangements with Accelerator Operations for day-to-day delivery of the beam are expected to remain in effect. The Linac will operate better with minor modifications, and the Beams Division management is expected to accommodate these as they see fit. On the other hand, major changes to the Linac, such as a new front end or a replacement for the original low energy linac, should only be done in relationship to advice received from the Long Range Planning committee. MUCOOL is expected to require beam in the Mid Term, and beam maintenance and NTF are expected to last to the Long Range.

Downstream of the Linac, the experimental program in the Short Term requires protons for the following:

MiniBooNE: 8 GeV protons from the Booster;
Run II: 120 GeV protons for antiproton stacking from the Main Injector;
Run II: 150 GeV protons from the Main Injector for the Tevatron;
Meson 120: 120 GeV slow spill protons for E907 and the Testbeam.

In addition, the Main Injector will need 5 to 10% of the available beam time to prepare for operations in the Mid Term. This includes getting Slip Stacking working for Run II antiproton stacking cycles. It also includes getting 5 batch operation working with acceptable emittances. The Booster will also need beam time to establish an acceptably low loss multibatch transfer technique to the Main Injector.

2a. Short Term Demands

In the Short Term, the demands on the Booster and the Main Injector can be considered separately. In this section, we consider these demands in light of the combination of MiniBooNE and antiproton stacking.

There are several changes required in order to provide beam to experiments in the Short Term, and to meet the needs for the beginning of the Mid Term. Some of these changes are “modifications”, requiring the resources associated with projects (people, money and time). Some modifications will require downtime to install equipment. Most modifications also require commissioning which usually uses beam time. In addition to these usual kinds of “modifications”, other changes are better described as “operational” changes that mostly require beam study time. All of these are discussed in the next section under "Modifications”.

2a.1 Collider + MiniBooNE

The current demands on the Booster for these two programs are well understood. The Collider needs 1 pulse at 5E12 delivered to the Main Injector at an average rate of 0.5 Hz for antiproton production (antiproton stacking). The Collider also requires protons destined for the Tevatron during shot setup. However, this is not a Booster intensity issue and is not considered here. MiniBooNE needs 1E21 protons on target to complete the neutrino running. In the Mid-Term MiniBooNE may also request an additional 1E21 protons on target for antineutrino running to definitively address the LSND signal. (However, in the "short term” period considered in this section of the report, only neutrino running is relevant.)

Introduction of “Demands Consequences” Table

Once Fermilab begins to run multiple physics programs, the interconnections between the demands render separate assessments impossible. In order to address this problem, we introduce a tool for Program Planning that should help to assess proton economics issues, as they become more and more entwined. This tool is described in considerable detail in the Appendix “Proton Demands Consequences Spreadsheet”, but here we briefly describe some of the key concepts before proceeding.

In order to clarify the estimates for the number protons per year actually delivered by the Proton Source or the Main Injector, the committee introduces three concepts here. The first is the number of weeks “scheduled” per year. The second is the “reliability” of the accelerators for delivering beam during this scheduled time. The third is the “operational efficiency” which attempts to estimate gains or losses from nominal performance during operations.

The numbers of weeks the Proton Source or the Main Injector are scheduled to provide beam depend on the details of the schedule developed by Program Planning. For this report 44 weeks per year are used for the Proton Source and 42 weeks per year for the Main Injector.

The reliability of the Proton Source is measured to be 92%. This measurement was done by MiniBooNE, which counted the number of minutes during which beam was sent to the detector and divided it by how many minutes had elapsed, for each week in March and April 2003.

The combined Proton Source and Main Injector reliability is estimated by starting with the value 71%, which is the measured number [13] from July 7 to September 1, 2003 for the percentage of time stacking for Run II was taking place. (A slightly larger number, 72.7% was measured from June 2, 2003 to September 1, 2003, but it is not used here.) The other 29% includes downtimes for the Proton Source, the Main Injector, the Antiproton Source and all other systems (such as Controls), as well as time taken to prepare and provide beams to the Tevatron, and for studies. During the period from July 7 to September 2, 2003 these various downtimes accounted for 14% (almost half of the 29%), and the time devoted to the Tevatron accounted for 8%. The downtime for the Antiproton Source taken alone was 2.17%.

In determining the reliability for providing protons from the Proton Source and the Main Injector for Stacking, NuMI or Meson120 it is appropriate to remove the Antiproton Source downtime (2%). Thus, 73% is arrived at for the estimate of the reliability of the Main Injector for providing protons for Stacking, NuMI or Meson120. No credit is taken here for the possibility of NuMI using six batches instead of five during the downtime of the Antiproton Source. Nor is any credit taken for running any NuMI cycles, which could also be six batches instead of five, during the block of time the Main Injector is devoted to providing protons and antiprotons to the Tevatron for Collider physics. Nor is any credit taken for the possibility of reducing the downtimes, or the time devoted to providing beams to the Tevatron.

Thus, based on actual performance demonstrated during the last year and not taking credit for other possible gains, 73% is chosen for the reliability, meaning the percentage of scheduled time that the Proton Source and the Main Injector together are expected to be capable of providing protons to Stacking, NuMI, or Meson120.

The operational efficiency of the Proton Source for providing protons to MiniBooNE is estimated by combining two factors. The first factor assumes the average number of protons from the Booster will be 4.5E12 instead of the nominal 5E12. The second factor assumes the average repetition rate will be 4.5 Hz instead of the maximum of 5Hz. Together these give 81% for the operational efficiency.

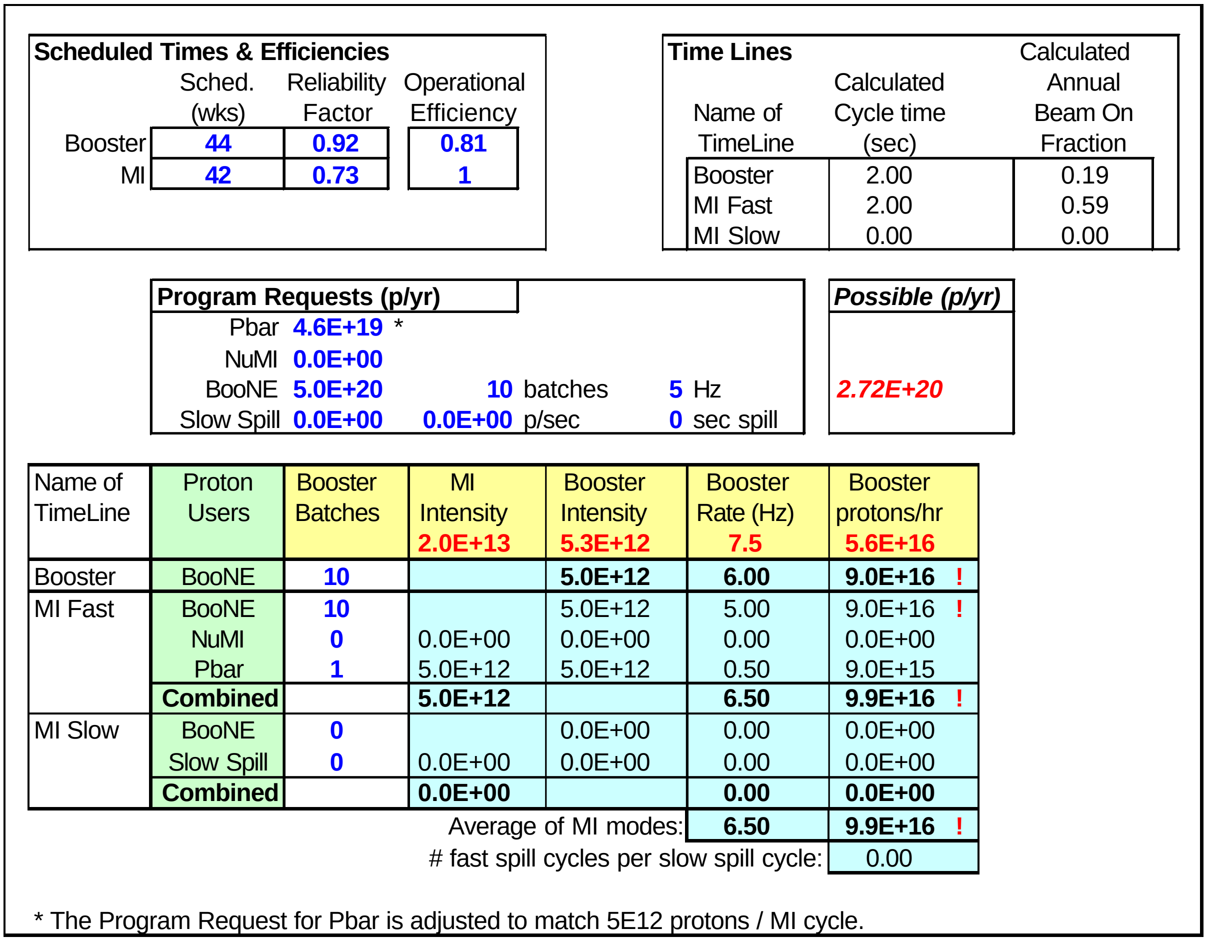
However, applying the concept of operational efficiency to the combined Proton Source and Main Injector has proved to be too uncertain given the information the committee has; and the chair has chosen to fix the value at unity. On the one hand, there are situations, which result in fewer protons per hour, notably whether the Main Injector cycle time needs to exceed 2 seconds. On the other hand, there are situations in which tend to deliver more protons per hour than the nominal, for example the number of protons per batch already exceeds the nominal 5E12 protons per batch. As experience is gained with operating the Main Injector in support of more than one physics program, the application of the concept of operational efficiency should become sensibly possible.

In addition, the simple concept of operational efficiency used here is not appropriate for Stacking or for Meson120 since the number of protons delivered in these cases is dominated by other considerations, such as scheduling. For example, Stacking expects to receive 8E12 at a repetition rate no faster than 2 seconds, and the number of protons per year in the tables is arranged so that this number is met. For Meson120, the number of protons per year is chosen so that no more than 5% of Main Injector beam time is used after applying all other constraints.

Demands Consequences Table for Collider + MiniBooNE

Table 2a shows the result of demanding 5E20 per year for MiniBooNE, and 4.6E19 for antiproton stacking. Two active "timelines" shown: "BooNE" runs for 19% of the year and "MI Fast" for 59% of the year. (The "MI Slow" timeline is included in the table but it is turned off.) The "Booster" timeline corresponds to 44 scheduled weeks with 92% reliability, and "MI Fast" corresponds 42 scheduled weeks with 73% reliability. The cycle time for each timeline is 2 seconds in this example. The operational efficiency for the Booster is set at 0.81, and at 1.0 for the Main Injector. The red numbers near to the top of the last four columns are the presently assumed limitations on the Main Injector total intensity (2.0E13), the Booster intensity (5.3E12), the Booster repetition rate (7.5 Hz), and the total number of protons/hour for the Booster (5.6E16). The "Average of MI modes" line at the bottom represents the result of combining the two timelines. For example, the combined timelines require the Booster to run at a rate of 6.5 Hz, which is within the capability of the Booster equipment (7.5 Hz), although this rate has not yet been demonstrated in operations. This rate includes two beam free prepulses for some of the Booster equipment; these two prepulses are also included in all the following examples.

The "MI Fast" timeline requires 9.9E16 protons per hour, and this exceeds the limit of 5.6E16 protons per hour, the highest throughput achieved so far. This is the main reason MiniBooNE has not yet achieved its demand of 5.0E20 protons per year. This limit is set by uncontrolled losses causing activation of equipment that requires maintenance in the beam enclosure. The red exclamation points indicated under Booster protons/hour indicate violations of this limitation. The "Possible" box calculates a maximum of 2.72E20 proton per year, instead of the request of 5E20.



Scheduled Times & Efficiencies

	Sched. (wks)	Reliability Factor	Operational Efficiency
Booster	44	0.92	0.81
MI	42	0.73	1

Time Lines

Name of TimeLine	Calculated Cycle time (sec)	Calculated Annual Beam On Fraction
Booster	2.00	0.19
MI Fast	2.00	0.59
MI Slow	0.00	0.00

Program Requests (p/yr)

Pbar	4.6E+19 *				
NuMI	0.0E+00				
BooNE	5.0E+20	10	batches	5	Hz
Slow Spill	0.0E+00	0.0E+00	p/sec	0	sec spill

Possible (p/yr)

2.72E+20

Name of TimeLine	Proton Users	Booster Batches	MI Intensity 2.0E+13	Booster Intensity 5.3E+12	Booster Rate (Hz) 7.5	Booster protons/hr 5.6E+16	
Booster	BooNE	10		**5.0E+12**	**6.00**	**9.0E+16**	!
MI Fast	BooNE	10		5.0E+12	5.00	9.0E+16	!
	NuMI	0	0.0E+00	0.0E+00	0.00	0.0E+00	
	Pbar	1	5.0E+12	5.0E+12	0.50	9.0E+15	
	Combined		**5.0E+12**		**6.50**	**9.9E+16**	!
MI Slow	BooNE	0		0.0E+00	0.00	0.0E+00	
	Slow Spill	0	0.0E+00	0.0E+00	0.00	0.0E+00	
	Combined		**0.0E+00**		**0.00**	**0.0E+00**	
Average of MI modes:					**6.50**	**9.9E+16**	!
# fast spill cycles per slow spill cycle:						0.00	

* The Program Request for Pbar is adjusted to match 5E12 protons / MI cycle.

Table 2a: Today's Booster performance requirements for the Collider + MiniBooNE.

The Importance of Booster Losses

Under present conditions, the cumulative losses sustained in delivering protons at 9.9E16 protons/hour would exceed an administrative limit that is related to the activation of high-maintenance equipment. Excessive radiation might not only damage the equipment but can also render it unserviceable under the present maintenance procedures. As a result, the Booster output is limited by administrative constraints on the losses.

Figure 2a shows the increase in loss as a function of protons per pulse (ppp) in late 2000. It can be seen that losses are significantly nonlinear with respect to proton intensity above 4E12 ppp. Therefore in the short term, solutions for losses focus on intensities that do not exceed 5E12 ppp. (Note that while 5.5E12 ppp has been routinely achieved for antiproton stacking, 5E12 ppp for antiproton stacking + MiniBooNE requires upgrades, as discussed below.)

The present priority for providing protons is defined in a May 15, 2003 memo from Mike Church to Bob Mau:

> "4.6E12 protons on the pbar target … without excessively tripping the Booster on losses. The Operations group shall attempt to tune Booster and MI to attain this. If after a reasonable effort, they are not successful, they shall obtain assistance from the MI machine coordinator or Proton Source machine coordinator. If necessary, beam to MiniBooNE shall be reduced to attain this goal, but not reduced below 3.6E16 protons/hour unless MiniBooNE is off, or requesting a lower intensity."

