Proton Source Task Force Report

Fermi National Accelerator Laboratory

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Executive Summary

The Proton Task Force, charged to assess the feasibility of operating the Fermilab Pre-accelerator, Linac, and Booster for the next 15 years, involved nearly thirty systems experts and looked at every major Proton Source technical system.

The conclusion of the Task Force based on the work completed thus far and pending additional inputs is that it is feasible to run the Proton source for another 15 years at the present proton output. However, many forty-year-old systems will require upgrades to maintain current-day operational availability. The items of greatest concern that impact proton availability, in order of highest to lowest concern, are:

1) Booster RF Systems
2) Low Energy Linac Systems
3) Booster Gradient Magnets
4) Utilities
5) Cockcroft-Walton Pre-accelerators

This report details proposed solutions to these concerns and to those of other systems considered. Beyond the present annual operating budget, an estimated $37 million (M&S) over the next 6 to 7 years is necessary to address these concerns.

With systems in their current state and given only a flat operating budget, a reasonable expectation of Booster output is about 1.3E17 protons per hour at a cycle rate of 7 to 8 Hz. Machine downtime is expected to be dominated by Booster RF and Linac low energy system failures. The number of those incidents will increase with aging and with higher operational demands. Failure of some Booster gradient magnets should also be expected, although recoverable.

Radiation damage to Booster components will remain an ongoing concern especially given expectations of higher proton throughput. The necessity for systematic replacement and maintenance of radiation-damaged hardware will increase at the expense of greater downtime and greater radiation exposure to workers, but should not preclude continued operation.

Final designs exist for Pre-accelerator replacement and Booster solid-state RF driver amplifiers, but await funding and assignment of required labor resources. Implementation of these improvements, though not sufficient to directly increase proton throughput, will help reduce beam losses, reduce accelerator downtime, reduce worker radiation exposure, and enable Booster 15 Hz cycle rate capability. The 15 Hz capability offers the operational flexibility of providing additional beam cycles within the overall beam loss and beam permit limits. The Task Force has not specifically addressed the issues of achieving increased proton flux

Investigation of options for replacement or redesign of the low-energy Linac RF modulators and the 200 MHz final RF amplifier tube is on going with a report due in early FY11.

Introduction

Conceived in February 2010 and established in April 2010, the Proton Task Force was created to assess the outlook of operating the Proton Source for the next 15 years. Roger Dixon, Accelerator Division Head, with the support of Fermilab management, wrote the following charge as the initial guidance for the task force:

February 19, 2010

R. Dixon

Draft Proton Source Task Force Charge

Background: The Linac and Booster will have to supply protons to the Main Injector and to the 8-GeV physics program until Project X and its follow on is available to the physics program. It is now estimated that this could happen as late as 15 years from now. Meanwhile both the H^- sources and the low energy Linac are becoming more difficult to maintain due to outdated electronics and the expected difficulty of acquiring spare tubes for the modulators and amplifiers. The reliability of this machine has already become an issue. Meanwhile the 8-GeV Booster is also expected to have increasing reliability issues with time just as the physics program demands better performance. To simultaneously support the 8-GeV physics program and the high energy neutrino program it will be necessary to run the Booster at 15 Hz. This requirement will necessitate a substantial upgrade of the RF power system in the Booster, in addition to improvements in the control of beam losses, shielding of the accelerator enclosures, and improved reliability.

The charge to the Proton Source Task Force is:

1. Determine the vulnerabilities of each major subsystem in the Proton Source system including the
    a. The H- sources and pre-accelerators
    b. The low energy drift tube Linac
    c. The RF System for the low energy Linac including power amplifier tubes and other associated tubes
    d. The 8-GeV Booster magnet systems
    e. The 8-GeV vacuum system
    f. The 8-GeV RF cavities and modulators
    g. The and interlocks of all Proton Source systems
2. Review the planned, but unfunded upgrades of the H- sources, the Booster RF system, and the 15Hz upgrade.
    a. Identify weaknesses

Identify all systems that need to be upgraded or replaced in order to maintain both high energy neutrino and 8 GeV physics programs. Suggest possible upgrades or replacement solutions while taking into account the development of Project X.