An administrative limit on Booster losses has been in place since the turn-on of MiniBooNE (9/1/02). Because the stacking rate is guaranteed, this has meant that the MiniBooNE rate has been substantially lower than requested. In the autumn of 2002, the MiniBooNE rate was a factor of 8 low. However over the subsequent eight months, the Booster Group and MiniBooNE collaborators have made substantial improvements. The performance by May 2003 had climbed to about 50% of the required MiniBooNE rate with losses substantially reduced as shown in Figure 2b.

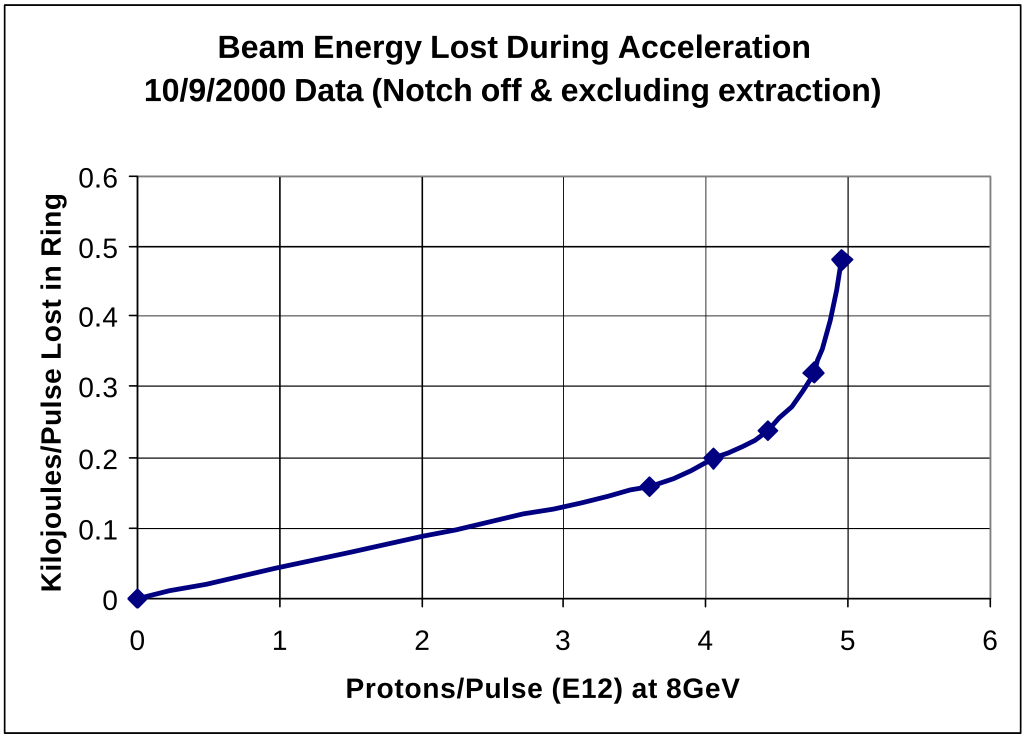


Figure 2a. Booster losses as a function of per pulse intensity. (The straight line between the origin and the point at about 3.6E12 is to be ignored.)

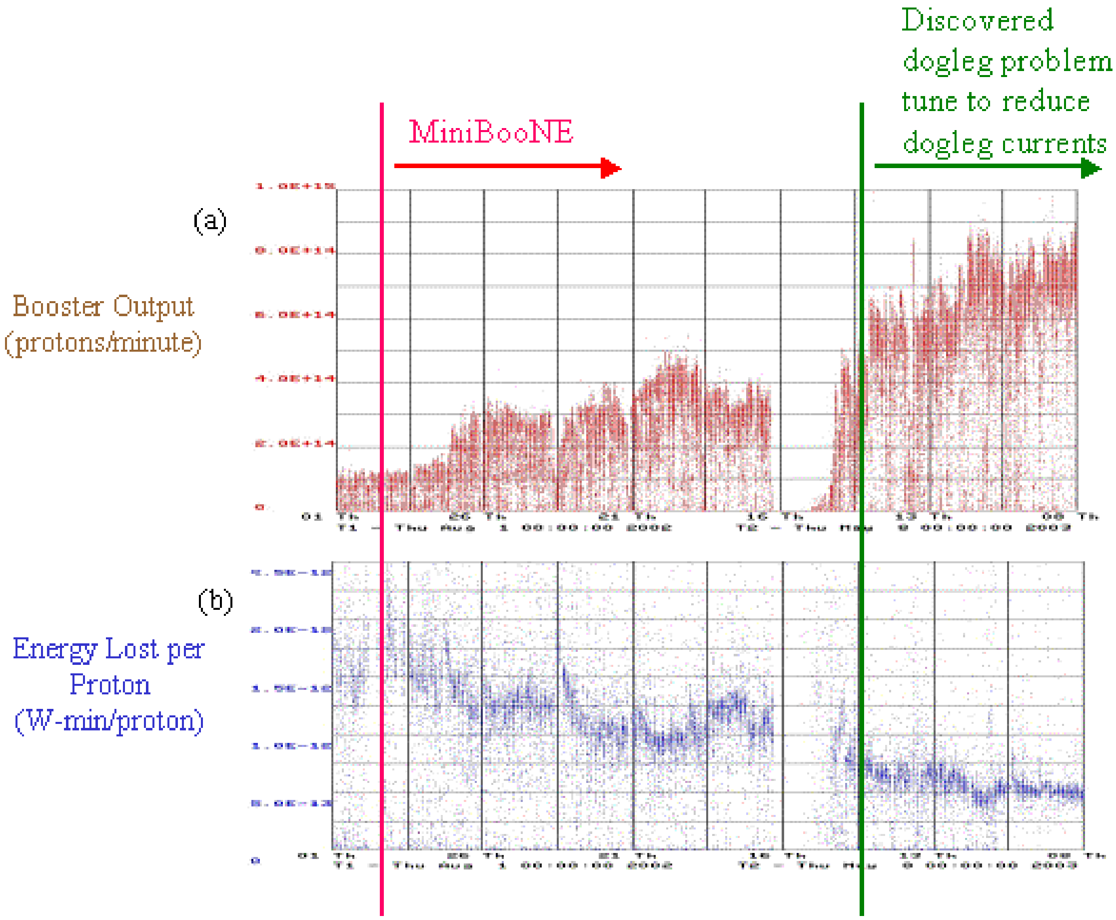
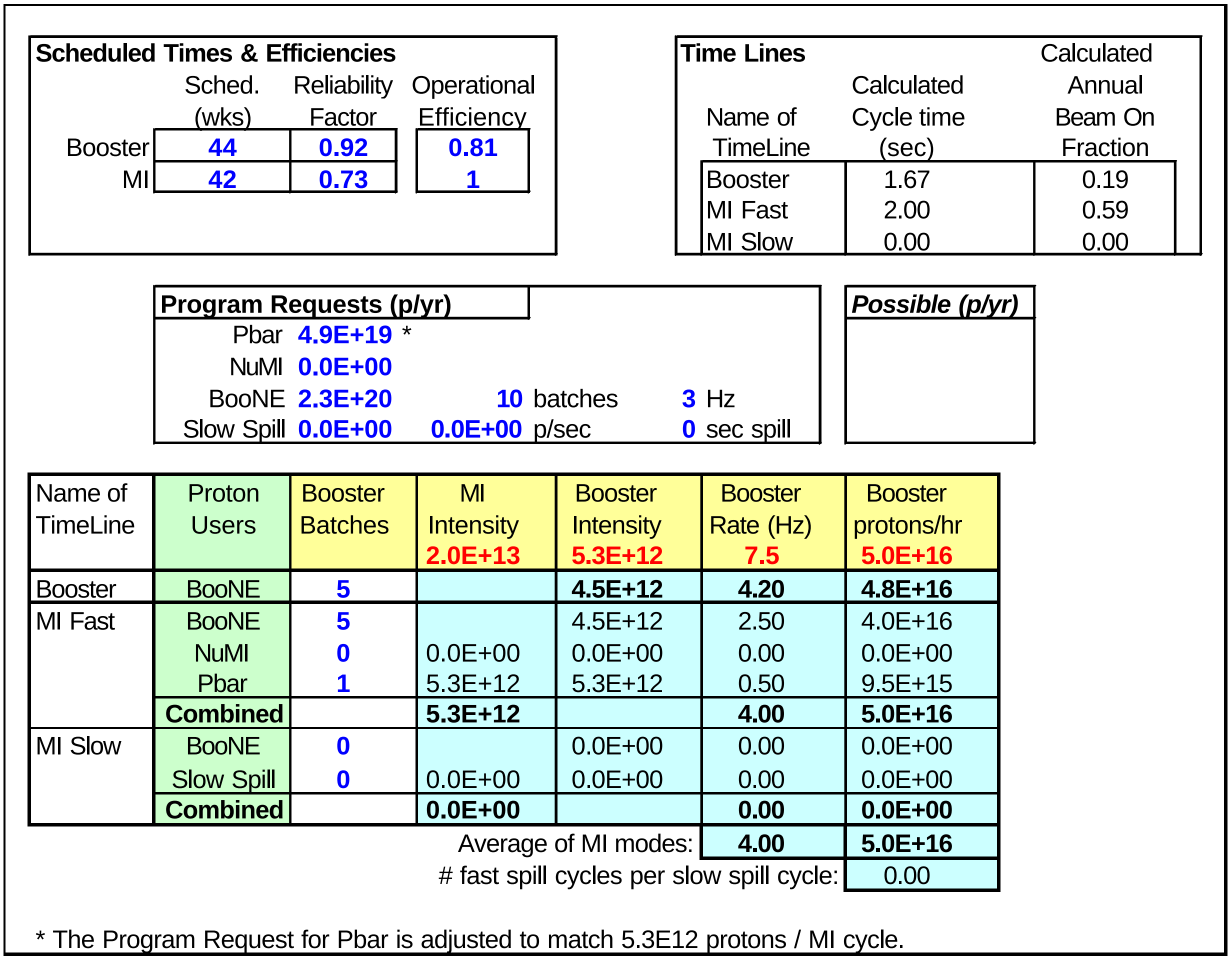


Figure 2b. Booster performance over eight months ending in May 2003. The upper plot (a) shows the output of the Booster; the scale goes from zero to 1E15 protons per minute. The lower plot (b) shows the energy lost per proton in units of Watt-minutes/proton; the scale goes from zero to 4.5E-12.

The Proton Demands Consequences spreadsheet for good running on May 18, 2003 is shown in Table 2b.

Table 2b lists a 2 second Main Injector cycle time. It is closer to 2.5 seconds because the Antiproton Source requires additional time for the stochastic cooling systems to remain efficient. The Run II plan calls for a Main Injector cycle rate of 2 seconds, although this will only be achieved after electron cooling is operational in the Recycler and additional improvements are made to the Antiproton Source. For most of the remainder of this report we will assume these changes have been made and the 2 second cycle time is the norm.



Scheduled Times & Efficiencies

	Sched. (wks)	Reliability Factor	Operational Efficiency
Booster	44	0.92	0.81
MI	42	0.73	1

Time Lines

Name of TimeLine	Calculated Cycle time (sec)	Calculated Annual Beam On Fraction
Booster	1.67	0.19
MI Fast	2.00	0.59
MI Slow	0.00	0.00

Program Requests (p/yr)

Pbar	4.9E+19 *				
NuMI	0.0E+00				
BooNE	2.3E+20	10	batches	3	Hz
Slow Spill	0.0E+00	0.0E+00	p/sec	0	sec spill

Possible (p/yr)

Name of TimeLine	Proton Users	Booster Batches	MI Intensity 2.0E+13	Booster Intensity 5.3E+12	Booster Rate (Hz) 7.5	Booster protons/hr 5.0E+16
Booster	BooNE	5		**4.5E+12**	**4.20**	**4.8E+16**
MI Fast	BooNE	5		4.5E+12	2.50	4.0E+16
	NuMI	0	0.0E+00	0.0E+00	0.00	0.0E+00
	Pbar	1	5.3E+12	5.3E+12	0.50	9.5E+15
	Combined		**5.3E+12**		**4.00**	**5.0E+16**
MI Slow	BooNE	0		0.0E+00	0.00	0.0E+00
	Slow Spill	0	0.0E+00	0.0E+00	0.00	0.0E+00
	Combined		**0.0E+00**		**0.00**	**0.0E+00**
				Average of MI modes:	**4.00**	**5.0E+16**
					# fast spill cycles per slow spill cycle:	0.00

* The Program Request for Pbar is adjusted to match 5.3E12 protons / MI cycle.

Table 2b. Booster performance as on May 18, 2003

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In order to meet the MiniBooNE demands shown in Table 2a, the following improvements are assumed to take place during the 2003 shutdown:

- The collimators are installed.
- The Long 3 extraction region is rearranged to maximize the separation between the dogleg magnets.
- Two wider aperture RF cavities are installed.
- The ramp monitoring software is in place.

Descriptions of these modifications appear in the Modifications section below. We note that the collimator will be used to implement the most likely technique for an improved notch creation by serving as a dump for the 400 MeV protons removed from the notch.

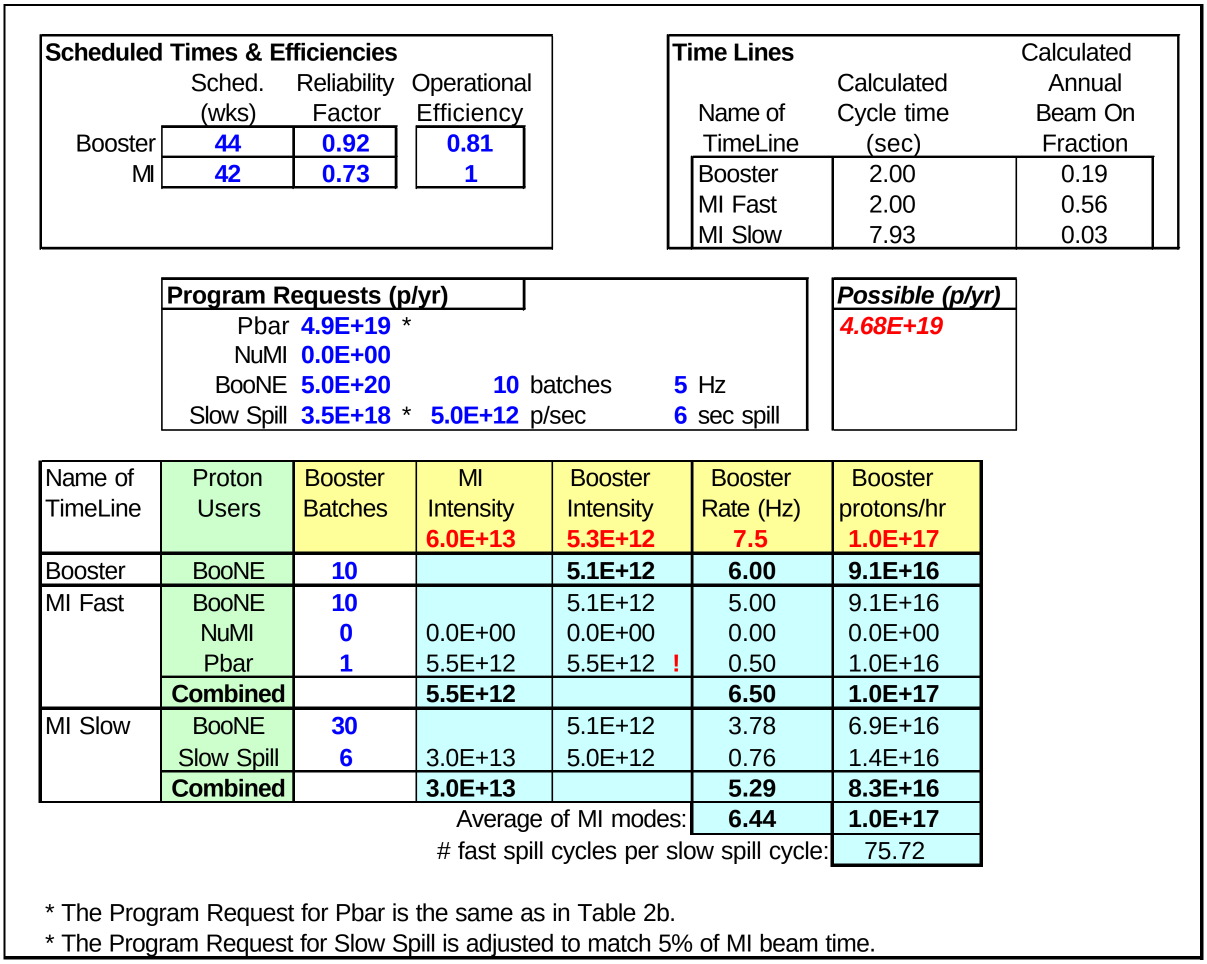
Though the benefits are difficult to quantify it is likely that these upgrades will enable the Booster to run at 5.5E12 ppp and 1E17 pph. The committee endorses installing these upgrades as early as possible, as these represent an important benchmark for what needs to be achieved in the future. With these upgrades it should be possible to meet the "Program Requests" performance requirements shown in Table 2a. We recommend that the Lab adopt this as a base goal for running conditions for the Fall of 2003.

2a.2 Collider + MiniBooNE + Meson120

The Meson120 program begins in the Summer of 2003 with beam provided to E907 and Testbeam. The requirements of the Meson120 program in terms of protons/year are quite modest since they require very low intensity. However E907 has stated their proton needs should be delivered in 1.33E6 slow spills of length 1 second. This would significantly impact the availability of the Main Injector for the Collider program. (E907 is working with the Beams Division to better determine their needs.)

Table 2c demonstrates the inclusion of Meson120, along with antiproton stacking and MiniBooNE, with the "MI Slow" timeline. It is 7.93 seconds long due to the 6 second of slow spill at flattop in the Main Injector. MiniBooNE also runs during this timeline. We have also made the following assumptions:

- The Booster protons/hour limitation has been increased as a result of the modifications listed in the previous section, to 1E17 pph.
- We have adjusted the Meson120 request so that no more than 5% of Main Injector beam time is used; the result is 3.5E18 protons per year.
- 4.9E19 protons/year are allocated to Stacking for the Collider, the same as in Table 2b. However, only 4.68E19 can be delivered for the "MI Fast" timeline (the Stacking timeline) because of the fraction of the year allocated drops to 56% from 59%, due to the "MI Slow" timeline.
- 5E20 protons/year are allocated to MiniBooNE.
- Each "MI Slow" timeline includes six batches for the Main Injector, which are extracted over 6 seconds. These are interspersed with "MI Fast" timelines containing many fast cycles. For reference, the calculation at the bottom of the table shows there is one slow spill cycle for every ~75 fast cycles.



Scheduled Times & Efficiencies

	Sched. (wks)	Reliability Factor	Operational Efficiency
Booster	44	0.92	0.81
MI	42	0.73	1

Time Lines

Name of TimeLine	Calculated Cycle time (sec)	Calculated Annual Beam On Fraction
Booster	2.00	0.19
MI Fast	2.00	0.56
MI Slow	7.93	0.03

Program Requests (p/yr)

Pbar	4.9E+19	*					
NuMI	0.0E+00						
BooNE	5.0E+20		10	batches		5	Hz
Slow Spill	3.5E+18	*	5.0E+12	p/sec		6	sec spill

Possible (p/yr)

4.68E+19

Name of TimeLine	Proton Users	Booster Batches	MI Intensity 6.0E+13	Booster Intensity 5.3E+12	Booster Rate (Hz) 7.5	Booster protons/hr 1.0E+17
Booster	BooNE	10		**5.1E+12**	**6.00**	**9.1E+16**
MI Fast	BooNE	10		5.1E+12	5.00	9.1E+16
	NuMI	0	0.0E+00	0.0E+00	0.00	0.0E+00
	Pbar	1	5.5E+12	5.5E+12 !	0.50	1.0E+16
	Combined		**5.5E+12**		**6.50**	**1.0E+17**
MI Slow	BooNE	30		5.1E+12	3.78	6.9E+16
	Slow Spill	6	3.0E+13	5.0E+12	0.76	1.4E+16
	Combined		**3.0E+13**		**5.29**	**8.3E+16**
				Average of MI modes:	**6.44**	**1.0E+17**
					# fast spill cycles per slow spill cycle:	75.72

* The Program Request for Pbar is the same as in Table 2b.
* The Program Request for Slow Spill is adjusted to match 5% of MI beam time.

Table 2c: The result of adding Meson120 to the Collider + MiniBooNE.

This scenario implies that Testbeam users will run parasitically with E907. Since 1E12 protons per pulse is the lowest batch intensity that can reasonably be accelerated in the Booster, some further intensity reduction will be required in the external beamlines. This has been done before with fixed target beams, and we believe it can be done again.

It is to be noted that an earlier plan for E907 and the Testbeam puts two batches of different intensity in the Main Injector. The first batch goes to the antiproton production target and it will have the largest intensity the Booster can deliver. The second batch would be lower intensity and it would be resonantly extracted over a second for Meson120 (both E907 and the Testbeam). This method will reduce the amount of time for Meson120, but this mixed mode Meson120 / antiproton stacking will have to be commissioned. The fall back is to have the Meson120 cycle independent of antiproton stacking as assumed in Table 2c.

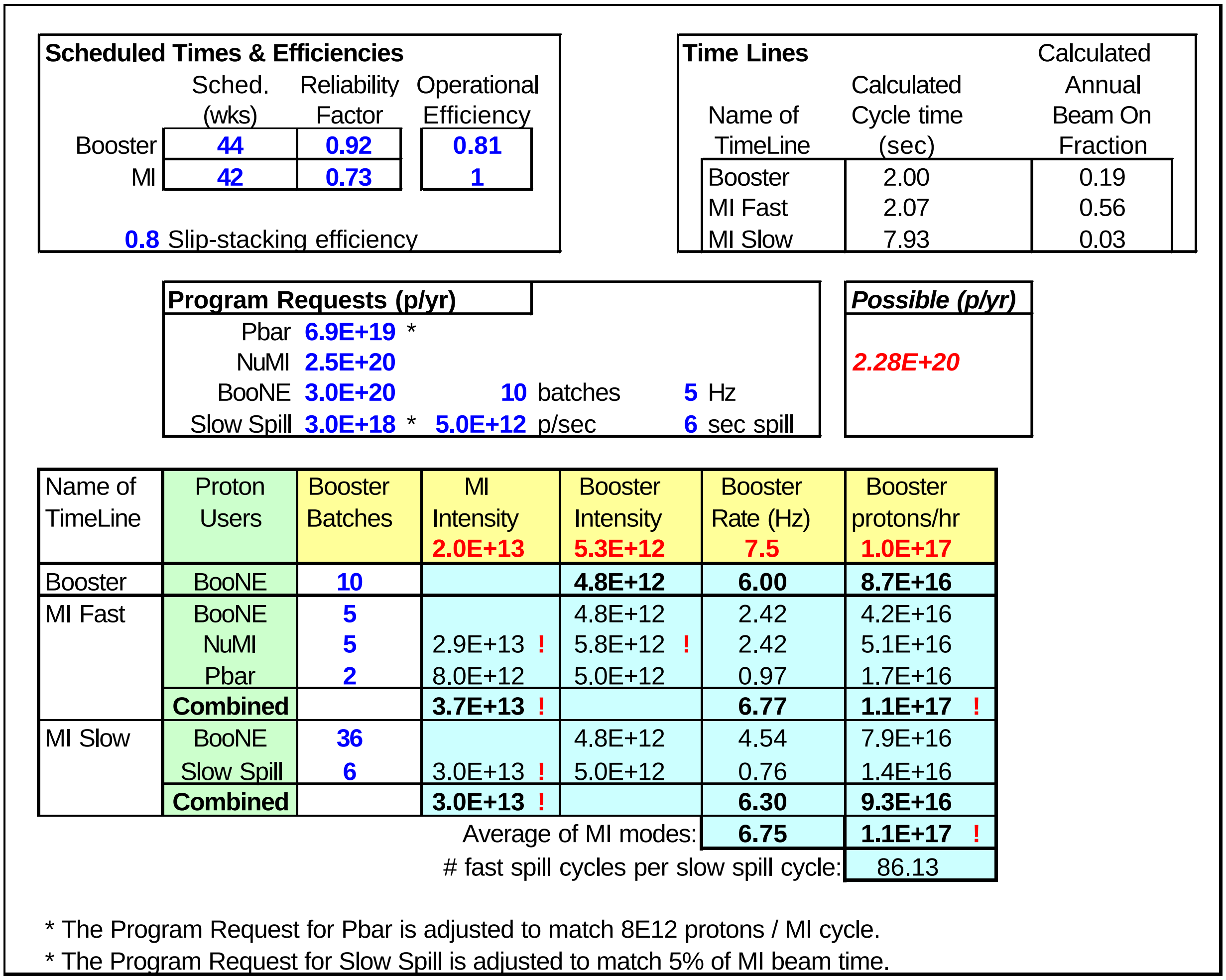
Another possible solution for the availability of the Main Injector for the Collider program has been suggested by the E907 experiment [9, 10]. Rather than establishing separate cycles for slow and fast spills, they propose injecting two high intensity batches into the Main Injector. Once the machine has reached 120 GeV, one batch would be fast extracted to the Antiproton Source. A small part of the second batch would then be slow extracted to the Meson120 users and, when the Antiproton Source is ready, the remainder of the batch would be fast extracted. Although this scheme could result in a negligible impact to the collider program from the Meson120 users, it probably is operationally more problematic.

We note that regardless of the timelines used, there are technical modifications to the Main Injector that are required in order to meet the demands of this program. These include:

- The equipment to do resonant slow-spill extraction needs to be reinstalled.
- If the “double fast extraction” scheme is adopted then slow extraction will need to be made to work at high batch intensity.
- Both the present plan and “double fast extraction” scheme require multibatch transfers into the Main Injector. However, multibatch transfers at this time do not work with acceptable Booster losses.

2a.3 Preparing for Collider Improvements and NuMI

It is instructive to see what it takes to approach the initial goals of the Mid Term, as shown in Table 2d. We include 6.9E19 protons per year for antiproton stacking (including slip stacking) and a request of 2.5E20 protons per year for NuMI. In addition we include a reduced rate for MiniBooNE of 3E20 protons per year (instead of 5E20 protons per year). However, the “Possible” box shows that NuMI can only achieve 2.28E20 protons per year due to the assumed Booster intensity limit of 5.3E12 protons per batch. This is the combined result of the requirement for 2.5E20 protons per year, the scheduled time, the reliability, and using 1.0 for the operational efficiency. If one uses an operational efficiency more or less than this, NuMI would receive proportionately more or less. The table also shows it would take 5.8E12 protons per Booster cycle to deliver 2.5E20 protons per year for NuMI. This exceeds the assumed limit of 5.3E12 protons per cycle.



Scheduled Times & Efficiencies

	Sched. (wks)	Reliability Factor	Operational Efficiency
Booster	44	0.92	0.81
MI	42	0.73	1

0.8 Slip-stacking efficiency

Time Lines

Name of TimeLine	Calculated Cycle time (sec)	Calculated Annual Beam On Fraction
Booster	2.00	0.19
MI Fast	2.07	0.56
MI Slow	7.93	0.03

Program Requests (p/yr)

Pbar	6.9E+19	*					
NuMI	2.5E+20						
BooNE	3.0E+20			10	batches	5	Hz
Slow Spill	3.0E+18	*	5.0E+12	p/sec		6	sec spill

Possible (p/yr)

2.28E+20

Name of TimeLine	Proton Users	Booster Batches	MI Intensity 2.0E+13	Booster Intensity 5.3E+12	Booster Rate (Hz) 7.5	Booster protons/hr 1.0E+17
Booster	BooNE	10		**4.8E+12**	**6.00**	**8.7E+16**
MI Fast	BooNE	5		4.8E+12	2.42	4.2E+16
	NuMI	5	2.9E+13 !	5.8E+12 !	2.42	5.1E+16
	Pbar	2	8.0E+12	5.0E+12	0.97	1.7E+16
	Combined		**3.7E+13** !		**6.77**	**1.1E+17** !
MI Slow	BooNE	36		4.8E+12	4.54	7.9E+16
	Slow Spill	6	3.0E+13 !	5.0E+12	0.76	1.4E+16
	Combined		**3.0E+13** !		**6.30**	**9.3E+16**
				Average of MI modes:	**6.75**	**1.1E+17** !
					# fast spill cycles per slow spill cycle:	86.13

* The Program Request for Pbar is adjusted to match 8E12 protons / MI cycle.
* The Program Request for Slow Spill is adjusted to match 5% of MI beam time.

Table 2d. Initial demands for the Mid Term including a reduced MiniBooNE rate.

The program requests in Table 2d require the Main Injector intensity to exceed 2E13 protons per pulse and the Booster throughput to exceed 1E17 protons per hour. In order to alleviate some of these constraints, some or all of the following modifications will be necessary:

- Replacing the Long 13 extraction septum (MP01) and modifying the extraction dogleg to match that at Long 3.
- Replacing the weakest parts of the ORBUMP system.
- Implementing improved Booster radiation protection including installation of the radworker robot.
- Implementation of the upgrades to the loss monitor system.
- Establishment of cogging for multibatch transfers into the Main Injector.
- Implementation of Main Injector damper systems and upgraded BPM system,
- Implementation of Main Injector slip stacking and beam loading compensation.
- Implementation of lattice changes for NuMI extraction.