Task Force Organization

Participants

The charge is broad and intended not to be limited, but rather inclusive of all systems in the Proton Source. After a period of two months, allowing for an initial investigation, several small modifications to the original charge allowed listing the names of responsible individuals along with systems identified as critical. The following task force personnel list was submitted and approved:

Linac Task Force Candidates:

- Larry Allen (AD/PS) (Modulator)
- Trevor Butler (AD/PS) (Modulator)
- Howie Pfeffer (AD/EE) (Modulator)
- Al Moretti (APC) (New Low Energy)
- Paul Czarapata (AD/HQ) (New Low Energy)
- Ken Quinn (AD/PS) (High Energy Reliability)
- Peter Prieto (AD/Inst.) (High Energy Reliability)
- Mike Kucera(AD/Controls) (Linac Controls)
- Bob Goodwin(AD/Controls) (Linac Controls)
- Steve Hays (AD/EE) (Linac Power Distribution)
- Bob Slazyk (AD/MS/Water Group) (Linac LCW Systems)
- David Hixson (AD/MS/Water Group)(Linac LCW Systems)
- Ben Ogert (AD/MS) (Linac Vacuum)
- David Augustine (AD/MS) (Linac Vacuum)

Booster Task Force Candidates:

- George Krafczyk (AD/EE)(Pulsed Systems)
- John Reid (AD/RF) (High Level RF systems)
- Jim Lackey (AD/PS) (Pulsed Systems, Magnets)
- Dave Augustine (AD/MS) (Vacuum System)
- Craig Drennan (AD/PS) (Booster LL system)
- Peter Kasper (AD) (Booster Shielding)
- Davis Hixson (AD/MS) (Booster LCW Systems)
- Sharon Lackey (AD/Controls) (Booster)

Accelerator Systems

The accelerator systems associated with responsible individuals are divided into subsystems as below. The list includes some additional aspects of the subsystems, either major components or major avenues of consideration.

Linac Systems:

Low Energy Linac RF Modulators:

1. Present modulator design and issues/remedies with minor changes
2. Partial replacement and redesign of modulator system
3. New modulator in design with present function

New Low Energy Linac:

1. Replacement of present 200 MHz systems
2. New Cavities
3. New Power Sources (Amplifiers)
4. New Modulators
5. Design effort cost and modification to accommodate new system

High Energy Linac:

1. Present Klystron System
    a. Klystrons
    b. PFN systems
    c. High Level, Low Level and Interface systems
2. Utilities
3. Quadrupoles and related systems

Linac (including system interfaces as well as beam control and diagnostics):

1. Injector Control System
2. Low Energy Control System
3. High Energy Control System

Linac Utilities:

1. Power Distribution
    a. Feeders
    b. Transformers
    c. Line Power Distribution
2. Water systems
3. Vacuum Systems

Pre-Accelerator:

The present plan is to replace the aging Cockcroft-Waltons with an RFQ-based injector. Work toward this objective was begun in 2009 and, pending availability of manpower and funding, the upgrade could be installed during a shutdown in 2012. A review of the final design is planned for the first or second quarter of FY11.

Booster Systems:

Booster Pulsed Magnet Power Systems:

1. Corrector systems
2. Injection and Extraction systems
   a. Kicker Systems
   b. Septa Systems
   c. ORBMP systems

Booster High Level RF Systems:

1. RF power distribution
   a. Bias Supplies
   b. Modulators
   c. Anode Power Systems
2. Cavities
   a. Present RF Cavities
   b. New RF Cavity
   c. Spare RF Cavity
3. RF Utilities
   a. Power Distribution
   b. Water cooling systems

Booster Magnets:

1. Repair of replacement combined function dipole magnets
2. Miscellaneous Booster magnets and spares

Booster Utilities:

1. LCW distribution
   a. Central Utility System
   b. Gallery System
   c. Tunnel System
2. Vacuum systems
   a. Tunnel Vacuum systems
   b. Gallery systems

Booster Low Level RF System:

1. New Low Level control and distribution
2. New Longitudinal Damper system
3. Timing and control systems

Booster Shielding:

1. Assessment of present system
2. Analysis of future operational scenarios

Booster:

3. Beam diagnostics hardware
4. Control system interface hardware
5. Dedicated processors/stand alone systems

Task Force Strategy and Concern Criteria

The responsible person(s) for each system were asked to review their respective system and submit a document listing what is required to repair or replace their reviewed system(s) to meet the task charge of reliable operation for 15 years. The documents were collected in a public data storage area to allow for changes and review. (Due to limited time, proposed solutions will not be fully scoped and all estimates are preliminary)

The document should include:

1. System description and issues
2. Replacement/repair suggestions
3. Cost and manpower to meet suggested replacement and or repair of systems
4. A concern level of low, medium or high is then given based upon the below criteria.
    - Replacement available
    - Failure does not result in substantial downtime – several weeks
    - Cost below 200,000 dollars

    Concern level is assigned as follows:

- Low, if all three points of the criteria can be met
- Medium, if one of the three criteria is not met
- High, if two of three criteria is not met

Note that even items in the Low concern category can have a significant impact on operational budgets and machine availability. The $200,000 threshold represents a large fraction of the Accelerator Division's historical annual discretionary operational M&S budget and unscheduled downtime(s), on the scale of one week in the Preacc, Linac or Booster, is not presently considered in planning beam delivery performance goals.

Report Format

After a brief historical introduction, the task force report that follows is divided into three sections. The first section is a compilation of tables generated by the listed responsible persons for the systems they reviewed. Following some tables, additional information is provided when needed for clarity. The tables are of two types: Data tables and Replacement tables. Data tables are used for systems where reliability and not replacement is considered. Replacement tables categorize the parts, costs and manpower associated with repairing, replacing or maintaining their respective systems. Both types of tables list the above mentioned concern level. Table order is of no significance.

Several large systems; New Booster RF cavity, Linac modulator, new low energy Linac and new Injector will be discussed only in a "concern and solution" section. The information on these large systems, except the new injector system that is already designed and cost estimated, will take many months to investigate before getting possible solutions and accurate numbers. A discussion on "Radiation/Activation and Related Issues" will also only be discussed in the "concern and solution" section.

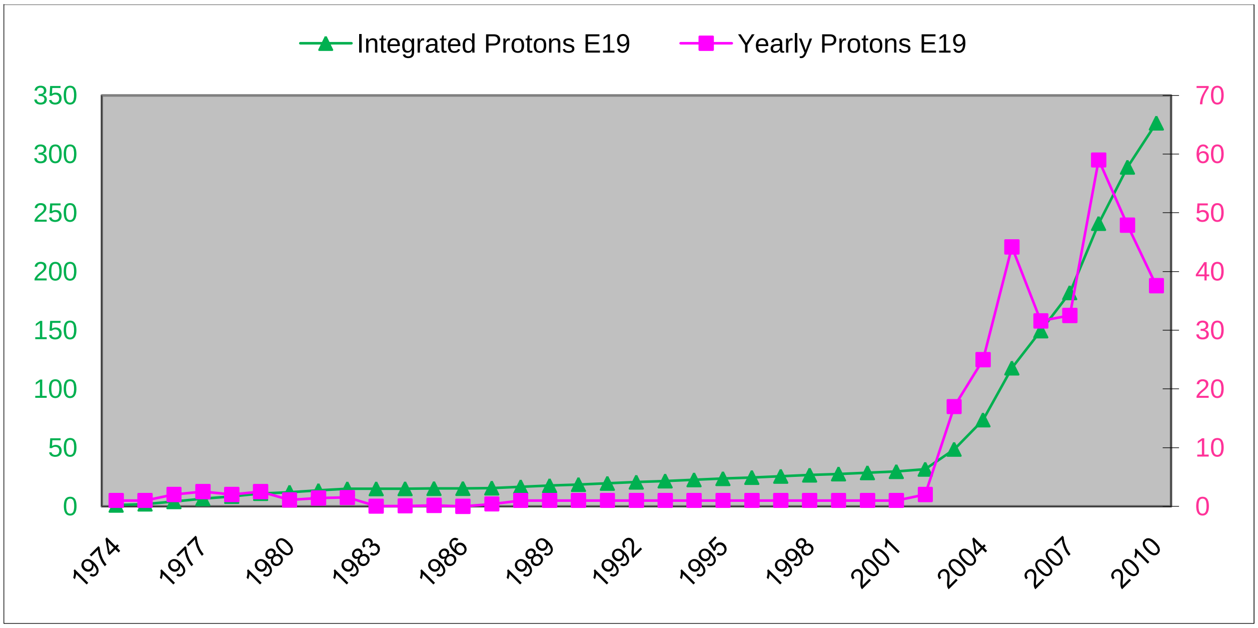
The second part of the report highlights concerns and lists possible solutions for the most critical areas. Included in the second section is a review of our radiation shielding and operating at a higher proton throughput.

The last section shows a possible timing and funding profile to meet the objective of running the Proton Source for 15 more years.

Proton Source Introduction

The Proton Source has delivered almost 3.3E21 protons over the past forty years; ninety percent of those in the past ten years mostly for modern neutrino programs (see in figure 1.1.) The early Fermilab fixed target experimental programs and then, starting in the mid 1980's, FNAL Collider program required only a low average beam pulse rate from the Proton Source. Booster rates were then typically less than 1 Hz. Starting in 2002, the MiniBooNE neutrino experiment began with an operating request of 5E12 protons per pulse at 5 Hz. Beam losses and pulse rate limitations of some hardware components severely constrained the Booster's capability to meet this demand. Over the following eight years, there was a major effort to upgrade the Booster shielding, hardware, and beam physics understanding. Some of the larger tasks accomplished include: Booster shielding improvements, a new injection line, removal of a secondary beam extraction region, improved optics and orbit control, and new Booster orbit correctors. A program known as the Proton Plan funded and managed part of these upgrades.