- Establishment of simultaneous operation of NuMI and antiproton stacking in the same Main Injector cycle.

Given these modifications, a reasonable Main Injector intensity goal is 6E13 protons per pulse, and a reasonable goal for the Booster radiation limit is the current shielding assessment limit of 1.8E17 pph. These goals will be assumed in the next Section for the Mid Term. 6E13 protons per pulse are the maximum intensity the presently installed Main Injector RF can accelerate with the present ramp rate. However, limitations on the Booster single batch intensity requires some kind of fast proton stacking in the Main Injector to approach this maximum intensity. Or one can consider designing and implementing a new Proton Driver to achieve this level of intensity.

2b. Short Term Modifications

We list here most of the modifications needed in the Short Term to address the demands and goals presented above. We include a short description of each and some of the issues which management should consider in making decisions to provide protons for the physics program.

The list is long, but it is indicative of what is needed. In the case of the Main Injector, the "Proton Team" (i.e., this committee) recognizes that these modifications must be integrated into modifications required for improvements for antiproton operation.

Short Term Highly Recommended Modifications and Activities

Here we list the modifications that the committee *highly* recommends be done as soon as possible. The urgency is based on the need to gain knowledge about the performance of the Booster and Main Injector so that further plans can be made sensibly.

Booster Collimators. This ongoing project is crucial for raising the number of protons delivered by the Booster. The purpose of the collimator is to control losses, and in doing so render obsolete the presently implemented administrative global limit (the so called "Watt-meter"). The committee strongly recommends this be completed as soon as possible.

Booster Dog Leg Rearrangement. This is needed to reduce Booster losses. Edge focusing effects in the dogleg magnets are responsible for significant distortions in the lattice. Beam measurements show that this effect is a main cause of losses today that limit the Booster intensity. Reducing the fields in these magnets led to a factor of two reduction in the uncontrolled losses in the Booster and allowed one of the major steps upward in the last six months for the MiniBooNE hourly proton rate. Much of the effect may be alleviated by this modification, and the committee strongly recommends this be completed as soon as possible. Moving the magnets further apart longitudinally along the beam line will compensate for the reduction in field.

Booster Installation of Two Wider Aperture RF Cavities. These wider aperture RF cavities replace the two most radioactive RF cavities in the Booster, and thus reduce the amount of radiation received by people performing regular maintenance on the RF power tubes adjacent to the cavities. These wider aperture RF cavities are being made in collaboration with MiniBooNE and MINOS collaborators. The committee strongly recommends these be installed as soon as possible.

Booster Cogging for Multibatch Transfers into the Main Injector. This is needed for Run II and NuMI. At present the Booster extracts a single batch with acceptable extraction losses by creating, at 400 MeV, a beam-free notch used by the extraction kicker at 8 GeV. At present there is a concept for how to transfer multiple Booster batches to the Main Injector by also creating a notch, cogging it in the Booster to where the Main Injector requires it for subsequent injections, and extracting it. This has been done for low intensity beam for which uncorrected pulse-to-pulse variations in the arrival of the notch at 8 GeV of up to two Booster turns is typical. This variation can be measured and corrected for by controlling the radial position for low intensity beams, but correcting these variations with high intensity beams is not possible without unacceptable beam losses during acceleration. If cogging cannot be made operational for high intensity multibatch transfers, or the source of the variations are not found and eliminated, then the extraction losses will have to be controlled in some other manner. Either that or the number of protons delivered to the Main Injector will not even approach the Mid Term demands of NuMI and Run II.

Main Injector Damper Systems. These are needed for Run II and NuMI. A new longitudinal damper is being developed to reduce the longitudinal emittance growth in the Main Injector, and its first use will be for antiproton stacking cycles. These dampers are essential to achieve NuMI's beam quality requirements. A set of transverse dampers will be needed to reduce the transverse growth of the proton beam at NuMI intensities. Longitudinal damper technology will be used to develop these transverse dampers. It is crucial to know as soon as possible whether the current plan for Main Injector dampers is adequate or whether additional dampers will be required. The committee strongly recommends that these dampers be completed and undergo beam testing at the highest intensity as soon as possible.

Main Injector Slip Stacking. This is required for Run II antiproton stacking. Slip stacking is the process where two Booster batches are stacked in longitudinal phase space and both end up where a single Booster batch would normally be found. In principle, one could nearly double the intensity of the Main Injector with this process. In early 2003, the achieved best performance was about a factor of six below the required intensity of 8E12; by mid-2003 the required intensity had been achieved at 8 GeV. It is expected that progress with this technique will be limited by the success of beam loading compensation systems and collective beam phenomena. Knowledge gained in making this technique operational will help determine how to implement some kind of stacking which will be required to exceed NuMI's initial demand of 2.5E13 protons per pulse. The committee strongly recommends that time and people be devoted to developing this technique as soon as possible.

Short Term Recommended Modifications and Activities

Here we list modifications that are to be pursued as soon as resources permit. However, the committee emphasizes that delays will have a negative impact on the physics program.

Booster Notch Creation Improvements. This is required to reduce the losses at Long 10 where the protons from the notch are deposited. At the present time, (ignoring 8 GeV losses from multibatch extraction with no notch) this is the limiting single point loss location in the Booster. Early in the Booster acceleration cycle, a vertical kicker is used to create a beam-free "notch" in the circulating beam, currently about 3 RF buckets (60 ns) long. Extraction is timed so that the position of this notch is at the extraction septum as the beam orbit is sweeping across it, thereby significantly reducing extraction losses. Even though this notch is created early in the cycle at low energy, its creation leads to one of the worst losses in terms of total energy lost, and in fact will be unacceptable at higher intensities. A number of schemes are being considered to ameliorate the situation, including:

- Shielding the area where the extracted beam hits and just living with the situation.
- Resonantly pinging the beam and extracting the protons from the creation of the notch at the collimator (this is the simplest method to implement).
- Creating the notch in the Linac, either at the ion source or with a laser by stripping the H-minus ions early in the Linac so they never make it to the Booster.

It should be noted that notch creation schemes in the Linac are not necessarily compatible with the low intensity beam cogging schemes for multibatch transfers to the Main Injector.

Booster Monitoring Software. This improves Booster operations for all physics programs. The Booster tune changes over a period of days, which apparently indicates that ramped devices are drifting. The monitoring software is expected to be an extremely valuable tool for understanding the observed tune changes. Although the existing accelerator control system has a fairly sophisticated alarms and limits system, it is designed primarily to monitor DC values. A great deal of time in the Booster is lost tracking problems which manifest themselves as deviations from nominal time-dependent behavior, in both ramped devices and beam measurements. For this reason, the Computing Division has been aiding in the development of a “ramp monitoring” system, which will automatically monitor a specified number of measurements throughout the Booster acceleration cycle, and alert the operators if significant deviations are seen. This project has been underway for some time and is nearly ready to be implemented in normal operation. It is expected this will greatly reduce the time needed to track down a large class of Booster problems.

Booster Radiation Protection. The Lab has a continuing need to reduce the radiation dose received by its employees, contractors and users. A rad worker robot, once successfully implemented and integrated into operations and maintenance, will reduce the radiation people absorb in performing routine radiation surveys. It will also enable ongoing calibrations and testing of the BLM system that will become the primary diagnostic for limiting losses and subsequent activation once the collimators are installed.

Booster to Main Injector 8 GeV Line Aperture Increase. This removes the tightest aperture restriction and loss point in the beam transfer line between the Booster and the Main Injector. The 8 GeV beam line from the Booster to the Main Injector utilizes permanent magnets over much of its length. At the Booster end, however, higher fields were required and available beam line magnets were used. These magnets were refurbished at modest cost as part of the Fermilab Main Injector project; however, their aperture is not as large as needed, especially in a region that is under-shielded and in close proximity to the west Booster tower office building. While personnel radiation protection is assured through the use of interlocked detectors, the tight magnet aperture is an unnecessary loss point.

Booster Upgraded Loss Monitors. These loss monitors will become the primary diagnostic for measuring and limiting the losses in the Booster. They will independently monitor the radiation along several segments of the Booster. They will replace the present global system (the so-called “Watt meter”) that is used to limit the Booster losses and is based on measuring the beam current in the Booster. Thus, it is insensitive to where the losses actually are, and it cannot distinguish uncontrolled losses from the controlled losses that will be done with the collimator. The committee notes these are needed as soon as the collimators are operational, and thus strongly recommends they be installed and become operational as soon as possible.

Main Injector Beam Loading Compensation. This is required for Run II antiproton stacking and NuMI. Cavity beam loading becomes increasingly important when the cavity voltage is low or the beam current is high. Further improvements to the beam loading compensation will be needed for slip stacking.

Main Injector Upgraded BPM System. This is needed for Run II, NuMI and for operational efficiency. The recently initiated Main Injector BPM upgrade will continue into 2004 due to budget and manpower limitations. This recently initiated upgrade is needed for the 2.5 MHz operation that is used for making coalesced beams for the Tevatron. The present BPMs in the Main Injector have considerable operational limitations primarily since they are based on a design for Main Ring fixed target operation in which the bunches were spaced at 53 MHz. This system can only measure beam positions for 30 to 420 bunches, whereas the Main Injector will hold 504 bunches for antiproton stacking and NuMI. The Main Injector also supports several modes of operation in a supercycle of the accelerator complex. Due to the buffer limitation in the present system, data from one acceleration cycle gets overwritten by the subsequent beam acceleration cycle. Consequently, considerable time is required to tune up the machine.

Main Injector Lattice Changes for NuMI Extraction. This is required for NuMI operation, but it is included in the Short Term because it will be needed for commissioning with lower intensity beam before NuMI turns on. NuMI extraction will require a distortion in the Main Injector closed orbit, and since the NuMI extraction point is located in the Main Injector RF section, one concern is synchro-betatron coupling. Many beam studies will be needed to make the NuMI high intensity operation reliable. The loss of beam at the extraction septum magnet is a concern due to its proximity to the Main Injector RF cavities. Possible modifications to the Main Injector lattice, larger aperture magnets etc., should be examined to reduce losses during the extraction process.

Main Injector Operation of NuMI and Antiproton Stacking In The Same Cycle. This will be required in order to meet the initial annual proton demands for MINOS and antiproton stacking. Although this mode of operation is not scheduled until the Mid Term, it will be wise to get started on it in the Short Term to find out what needs to actually be done to make it into an operationally smooth activity.

Short Term Modifications Needing More Information

Here we list modifications that are in conceptual development, or ones that simply need more information. The committee leaves to management the decisions on which to encourage because the available information is not sufficient for a clear recommendation. This is NOT a list of things the committee rejects. In order to be helpful, we have listed some of the information that management will need in making their decisions.

Linac Low Energy Replacement. This should be considered as an option for eliminating the vulnerability of the single vendor for the Linac tubes. However, it should also be considered by the Long Range Planning committee in the context of a New Proton Driver.

Booster Dog Leg Replacement. As noted above, the edge focusing effects in the dogleg magnets are responsible for distortions in the lattice, which cause the most significant beam loss in the Booster at the moment. Much of the effect may be alleviated by the Booster dogleg rearrangement. Nevertheless, the concept and design of a replacement should be pursued along with cost estimates. Large M&S

expenditures should wait until the gains from the Booster dogleg rearrangement are demonstrated and understood.

Booster Replacement of Remaining RF Cavities. After the two larger aperture RF cavities are installed, it is an open question as to whether the remaining RF cavities should also be replaced. It is possible that the collimator for the Booster will reduce the radiation levels in the RF cavities to acceptable levels. The beam physics models are not good enough to predict what will happen in detail. This modification is estimated to cost several M$'s. Thus, it seems prudent to wait until it is clearer that this modification will do some good.

Booster Replacement of High Power RF System. The RF power tubes for the Booster are located adjacent to the RF cavities in the beam enclosure. These tubes require regular maintenance and the people who do the work receive radiation from the cavities and other nearby components. The replacement system has these design features: 1) It would not have high maintenance tubes, 2) The equipment that does require regular maintenance would be moved out of the beam enclosure as much as possible, 3) The replacement system would use more reliable solid state components which would not be located in the beam enclosure, and 4) Replacement parts for the system would be more available since the system would be modern. Although this modification is estimated to cost about $10M, a cost benefit analysis may indicate the replacement system would easily pay for itself by the end of the decade if it were started in the next year or so. Before a decision is made to support this modification, the amount of downtime needed to install the system must be evaluated.

Main Injector Aperture Increase. The Main Injector is designed to have an aperture of 40-pi mm-mr. The quadrupole and Lambertson magnets placed in the lattice for injection and extraction of the beam are currently limiting the apertures and are a cause of beam loss. A calculation effort is underway with the goal of proposing improvements to these magnet apertures. A total of 12 larger aperture Lambertson and 4 quadrupole magnets could be required.

Main Injector Mixed Mode E907 and Antiproton Stacking. This method increases the amount of beam for E907, and is presented as an alternative to the present plan presented above. A Main Injector cycle with E907 alone would put a single Booster batch into the Main Injector, ramp it to 120 GeV and extract it over about a second. A pinhole collimator in the external beam area will be used to reduce the intensity to the few x E9 that E907 requires. The majority of the beam (1E12 or so) is dumped. Another scenario has been suggested [10] in which E907 would receive a factor of several more beam per hour, and very little beam would be dumped. In this scenario, two batches are put in the Main Injector, and ramped to 120 GeV. One batch is sent to the Antiproton target, and a small fraction of the second batch is resonantly extracted to E907 over a time interval of a few seconds. At the end of the interval, resonant extraction is turned off, and the remainder of the second batch is sent to the Antiproton target. Thus, the time interval between the two extractions to the Antiproton target sets the time during which the Main Injector is at flattop and delivering beam to E907. (The actual time would be a little smaller, but the basic idea is the same.) Low intensity beam studies show that this scenario might just work [10]. However, operation of the Main Injector becomes more complicated. Also, Program Planning might be able to allocate sufficient time to E907 to meet its demands with the present plan.

Main Injector Radiation Protection. As the beam throughput - and consequent beam losses - increases, better protection for people doing maintenance on the equipment in the beam enclosures will be required. This will have to be continued in the Mid Term and Long Term. One particular concern is due to the fact that resonant extraction is by its nature a lossy process. Also, conventional machines such as the Main Injector are notorious for creating losses during resonant extraction.

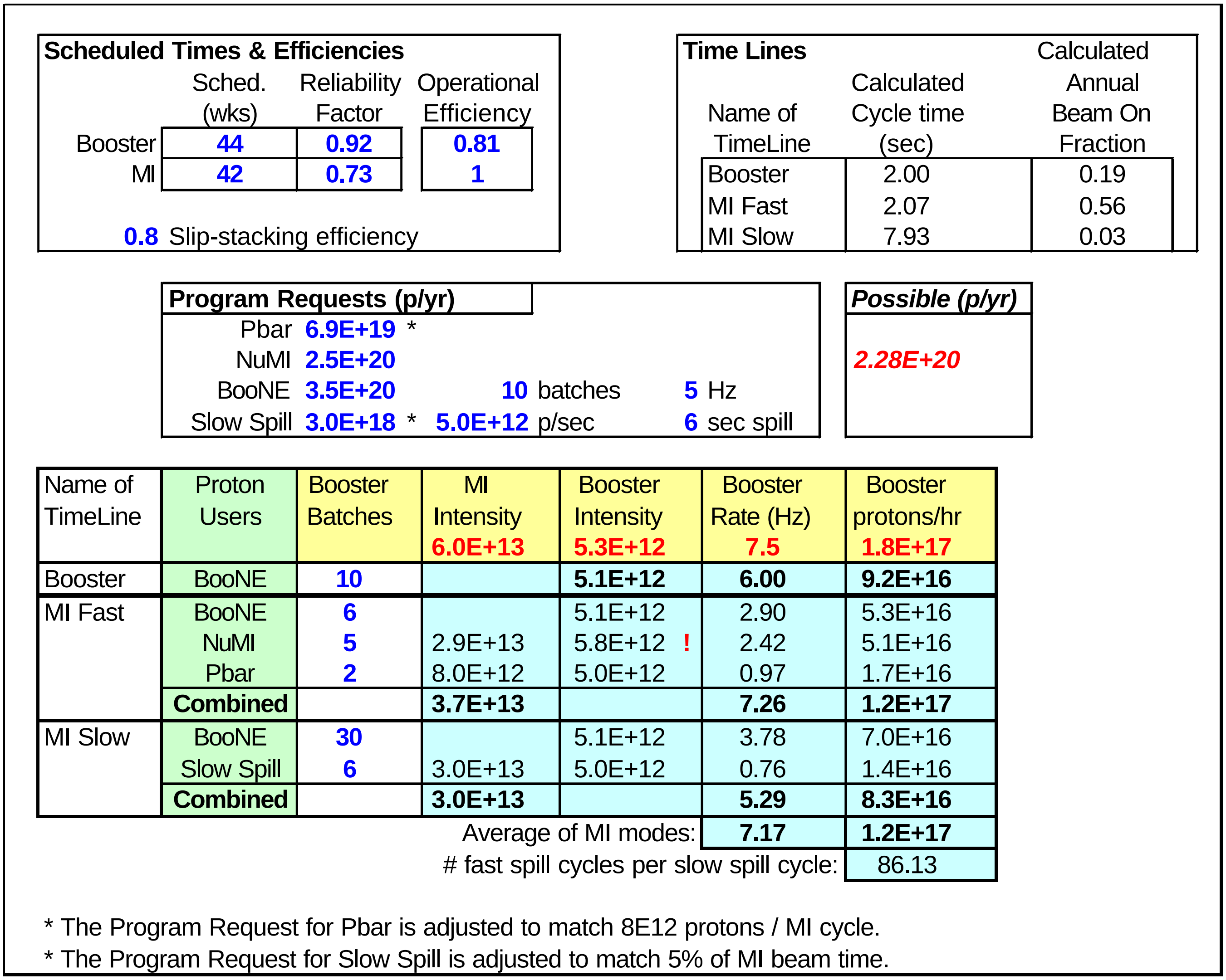
Main Injector Beam Loss Control. A collimator system to control losses in the Main Injector should be considered, perhaps similar to the one in the Booster. This will likely be required as the total beam throughput in the Main Injector continues to increase. Appropriately placed collimators can also help to control losses from resonant extraction.

Main Injector Fast Proton Stacking. This will be needed as the demands of MINOS increase beyond the initial demand. High intensity operation of the Main Injector for MINOS will require some means of stacking Booster batches. Also, stacking higher intensity protons for antiproton production may be possible using alternatives to slip stacking. These alternatives includes development of concepts such as RF “barrier bucket” stacking and “fast stacking” considered for the Recycler, as well as fast slip stacking similar to that needed for antiproton stacking cycles. R&D should go on in the Short Term, but implementation will likely not happen until the Mid Term.

3. Mid Term: Through E906 and CKM Turn On

This period starts with NuMI turn on and extends until E906 and CKM are running. Table 3a shows the goals that can be reasonably set for the Mid Term.

The committee notes that it is assumed that several operational schemes will be commissioned early in the Mid Term, because they are crucial for meeting the demands for Run II and NuMI. Multibatch transfers from the Booster to the Main Injector with acceptable Booster losses need to be demonstrated. Table 3a sets the Booster hourly throughput to the shielding assessment value of 1.8E17 protons per hour; this assumes significant progress on handling beam loss. Slip stacking needs to be demonstrated to work operationally at high intensity. The Main Injector needs to demonstrate the simultaneous achievement of intensity and emittances required for extraction to the NuMI beamline. Work on all of these must be started in the Short Term.



Scheduled Times & Efficiencies

	Sched. (wks)	Reliability Factor	Operational Efficiency
Booster	**44**	**0.92**	**0.81**
MI	**42**	**0.73**	**1**

0.8 Slip-stacking efficiency

Time Lines

Name of TimeLine	Calculated Cycle time (sec)	Calculated Annual Beam On Fraction
Booster	2.00	0.19
MI Fast	2.07	0.56
MI Slow	7.93	0.03

Program Requests (p/yr)

Pbar	**6.9E+19**	*				
NuMI	**2.5E+20**					
BooNE	**3.5E+20**		**10**	batches	**5**	Hz
Slow Spill	**3.0E+18**	*	**5.0E+12**	p/sec	**6**	sec spill

Possible (p/yr)

2.28E+20

Name of TimeLine	Proton Users	Booster Batches	MI Intensity **6.0E+13**	Booster Intensity **5.3E+12**	Booster Rate (Hz) **7.5**	Booster protons/hr **1.8E+17**
Booster	BooNE	**10**		**5.1E+12**	**6.00**	**9.2E+16**
MI Fast	BooNE	**6**		5.1E+12	2.90	5.3E+16
	NuMI	**5**	2.9E+13	5.8E+12 !	2.42	5.1E+16
	Pbar	**2**	8.0E+12	5.0E+12	0.97	1.7E+16
	Combined		**3.7E+13**		**7.26**	**1.2E+17**
MI Slow	BooNE	**30**		5.1E+12	3.78	7.0E+16
	Slow Spill	**6**	3.0E+13	5.0E+12	0.76	1.4E+16
	Combined		**3.0E+13**		**5.29**	**8.3E+16**
				Average of MI modes:	**7.17**	**1.2E+17**
				# fast spill cycles per slow spill cycle:		86.13

* The Program Request for Pbar is adjusted to match 8E12 protons / MI cycle.

* The Program Request for Slow Spill is adjusted to match 5% of MI beam time.

Table 3a. Mid Term goals.

Assuming the Mid Term goals are met, several other issues are expected to become important regarding proton intensity as this term develops. These will likely include the following:

- Increasing the protons per pulse from the Booster and continued reduction and control of losses.
- Keeping the cycle time of the Antiproton Source as small as possible, hopefully close to 2 seconds.
- Developing the operational ability of the Main Injector to handle intensities beyond 3.6E13 per pulse, which would result from a successful implementation of fast slip stacking for NuMI.

The committee endorses continued efforts to increase the Booster protons per pulse beyond 5.3E12 protons per pulse, in order to lay the groundwork for more margin for successful NuMI running, and better antiproton production. Increased protons per pulse could help make up for other operational needs such as the Antiproton Source cycle time and time for Meson 120. It is clear that more antiprotons can be produced if the Antiproton Source can be cycled more rapidly. However, because the Main Injector cycle time will be tied to that of the Antiproton Source, the number of protons that can be delivered to NuMI will also depend on the Antiproton Source cycle time. Hence, it is also crucial for NuMI that the planned upgrades for Run II, permitting a 2 second cycle time, are successfully completed.

3a. Mid Term Demands

This time frame will consist of running the Collider for CDF and D0, running the NuMI beamline for MINOS, running the Main Injector for slow-spill extraction experiments and test beams, and possibly an extension of MiniBooNE. Although preparations for E906, CKM and BTeV are also required, these experiments are not expected to be ready for any large-scale use of protons in this time frame. The primary focus of accelerator work in this timeframe will be the ongoing improvements to Run II luminosity and increasing the proton intensity delivered to the NuMI beamline.

3a.1 Collider + NuMI + Meson120

All of these programs depend on protons accelerated through the Main Injector. The most common mode of operation will be Main Injector cycles that will simultaneously accelerate protons to 120 GeV for antiproton production and for NuMI.

The Run II plan for antiproton production calls for two batches of at least 4E12 Booster protons to be slip-stacked in the Main Injector into a single batch of 8E12 and delivered to the antiproton target with a Main Injector cycle time of 2 seconds. It is hoped that the intensity can eventually be increased to a total of 10E12 protons. This will depend on the ability to successfully address beam loading issues during slip stacking in the Main Injector. Likewise, the exact Antiproton Source cycle time depends on the successful completion of several Run II upgrade plans. If everything works very well, it is possible that the Antiproton Source cycle time will be limited by the total time it takes to fill the Main Injector with protons from the Booster combined with the Main Injector ramp time. On the other hand, if some of the Run II antiproton upgrades do not work as well as expected, the Antiproton Source cycle time, and hence the Main Injector cycle time, and hence the NuMI cycle time will have to be >2 seconds, perhaps as high as 2.5 seconds on average. The most critical Run II upgrades from this perspective are the Debuncher cycle rate capability, electron cooling in the Recycler, and a stacktail upgrade in the Accumulator.

The demand for protons to the NuMI target is determined by the needs of MINOS. The nominal plan delivers 2.5E20 120 GeV protons per year of operation for MINOS starting in April 2005 and continuing through April 2009, for a total of 10E20 protons delivered. This number of protons per year can be delivered by injecting five batches of Booster protons, each with 5E12 protons, into the Main Injector every 2 seconds, accelerating to 120 GeV and then repeating this cycle for a total of 2E7 seconds per year. Of course, there are several factors which can reduce this total number of protons, including issues of the Antiproton Source cycle time, time required for antiproton transfers during shot setup for the Collider and transfers to the Recycler from the Accumulator, time spent running Meson 120, difficulties accelerating this total number of protons and other downtimes of the accelerator complex and beamline which may result in less than 2E7 seconds of operation per year. One possible result is that fewer total protons will be delivered in the planned four-year running period. We note that previously published physics sensitivity plots for MINOS have been based on a total of 7.4E20 protons on target, an approximate match to the running scenario stated here taking some account of realistic reduction factors.

The MINOS Collaboration has made a formal request to Fermilab for more protons to be delivered in this period than the nominal plan described above. Rather than the nominal 10E20 protons in four years of running the request is expected to be for 25E20 protons in five years of running. The request is based on an improved sensitivity for all of the physics measurements (all are statistics limited) but with particular emphasis on the energy dependence of the disappearance of ν_μ CC events, the associated measurement of the oscillation parameters, and discovery potential for ν_e appearance. The addition of one extra year of running compared to the nominal plan can boost the expected number of protons to roughly 9.5E20. However, it is clear that to deliver any significantly larger number of protons will require both some qualitative and quantitative improvements in providing protons for NuMI. The major assumptions on which the MINOS request is based are:

- Increased protons per pulse (cycle) from the Booster
- Stacking of batches of Booster protons into the Main Injector for NuMI, perhaps similar to that planned for antiproton production
- Reduction of the Main Injector cycle time either by reducing the ramp time or elimination of the filling time at 8 GeV [11], or both.
- Ability of the Main Injector to accommodate up to 6E13 protons per cycle.

During this period Program Planning will set the allotment of time among slow-spill for Meson120, the 120 GeV Neutrino program, and the Collider's need for antiproton stacking. The main technical requirement for Meson120 is the establishment of resonant extraction with acceptable losses. The spill length can be as long as 6 seconds.

3a.2 Collider + NuMI + MiniBooNE + Meson120

The schedule shows the Booster Neutrino beamline as "Open" starting in 2005. The MiniBooNE Collaboration is expected to request running with antineutrinos during this time; the request is expected to be for a total of 1E21 protons during 2005 and 2006. Also, should MiniBooNE not have completed its neutrino run with 1E21 protons on target by the time NuMI turns on, it is expected to request to continue to run until that program is complete.

Early in the Mid Term, it is expected to be technically possible for the Booster to simultaneously satisfy Run II antiproton stacking, NuMI, Meson120 as well as some level of MiniBooNE running. An example of this scenario was shown in Table 3a, and here we discuss the limits of this scenario. MiniBooNE would continue to receive pulses while the Main Injector is ramping. Although the MiniBooNE horn is limited to 5 Hz maximum operation, this rate will not be possible continuously in this period due to Booster equipment limitations. (Primarily the ORBUMP system and the cooling for the RF.) In 2005, the Main Injector's highest demand will require 7 batches of Booster protons every 2 seconds (3.5 Hz average maximum). Two batches will be required for antiproton production and five batches will be required for NuMI. However, the 2 second cycle time is only possible when the antiproton stack is small, since the Antiproton Source will require a longer Main Injector cycle time (up to about 3 seconds) until electron cooling is operational in the Recycler. If MiniBooNE were to receive 5 Hz when the Main Injector cycle time is 2 seconds, the total maximum Booster acceleration rate would be 8.5 Hz. In addition, some of the Booster equipment requires two beam-free "prepulses", giving a total of 9.5 Hz for some of the equipment. The Booster equipment at present is limited to 7.5 Hz. Thus, MiniBooNE would be limited to about 3 Hz when the Main Injector cycle time is 2 seconds, and to about 4.5 Hz when the Main Injector cycle time is 3 seconds. Table 3a demonstrates the 7.5 Hz limitation by limiting MiniBooNE to only 6 batches when the Main Injector is cycling at 2.07 seconds, and restricts MiniBooNE to its own 5 Hz limitation the rest of the time.

However, later in the Mid Term the demand for protons for the Main Injector still will require 2 batches slip-stacked for antiproton production but the demand will go up to 8 batches to be fast-stacked for NuMI. This is a total of 10 Booster batches every ~2.2 seconds (~4.5 Hz average), and the Main Injector cycle time is no longer assumed to increase because electron cooling is assumed to be operational in the Recycler. In this case, about 1 Hz will be available for MiniBooNE if the Booster equipment remains limited to 7.5 Hz. If a physics case can be made for experiments in the 8 GeV Neutrino beamline, then the Lab could consider going beyond the 7.5 Hz limitation. The recommendations of the Long Range Planning committee would also be part of the considerations.

Finally, we note that proton losses must be adequately controlled in any of these running conditions. A final note is that MiniBooNE personnel contribute to keeping the Booster running smoothly and their ongoing involvement during NuMI running may prove beneficial.