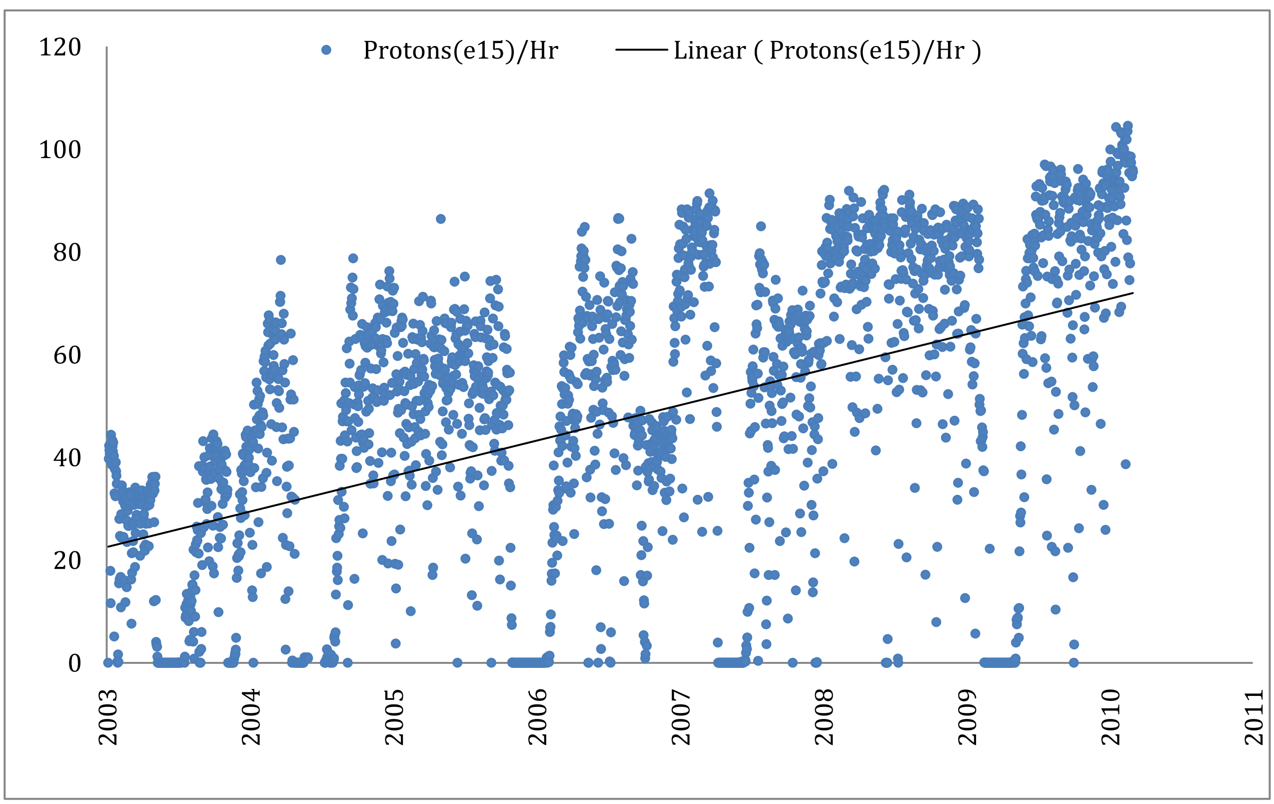
Figure 1.1 Protons Delivered



In 2005, the MINOS neutrino experiment began. The MINOS goal of 400kW on target required that Booster deliver eleven pulses of 4.3E12 protons every 2.2 seconds. Concerns for beam loss induced residual activation of components in the Booster limited average output to 9.2E16 protons per hour to be divided among MINOS, MiniBooNE, and Tevatron collider programs. After the completion of the Booster corrector upgrade in 2009 and continued orbit/optics work Booster was able to reach an average rate of 1.1E17 protons per hour.