3a.3. Preparing for Protons Beyond 9/08

The issues for running in the Long Term are described in Section 4. However, some of the tasks to be undertaken in that time frame require substantial planning, and a decision process in the Mid Term is required. A good example is decreasing the Main

Injector ramp time. This would require substantial investment in magnet and RF power. It is apparent that essential decisions would need to be taken during the Mid Term to accomplish this in the Long Term. An ongoing evaluation process will be an important part of the decision process. (More will be said about this in the Organization section.)

3b. Mid Term Modifications

Here we list the modifications needed for the Mid Term.

Mid Term Recommended Modifications and Activities

Booster Dampers. These will be needed as the Booster intensity is increased, and will be required to control the longitudinal phase space for proton stacking in the Main Injector. These dampers control phase space oscillations, which if left unchecked, lead to emittance growth and probable beam loss. These dampers should provide lower losses for higher intensity batches. Although this is thought to be necessary to develop a contingency for NuMI's intensity demands, it might turn out to be crucial for proton stacking as well. The Booster currently employs a longitudinal damping system to damp coupled-bunch oscillations. This is a mode-based system, which detects individual resonance lines and feeds a damping signal to a dedicated cavity. The philosophy is sound, but the system suffers from power limitations, as well as maintenance and scalability problems. A new system is being designed which will be easier to expand and to maintain, and eventually adding a second solid state amplifier will increase damping power.

Booster Gamma-t Jump Recommissioning. This will be needed as the Booster intensity increases. This allows beam to pass more rapidly through the transition energy, where the inevitable push for higher intensity typically leads to beam loss. This should allow for lower losses for higher intensity batches. This is part of developing a contingency for NuMI's intensity demands, but most other programs will also benefit from it. The Booster already includes a pulsed quadrupole "gamma-t" system to preserve longitudinal emittance through transition. The system has been demonstrated to work, but is not currently used, both because of alignment problems and because the reduced longitudinal emittance actually exacerbates the coupled-bunch problems after transition. There is a plan to recommission the system, in the hopes of reducing post-transition losses, as intensity increases require it.

Main Injector Hardware Beam Permit For NuMI. This is required to commission the NuMI beam to assure the beam losses in the NuMI beam line are acceptable. Thus, this modification should be completed in the Short Term.

Mid Term Modifications Needing More Information

Booster Repetition Rate in Excess of 7.5 Hz. This could enable additional running in the Booster Neutrino beam line even as NuMI demands more Booster beam cycles, or it could be used to help satisfy NuMI once the Main Injector cycle time decreases significantly. Primarily this requires the replacement of the ORBUMP magnets (used for injection into the Booster) and refurbishing the RF cooling system.

4. Long Term: Protons Beyond September 2008

4a. Long Term Demands

The schedule shown in Figure Ib calls for the physics program to undergo important transitions in the period 2008-2010, especially with regard to proton demands.

- In 2008 BTeV starts commissioning as CDF and D0 enter their final year.
- E906 is commissioning in 2008 and CKM is commissioning in 2009.
- MINOS finishes in 2009.

If these were to take place as stated, then there would be a transient crunch for protons while all three programs were running: Collider, 120 GeV Neutrinos, and Meson120. However by late 2009, proton demands would drop to less than pre-MiniBooNE levels. And the present Linac, Booster and Main Injector could likely provide for the demands.

However, the committee added a few assumptions full well knowing that the Long Range Planning committee may or may not make similar assumptions. In addition, the PAC and the Director may or may not approve the physics program implied by these assumptions. But these assumptions do serve to focus on a potential proton crunch that derives from using the Main Injector to run the three physics programs at the same time: Collider, 120 GeV Neutrinos, and Meson120. These assumptions are:

- The Collider program, in serving BTeV, will continue to demand protons for antiproton stacking at a level no less than CDF and D0 in the Mid Term.
- CKM and E906 require a slow spill, and thus it is assumed that whatever time the Main Injector is at 120 GeV providing slow spill will reduce the time available for antiproton stacking and the 120 GeV Neutrino program. Ideally, the Main Injector would remain at 120 GeV for six seconds during this slow spill [12].
- MINOS has recently submitted a request for running which will extend into 2010. Also, several new experiments are under consideration for the NuMI beamline. The main experiment in terms of proton demands is a new off-axis, long-baseline experiment. The LOI for this experiment has assumed at least 4E20 protons per year of operation, and a higher number of protons per year will certainly be

useable (assuming the NuMI beam line can be made to handle it). Already the experiment is proposing a rather large 40 kT far detector, but it may be sensible to invest some fraction of the cost of this new experiment in proton intensity from the Main Injector. A working assumption for the ultimate demand is the same as the demand for the final year of MINOS running, namely 7.2E20 protons per year. In addition to the long-baseline experiments, three new short-baseline experiments are under consideration for high-statistics measurements of neutrino cross-sections and related physics in the NuMI near detector hall. A 120 GeV Neutrino program such as this will certainly increase the demands for protons, possibly beyond what the present arrangement of Linac, Booster and Main Injector can provide.

- The committee notes that the ability to supply 8 GeV beam directly to experiments should be maintained in the Long Term because this allows the Lab to respond to new physics proposals. For example, FINeSSE is considering a measurement of the strange content of the nucleon and neutrino cross-sections in the present 8 GeV MiniBooNE beamline. Also, should MiniBooNE confirm the LSND oscillation signal, it is very likely that a follow-up experiment (BooNE) to provide more precision in the oscillations measurements will be of great interest and the Lab will very likely make use of the beamline.
- If the Main Injector eventually becomes capable of satisfying the demands of a 120 GeV Neutrino program, it could easily use up the 7.5 Hz capacity of the present Booster for delivering beam. One can imagine going beyond this to the 15 Hz capacity of the Linac and upgrading the Booster to accept the additional protons, including methods for further reducing and controlling losses. One would consider this if the Main Injector is not in fact a bottleneck for accepting 8 GeV protons, and/or an 8 GeV Neutrino physics program is required.

Finally, as the Fermilab physics program actually shifts from being dominated by the Collider program to the Collider sharing with Neutrino programs based on beamlines driven by the Main Injector and Booster, and both of these sharing with the Meson120 program based on beamlines driven by the Main Injector, it will become increasingly important to invest wisely in these machines. In particular, the Neutrino programs will directly benefit from higher beam intensities per pulse as well as higher beam pulse repetition rates. The nominal demand of the 120 GeV Neutrino program could easily require ~1 MW of beam power by 2010. Indeed, in the time frame beyond the charge of this committee (beyond 2010), but within that of the Long Range Planning committee, the existence of a New Proton Source - a replacement of the Linac and Booster – could very easily be essential for the future physics program at Fermilab. It should be apparent that modifications increasing the capabilities of the Main Injector, such as handling higher beam intensities and decreasing ramp time, must be done in a manner that will be consistent with the recommendations of the Long Range Planning Committee.

4b. Long Term Modifications

Here we list the modifications that are likely needed to meet the proton demands in the Long Term. They are fewer in number than the Short Term and Mid Term because most modifications considered by the committee are required in order to finish the Mid Term successfully.

Long Term Recommended Modifications and Activities

Main Injector Debunched Resonant Extraction. This is required for CKM [12] and must be done in a way that preserves the information from the beam diagnostics. In addition, CKM requires a 6 second 120 GeV slow spill. A recent study indicates this should not be a problem [8]. The total amount of slow spill time CKM requires for its physics goals will clearly require Program Planning to balance this Meson120 program with the Collider and the Neutrino programs.

Long Term Modifications Needing More Information

Faster Main Injector Ramp. Increasing the Main Injector ramp rate can obviously increase the number of protons per hour delivered by the Main Injector for the 120 GeV Neutrino Program. An ongoing recent study, if demonstrated to be technically feasible, shows the Main Injector ramp time can be reduced from the current 1.5 sec to 1 second, or perhaps less. This modification requires both more RF power and more magnet power supplies. This will provide more protons per year to the 120 GeV Neutrino Program as long as antiproton stacking for Run II does not slow the Main Injector cycle time down. It appears to be a relatively low risk approach to getting more protons per year in that it requires engineering development to get more cycles per year rather than the beam physics R&D that is needed to get more protons per cycle. This modification alone is expected to cost a few $10M's. A decision on this must fold in with the recommendations of the Long Range Planning committee, since ideally a new Proton Driver would also make use of this modification.

5. Collaboration and Organization

5a. Collaboration

Collaboration divides into three types: within the Lab, with members of the accelerator physics community outside Fermilab, and with the Fermilab's HEP users. We recommend that the Director appoint a senior member of the Lab to investigate methods of facilitating collaboration. In particular, we hope that those who have had substantial experience with collaboration will be interviewed to understand what works and what does not. Subsequently, it might make sense for the Director or the Beams Division Head to appoint an ombudsperson, or other staff position, to assure that appropriate collaboration resources will indeed be brought to bear on activities that will increase the performance of the accelerators for the benefit of the collaborators.

The committee offers the following as input to this process.

By all accounts, the accelerator departments that must carry out work for increased proton intensity have fewer people than are required to carry out all of the work necessary to meet the experiments' demands. Of course, one way to address this is to add people to these groups via hiring, and the committee strongly recommends that such hiring be a high priority of the laboratory. Although this is perhaps the most direct solution, on its own it may not represent a complete or most optimal solution in terms of achieving the necessary work for a particular cost. Collaboration with other Fermilab and outside institutions can offer:

- Additional people and infrastructure resources to carry out work in parallel.
- Lower personnel costs.
- Advantageous purchase and fabrication policies.
- Additional particle physicist intellectual involvement in accelerator issues.

Although still a very small part of the total accelerator activity, important examples of such collaboration have already been underway in the last few years. The examples listed here are familiar to most of the committee members; there are certainly others.

- MiniBooNE has had collaborators working together with Booster staff on several projects such as quadrupole correctors, wider-aperture RF cavities, and better monitoring software.
- MINOS has had Fermilab and non-Fermilab collaborators working on proton intensity and plans to continue to increase the number of people involved as the MINOS detector construction is completed. Some of the projects that have been addressed or are being addressed include Main Injector beam characterization, Main Injector multibatch operation, Booster wider aperture RF cavities, Linac steering, and Main Injector dampers.

Detector Collaboration Tools

For construction of detectors, Fermilab has a very well established history and protocol for collaboration with various outside institutions that permit effective collaboration. To a first approximation, there is little history of this type of collaboration with the Beams Division. Understandably, few "collaboration tools" currently exist within Beams Division, but the committee believes that this is a crucial issue that should be addressed. Important examples of such collaboration tools are:

- Involvement in the management process. This can take several possible forms:
    - A "Proton Intensity" Strategy Board: This is a group of Beams Division managers and senior collaborators who meet regularly to discuss the status of various projects and appropriate management response to the challenges presented. Ideally, such a board will find consensus on actions to be taken; but when necessary, Fermilab managers may have to simply make difficult decisions after consulting with the Board.
    - Involvement of collaborators in line management positions. This is routine within detector construction projects. Even a very few "high level" managers can make a very big difference in the effectiveness of collaboration.
    - A senior manager within Beams Division specifically charged to assure that collaboration is effective. One natural position for this responsibility is the Deputy Head of the Beams Division.
- Clear definitions of tasks to permit as much outside ownership of responsibility as possible.
- Deliberate and transparent management processes which permit collaborators to understand that management decisions have been taken fairly and for optimum technical and cost reasons.
- Assignment of responsibility for complete sub-systems, possibly using Memoranda of Understanding (MOUs) and Statements of Work (SOWs), outside of Fermilab with Fermilab holding management oversight responsibility.

Arranging For Collaborations To Succeed

Beyond the tools required for such collaboration, it is essential that Fermilab personnel at all responsibility levels at least accept and ideally embrace the concept of collaboration. The current level of collaboration with accelerator groups might best be referred to as "primordial/developing". Over the last couple of years, there have been some examples of successful, satisfactory collaboration. But even in these cases there have been substantial barriers to overcome in development of the collaboration. In other cases, collaboration has been a complete failure due to a complicated collection of reasons. However, in most such cases the outside collaborators have come away with an impression (at least) of hostility towards such collaboration at several levels of responsibility. The success of future collaboration will require that the Beams Division both adopt the essential tools to permit effective collaboration and that there be a commitment to such collaboration at all levels within the Division. Such a commitment must originate with the Director and follow an unbroken chain to those doing "hands-on" work. It is the finding of the committee that this is not clearly the case at the present time, or if so it is not clear to everyone within that chain that this is in fact the expectation. If necessary, changes in management responsibility should be effected to accomplish a clearly unbroken chain of commitment to collaboration.

On the part of outside collaborators, it must be realized that machine improvement projects are rather similar to detector construction projects. They both take years rather than weeks or months to plan and carry out. Although relatively short-term collaborators can make some contributions, a far more effective model for collaboration will be substantial involvement of time and resources over an extended period of time. It is important to note that most physicists available for collaboration on Beams Division projects are “particle physicists” rather than “accelerator physicists”. Although it is generally understood what these two terms mean, we find the distinction unnecessary and actually destructive to a healthy collaboration process. Particle physicists are not without interest in the technical issues in the accelerator complex, but understandably their primary motivation comes from the desire to have successful experiments. In order to do this, such physicists must devote time and effort to activities other than just work on accelerator issues full time. This is generally not the way that most “accelerator physicists” within Beams Division work however, and the expectation can be that unless collaborators are prepared to also work in this way that nothing useful can be done.

We believe that on average there is currently too much separation between many Beams Division physicists and particle physics experiments. Nevertheless, the committee notes that experiments having substantial Beams Division participation from the outset have benefited greatly in their development of rational beam delivery programs. Beams Division and Technical Division management should encourage its physicists to join experiments as full-fledged collaborators from the time of Letter of Intent. Similarly, we recommend that the Director encourage nascent experiments to seek Beams Division and Technical Division collaborators as active and full members. Experiments are interested in getting the protons they need and are likely to warmly welcome such explicit participation. The lower the barrier between “particle physics” and “accelerator physics”, the easier collaborations will become, and the more the Fermilab physics program will thrive.

There are a few final points that we think are important to call out to help encourage collaboration. First, it must be realized that projects to be undertaken must have some intellectual interest for outside collaborators, not just tasks to be mindlessly carried out. This requires packaging work in relatively complete subsystems as much as possible and then “giving responsibility” to the collaborators. The second thing is that institutions outside Fermilab will generally not have their own funds to cover the costs of material purchase and fabrication. Rather, they have funds that are to be directed for the best use of carrying out their specific projects, and these funds are primarily to be allocated towards salary and travel for physicists and students within the groups. It is important that Beams Division personnel understand these issues and work together with collaborators to identify tasks that will be a good fit for collaboration.

5b. Organization

Planning for delivering the proton intensities needed for the Fermilab physics program is important and complicated. It will be similar in many respects to the planning and organizing currently underway for increased collider luminosity. Each requires coordinated efforts across several Beams Division departments and interactions outside Beams Division in order to produce a unified effort.

The Director or the Beams Division Head should seriously consider appointing an individual responsible for and with the authority to develop the proton intensity plan and coordinate the efforts required to prepare for and deliver the required intensity. The plan must be fully integrated with all Beams Division efforts and thus some authority must derive from Beams Division Headquarters. This individual will also need to work especially closely with the Directorate, especially Program Planning, and/or the spokespersons of experiments to determine what proton demands are needed, and when. Finally the individual needs to have sufficient authority to work effectively with people in the Computing, Particle Physics and Technical Divisions, and the Sections. These planning efforts should begin in the very near future. The position this individual holds could also eventually become responsible for Run II as well, and thus all beam operation and supporting projects would be integrated under one person.

Also, the laboratory should consider establishing a PMG-level standing committee for oversight and coordination of the proton intensity effort. This lab-wide oversight should begin soon after the establishment of the planning process. However, some caution is in order here, because PMG's usually have spokespersons from all interested experiments; and in this case that would be a lot of people. Some thought should be given to whether such a PMG would become unwieldy and thus ineffective.

The committee recommends that there be a permanent group whose job is to perform impartial technical evaluations of ideas for improving the accelerators. This group's purview should not be limited to "protons only", but it should include all ideas that can improve the performance of the accelerators. The members of this group should include physicists and engineers (as appropriate) from within and outside the Beams Division. The point of this group is to help to promote ideas fairly, so that the best technical ideas survive. The group would deal with ideas at varying levels of completeness, but nevertheless it will try to assure that all the associated technical complications have been identified and considered. Once such a group is effective technically and supported by management, it should be able to provide credible input for management to bring the best ideas into reality most efficiently.

Finally, the committee suggests that a group be formed to nurture and develop ideas in addition to evaluating them. This group could be a natural connection to help get collaborations started with initial idea processing, and it could provide a natural place to educate people in accelerator physics.

6. Summary

Here we summarize the information given above.

The combined capability of the present Linac, Booster and Main Injector cannot meet the proton demands expected by the end of the decade, especially the demands of the 120 GeV Neutrino program. Nor can they meet the demands expected by the beginning of 2005. Technical modifications as well as organizational changes are required in order to come closer to meeting the proton demands. The most important organizational change will fully integrate the demands of the overall physics program, will not be limited to "protons only", and thus will incorporate Collider, Neutrinos, and Meson120. The demands for protons by the Collider program and the 8 GeV Neutrino program can be met if several modifications are implemented. The demands for the 120 GeV Neutrino program require an ongoing series of modifications. All of these modifications are challenging, some depend on the success of previous modifications, and the 120 GeV Neutrino program benefits from the modifications initially implemented for the 8 GeV Neutrino program. Together these modifications will require a few $10M's. The demands of Meson120 are primarily for time, rather than for large increases in protons, and these demands appear to be capable of being handled by Program Planning. The Linac tube problem has to be addressed in any case.

Summary of Technical Matters

1. First, the committee notes that the reliance of the Linac on a single vendor for the 5MW 7835 power tubes represents a significant vulnerability that may result in no protons at all for Fermilab for an unacceptably long period, and the Lab obviously has to mitigate this vulnerability.

2. The committee recommends the following be done as soon as possible.

   In the Booster to reduce or control losses:
   - Install the collimators and make them operational.
   - Rearrange the Long 3 extraction region.
   - Install two wider aperture RF cavities.
   - Develop and implement notching and cogging for multibatch transfers.

   In the Main Injector to increase intensity and control beam quality:
   - Fully develop the damper system.
   - Implement slip stacking.

3. Insufficient control of radiation in the Booster is expected to continue to be the primary limitation on its performance, and control of radiation in the Main Injector is expected to become a limitation with or without a new Proton Driver. Either the Beams Division arranges to overcome these radiation limitations, or better

understands the actual limitations and consequently redefines what is acceptable, or those parts of the physics program demanding more and more protons will continue to be limited.

4. Run II, NuMI, Meson120 and MiniBooNE can run at the same time assuming the Booster losses are reduced or controlled by a combined factor of almost three better than today. However, if the Booster remains limited to 7.5 Hz operation (including 2 prepulses), and Run II and NuMI receive their demands of 1 Hz and 2.5 Hz respectively in a combined 2 second Main Injector cycle time, then MiniBooNE will be limited to receiving beam at a rate of 3 Hz instead of its maximum of 5 Hz. For a Main Injector cycle time of 3 seconds, MiniBooNE would be limited to 4.5 Hz.

5. Proton stacking in the Main Injector is required for Run II and the later stages of MINOS. Slip stacking appears to be the best hope for meeting the Run II proton intensity demand for antiproton stacking of 8E12 protons per pulse. Fast stacking of some kind appears to be the best hope for meeting the MINOS proton intensity demands beyond the initial value of 2.5E13 protons per pulse. In the spring of 2003, the performance of slip stacking was about a factor of six too low for Run II, and fast stacking had not yet been attempted. Subsequent to the June PAC, studies for slip stacking met the Run II intensity requirement at 8 GeV. Additional time will be needed to develop proton stacking into an operational technique, or Run II will continue to be limited by the Booster intensity level to about 5.3E12 protons per pulse for antiproton stacking, and MINOS will be limited to its initial demand.

6. Multibatch transfers between the Booster and the Main Injector are demanded both by Run II (two batches starting in 2004) and NuMI (five batches starting in 2005). At present the Booster extracts a single batch with acceptable losses by creating a beam-free notch at 400 MeV that is then used for the extraction kicker at 8 GeV. At present there is a concept for how to transfer multiple Booster batches to the Main Injector by creating a notch, cogging it in the Booster to where the Main Injector requires it, and extracting it. This has been done for low intensity beam in which uncorrected pulse-to-pulse variations in the arrival of the notch of up to two Booster turns can be accommodated by controlling the radial position. However, correcting these variations with high intensity beam is very likely not possible without unacceptable beam losses. If notching cannot be made operational for multibatch transfers, or the source of the variations are not found and eliminated, then the losses will have to be controlled in some other manner, or the number of protons delivered to the Main Injector will not even approach the Mid Term needs.

7. Proton intensity in the Main Injector will continue to be limited by the ability to implement operational control of instabilities. In the past, the Main Injector has consistently provided about 1.5E13 during operation, but the Mid Term demands are more than a factor of two larger, 3.3E13 (8E12 for antiproton stacking plus 2.5E13 for MINOS), and the requirements on the NuMI beam emittances are more stringent than in the past. Although on paper the total intensity limitation in the Main Injector

exceeds 5E13, progress will require sufficient beam study time as well as priority in assigning people to make modifications.

8. The continually increasing proton demands of the neutrino program will require modifications, but it is not clear at this point which ones are the most feasible. These include increasing the Booster batch intensity, some form of fast stacking in the Main Injector, and shortening the Main Injector cycle time. Determining which ones of these to pursue should start as soon as possible.

9. The committee notes that it is very likely the physics program will eventually demand more protons than reasonable upgrades of the present Linac and Booster can accommodate. At that point it would be prudent to have a new Proton Driver available.

Summary of Organizational Matters

1. Several organization changes should be made to help assure the maximum utilization of available resources. These changes should be integrated into the overall operation and organization of the Lab, and not considered as a "Protons Only" enterprise. An individual should be made responsible and given the authority to develop and implement a plan for delivering the protons demanded by the upcoming physics programs. This plan would likely include some incarnation of a PMG-style enterprise. It is most important that a group be formed to technically evaluate ideas for improving all the accelerators, perhaps incorporating some techniques that are more common in detector collaborations. And another group should be formed to nurture and develop ideas as well as to facilitate the intellectual involvement of physicists in accelerator physics.

2. For collaboration between the Beams Division and non-Fermilab institutions to succeed better than it has so far, the Beams Division or the Directorate must provide a high level point of contact with sufficient clout to wisely guide the department heads and group leaders along the path of success. The same point of contact could also make cooperative efforts between the Beams Division and other Divisions within the Lab work much better.

3. Program Planning will have to determine just how to timeshare the Main Injector between cycles using slow resonant extraction for Meson120 fixed target experiments, and cycles using fast, single turn extraction for antiproton stacking and MINOS.

Finally the members of the committee wish to thank all those that contributed to this report. Especially we wish to thank Mike Witherell for the opportunity to serve on this committee that we fondly called "The Proton Team". It was not boring. And the committee wishes to encourage the Lab's management to rise to the considerable challenge required to deliver protons as best as can be done.

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[12] Peter Cooper to P5.

[13] Alberto Marchionni, “Pbar stacking uptime”, October 2, 2003; http://www-bd.fnal.gov/proton/ProtonTeam/031002shot_setup.pdf

Appendix: Charge to the Proton Committee

February 19, 2003

From: Michael Witherell
To: David Finley

Thank you for agreeing to chair a committee to advise me on the use of protons at Fermilab through the end of the decade.

I am pleased that Janet Conrad of MiniBooNE and Doug Michael of MINOS have already agreed to serve on this committee. It is important that these neutrino experiments succeed as part of the Fermilab physics program. We all know that neutrino experiments do better the more protons are available. I expect your team to come up with a quantified realistic estimate of how many protons we can expect to provide. All users of protons should be included in your deliberations, of course. I am particularly concerned that the collider program continue to get the protons they need.

To be more specific, I would like you to

1) Identify users of protons over the period 2003-2010 and the demands represented by each.
2) Establish technical goals for delivery of protons, both from the Booster and Main Injector, over the period.
3) Identify major modifications to the Proton Source and Main Injector that will be required to meet these goals assuming availability of Fermilab resources at the few x $10M level over the period.
4) Identify possible resources and opportunities for collaboration by institutions outside Fermilab.
5) Suggest an organization for implementing a program of modifications, including opportunities for integration of collaborators outside Fermilab.

I want you to be prepared to provide a verbal status report at the April PAC, and a final written report before the June PAC at Aspen.

Cc:
Steve Holmes
Hugh Montgomery
Roger Dixon
Bob Kephart

Appendix: Proton Demands Consequences Spreadsheet

The "Proton Demands Consequences Spreadsheet" (see figures A, B and C.) expresses the proton requests ("demands") of a given physics program in terms of various machine performance parameters and compares these with assumed limitations.

Understanding how to use this spreadsheet requires a basic understanding of accelerator timelines. The accelerator complex operates by repeatedly executing a sequence of steps according to predefined timeline. The number of these timelines that can be executed and the number of protons delivered during each timeline determines the total number of protons that can be delivered in a year.

The Booster main magnets form part of a 15 Hz resonant power cycle that establishes a basic clock for all timelines. A timeline must be comprised of an integral number of 15 Hz Booster cycles and each Booster cycle requires a 1/15 of a second, or 1 "click". Not all Booster components operate continuously at 15 Hz. Many components are powered only during cycles where beam is accelerated and some of these require additional "prepulses" in order to ensure proper regulation of their power supplies. Thus a typical timeline involving only the Booster will consist of two beamless prepulses, followed by a string of beam pulses, followed by some number of empty cycles in which no beam is delivered and only the main magnets are powered.

A timeline involving the Main Injector typically starts with some number of clicks in which the Booster delivers beam to the Main Injector. This is followed by a Main Injector acceleration cycle in which the beam is accelerated to 120 GeV and extracted after which the Main Injector magnet current ramps back down to the 8 GeV values. The extraction process can either be "fast" (e.g. NuMI and Pbar) or "slow" (e.g. Meson120 for CKM). While fast extraction adds negligible time to the overall cycle, slow extraction requires the Main Injector to remain at 120 GeV for some number of seconds before ramping back down again. During this period the Booster is available to send additional beam to 8 GeV users (e.g. MiniBooNE). These Booster beam cycles occur immediately after delivering beam to the Main Injector so as not to increase the overall length of the timeline by requiring another set of prepulses. Similarly, the prepulses required for a Main Injector cycle are added to the end of the preceding cycle while the Main Injector magnets are approaching 8 GeV.

In general the Main Injector ring can accommodate a maximum of six Booster batches distributed around its circumference. However, this number can be exceeded by "proton stacking" schemes, in which two Booster batches are longitudinally combined into one. The RF manipulations required to do this are performed in the Main Injector and typically necessitate extending the overall cycle time.

Using input machine parameters and a user defined allocation of Booster batches, the spreadsheet constructs timelines as described above and calculates how many Booster batches can be delivered to each experiment in a year. From this it is able to convert each experiment's yearly proton request into a Booster batch intensity as well as other relevant machine performance parameters. If an experiment's batch intensity is larger than a predefined maximum, the spreadsheet will also calculate an appropriately reduced yearly proton allocation for that experiment.

The input parameters used by the spreadsheet are shown in blue on Figure A, and are organized into six categories:

1. Program Requests:
   A simple measure of the feasibility of any experiment is the total number of protons required to obtain an interesting level of statistical precision and the time required to accumulate those protons. For this reason we express the experiment requests in terms of protons per year. Of course, additional constraints often apply and those that affect the rate at which protons can be delivered are included as parameters. For instance the MiniBooNE horn cycle rate is limited to 5 Hz with the additional constraint that there be no more than 10 consecutive beam pulses in a row. In the case of slow spill experiments such as CKM, an additional constraint is imposed by the maximum instantaneous beam intensity that the experimental apparatus can tolerate. The length of the spill is an additional degree of freedom for these experiments and can affect the overall efficiency of the program.

2. Up time:
   The fraction of the year available to any physics program is never 100% and will naturally be less for those programs requiring both the Booster and the Main Injector to be available. We calculate the "Annual Beam On Fraction" using the number of weeks scheduled in a year, along with the reliability and operational efficiency of the Proton Source or Main Injector. The blue numbers in the box "Scheduled Times & Efficiencies" in Figure A are used for the calculations. (The main text contains more information about these numbers.) The fraction of the year during which beam is delivered (scheduled time times reliability) for each timeline is shown in the box "Time Lines".

3. Machine Parameters:
   Figure B shows the machine parameters that can affect the rate at which protons can be delivered to the program:
   - Main Injector RF power expressed in MW. This number is used in conjunction with the next two parameters to determine the maximum number of protons that can be accelerated in a single cycle.
   - Maximum acceleration rate in GeV/sec assuming a 1.5 second ramp cycle. This affects the maximum Main Injector intensity.
   - Main Injector acceleration time expressed in "clicks". This is the time required to ramp the machine energy from 8 GeV to 120 GeV and back down again, including short flattops, time to reset remnant fields etc.
   - Time required for proton stacking in the Main Injector. The Main Injector can hold a total of 6 Booster batches and the Antiproton Source can accept only

one batch, or more precisely beam confined to the length of one batch. If the total number of batches requested for a Main Injector cycle exceeds 6, or if the number of batches to be extracted to the Antiproton Source exceeds 1, then some sort of proton stacking scheme is required. Depending on the scheme being assumed, there may be a time overhead required to perform the necessary RF manipulations. This parameter allows this overhead to be taken into account.

- CKM is requesting debunched beam. There may be some time overhead required to do this. This parameter allows it to be accounted for.
- The number of beam-free Booster power cycles required to prepare for a train of beam cycles. These prepulses need to be accounted for when calculating the machine rep rate.
- The rate at which the Antiproton Source can accept beam is limited by the rate at which it can stochastically cool the antiprotons. This sets a lower limit on the total Main Injector cycle time for Stacking. (In the past this number has depended on the total number of antiprotons that are in the Accumulator, and hence this parameter should represent the average P-bar cycle time.)

4. Limitations:
   Figure B also shows the anticipated limitations against which the calculated performance parameters are compared are defined here. These numbers are not used in the calculations, however the spreadsheet will flag with a red exclamation mark (!), any calculated performance parameter that exceeds the corresponding limit. These limitations are not fixed in time, but will change as improvements are made. The parameters are:
   - The calculated Main Injector intensity limit due to RF power. This quantity is calculated from the assumed RF power, the maximum acceleration rate in a 1.5 sec ramp cycle (240 GeV/sec), and the length of the assumed ramp cycle. These three parameters are defined in the Machine Parameters box.
   - The Main Injector intensity limitation due to beam instabilities. The actual limit used is chosen to be the smaller of this and the preceding parameter.
   - The maximum intensity that can be accelerated in the Booster with reasonable losses.
   - The maximum Booster hardware rep rate. This limitation is due to thermal stresses on various pulsed elements and limits the number of beam pulses plus prepulses that can be tolerated in any timeline.
   - The maximum number of protons per hour that can be delivered by the Booster. The Booster radiation shielding assessment sets this limit at 1.8E17 protons/hour. However lower limits can arise from activation of accelerator components.

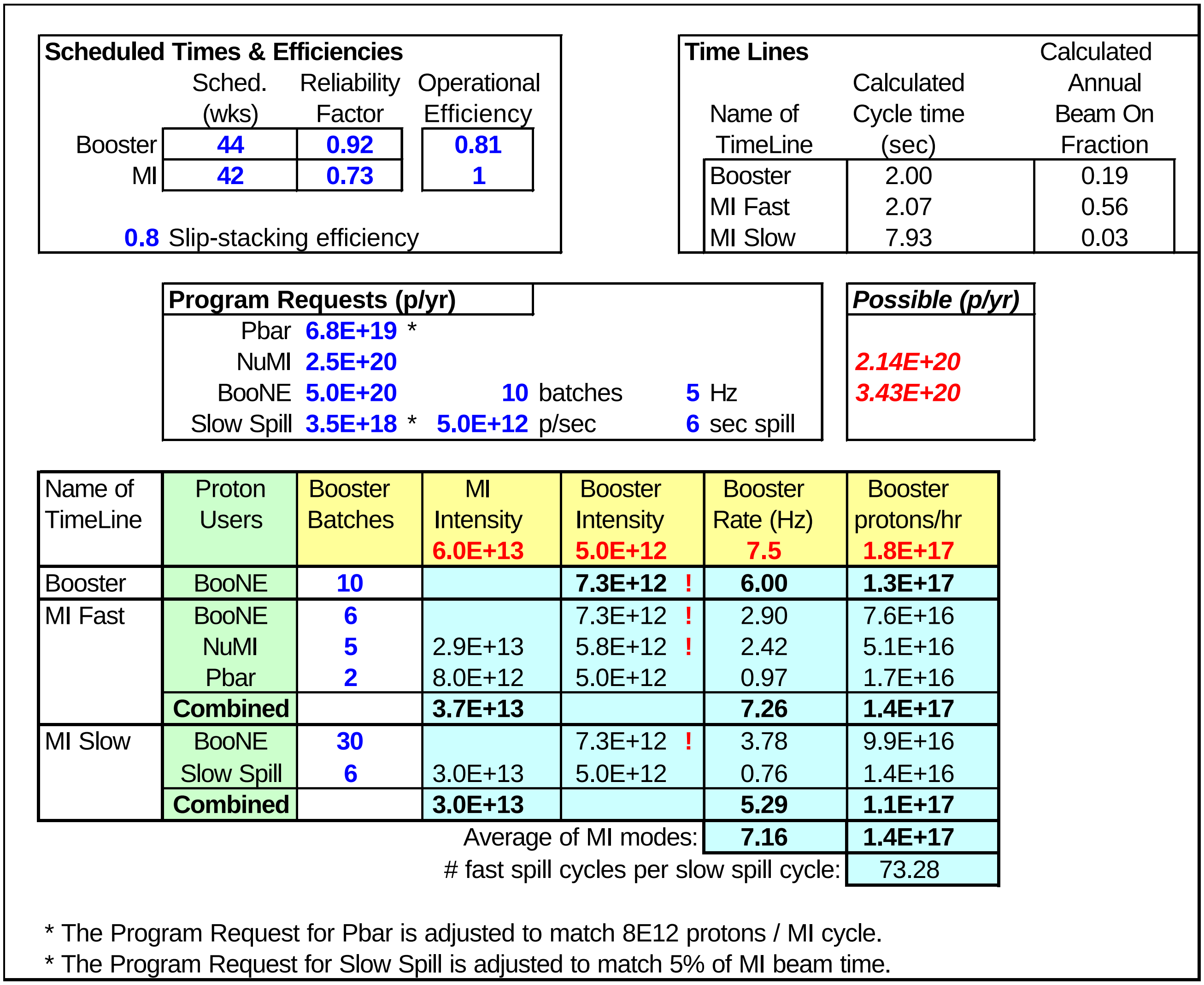
5. Constants:
   This box in Figure B defines the length of a year in seconds and, more interestingly, the length of a “click”.

6. Booster Batches:
   It is in this table column in Figure A that the spreadsheet user allocates beam to the three types of timeline. The three possible timelines are: Booster only, Main Injector fast spill, and Main Injector slow spill. The only user of the Booster only batches is the MiniBooNE experiment and the length of the timeline is chosen to match the rep rate constraint specified in the Program Requests section.
   The Main Injector fast spill timeline is activated if batches are allocated to either NuMI or Pbar. If the user assigns more than 6 batches to these two experiments or more than 1 batch to the Pbar source, the spreadsheet will assume that some sort of proton stacking scheme is being implemented and will add the appropriate time penalty to the timeline. MiniBooNE cycles can also be added, but if the user attempts to allocate more than the maximum allowed number of consecutive pulses or more than is allowed by the rep rate limit the spreadsheet will flag the entry with a red exclamation mark.

   The Main Injector slow spill timeline is activated if batches are allocated to the Slow Spill user. A red exclamation mark will appear if the user attempts to add more than 6 batches. MiniBooNE cycles can also be added to this timeline. In this case however, only the rep rate limit will generate an error flag. This is to allow extra Booster only timelines to be executed during the slow spill.

The spreadsheet results are highlighted in pale blue in Figure A. The following quantities are calculated for each experiment and compared with the corresponding limitations: MI Intensity (not relevant to MiniBooNE), Booster Intensity, Booster Rep Rate, and Booster Protons/hour. If any result exceeds the limits shown in the column headings the result will be flagged with a red exclamation mark. Note however, that when a mixture of slow and fast Main Injector cycles is called for, then one should pay attention to the average Booster rep rate and the average protons/hour, rather than the rates for the individual cycle types. Also shown is the admixture of fast and slow extraction cycles that is implied by these results.

If the Booster intensity required for a given experiment exceeds the specified limit, the spreadsheet will also calculate the reduced number of protons per year that can be delivered to the experiment whilst satisfying the Booster's intensity limit. This result will be displayed in red in the "Possible (p/yr)" box of Figure A.



Scheduled Times & Efficiencies

	Sched. (wks)	Reliability Factor	Operational Efficiency
Booster	**44**	**0.92**	**0.81**
MI	**42**	**0.73**	**1**

0.8 Slip-stacking efficiency

Time Lines

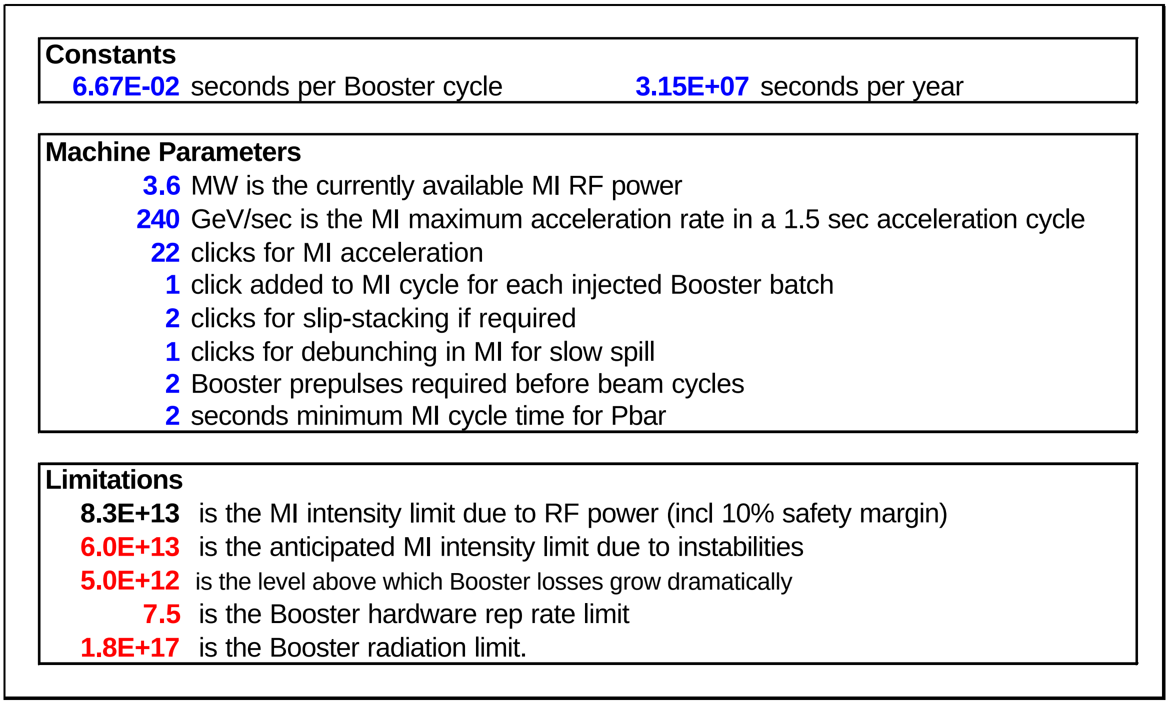
Name of TimeLine	Calculated Cycle time (sec)	Calculated Annual Beam On Fraction
Booster	2.00	0.19
MI Fast	2.07	0.56
MI Slow	7.93	0.03

Program Requests (p/yr)							***Possible (p/yr)***
Pbar	**6.8E+19**	*					
NuMI	**2.5E+20**						***2.14E+20***
BooNE	**5.0E+20**		**10**	batches	**5**	Hz	***3.43E+20***
Slow Spill	**3.5E+18**	*	**5.0E+12**	p/sec	**6**	sec spill	

Name of TimeLine	Proton Users	Booster Batches	MI Intensity **6.0E+13**	Booster Intensity **5.0E+12**	Booster Rate (Hz) **7.5**	Booster protons/hr **1.8E+17**
Booster	BooNE	**10**		**7.3E+12 !**	**6.00**	**1.3E+17**
MI Fast	BooNE	**6**		7.3E+12 **!**	2.90	7.6E+16
	NuMI	**5**	2.9E+13	5.8E+12 **!**	2.42	5.1E+16
	Pbar	**2**	8.0E+12	5.0E+12	0.97	1.7E+16
	Combined		**3.7E+13**		**7.26**	**1.4E+17**
MI Slow	BooNE	**30**		7.3E+12 **!**	3.78	9.9E+16
	Slow Spill	**6**	3.0E+13	5.0E+12	0.76	1.4E+16
	Combined		**3.0E+13**		**5.29**	**1.1E+17**
				Average of MI modes:	**7.16**	**1.4E+17**
				# fast spill cycles per slow spill cycle:		73.28

* The Program Request for Pbar is adjusted to match 8E12 protons / MI cycle.
* The Program Request for Slow Spill is adjusted to match 5% of MI beam time.

Figure A: Protons Demands Spreadsheet



Constants

6.67E-02	seconds per Booster cycle	3.15E+07	seconds per year

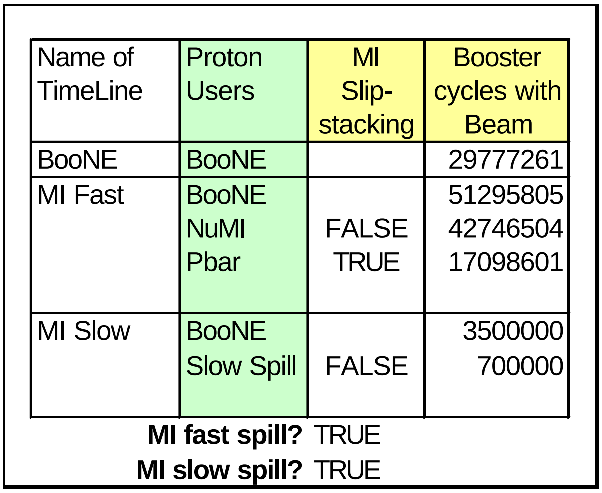
Machine Parameters

3.6	MW is the currently available MI RF power
240	GeV/sec is the MI maximum acceleration rate in a 1.5 sec acceleration cycle
22	clicks for MI acceleration
1	click added to MI cycle for each injected Booster batch
2	clicks for slip-stacking if required
1	clicks for debunching in MI for slow spill
2	Booster prepulses required before beam cycles
2	seconds minimum MI cycle time for Pbar

Limitations

8.3E+13	is the MI intensity limit due to RF power (incl 10% safety margin)
6.0E+13	is the anticipated MI intensity limit due to instabilities
5.0E+12	is the level above which Booster losses grow dramatically
7.5	is the Booster hardware rep rate limit
1.8E+17	is the Booster radiation limit.

Figure B. Constants, Machine Parameters and Examples of Limitations



Name of TimeLine	Proton Users	MI Slip-stacking	Booster cycles with Beam
BooNE	BooNE		29777261
MI Fast	BooNE		51295805
	NuMI	FALSE	42746504
	Pbar	TRUE	17098601
MI Slow	BooNE		3500000
	Slow Spill	FALSE	700000

MI fast spill? TRUE

MI slow spill? TRUE

Figure C. Example of Logical Constants and Calculated Booster Cycles