The hardware upgrades, hand-in-hand with the essential improvements in beam transmission efficiency,

Figure 1.2 Proton Throughput Past 7 Years



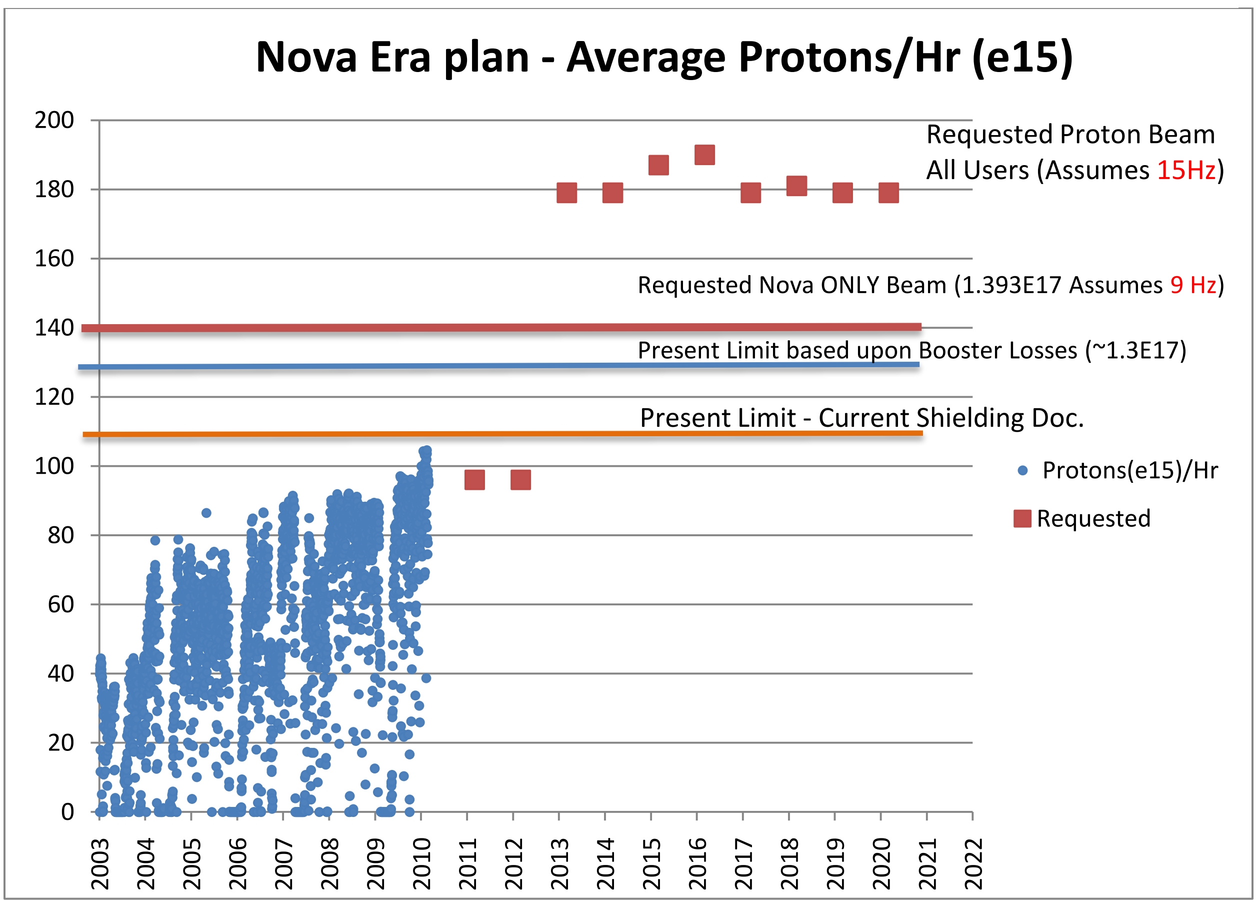
allowed for the steady increase in proton throughput as shown in Figure 1.2. This has been accomplished without correspondingly increased residual activation rates of Booster components. Higher per-pulse beam intensity and higher pulse repetition rate capability have both contributed to the performance gains.

By summer 2010, the limiting factor in proton delivery was no longer Booster losses but rather the operating limits allowed by the radiation shielding assessments for the Booster and Main Injector. New shielding assessments to support higher operating limits are to be completed in FY11. It is expected that Booster losses and hardware limitations will then again become the limiting factor.

The near term operating goals are to deliver 400 kW to MINOS, two 4.5E12 batches to the Pbar target, and the remainder of available beam to MiniBooNE (capable of taking 1E17 protons per hour; MiniBooNE will not reach its limit.)

The proton-per-hour demand is expected to remain constant through the end of the FNAL collider program. Subsequently, the projected demand will increase significantly. The planned high energy physics (HEP) programs Nova, Mu2E, MicroBooNE, G-2 and others require the Proton Source to run at a

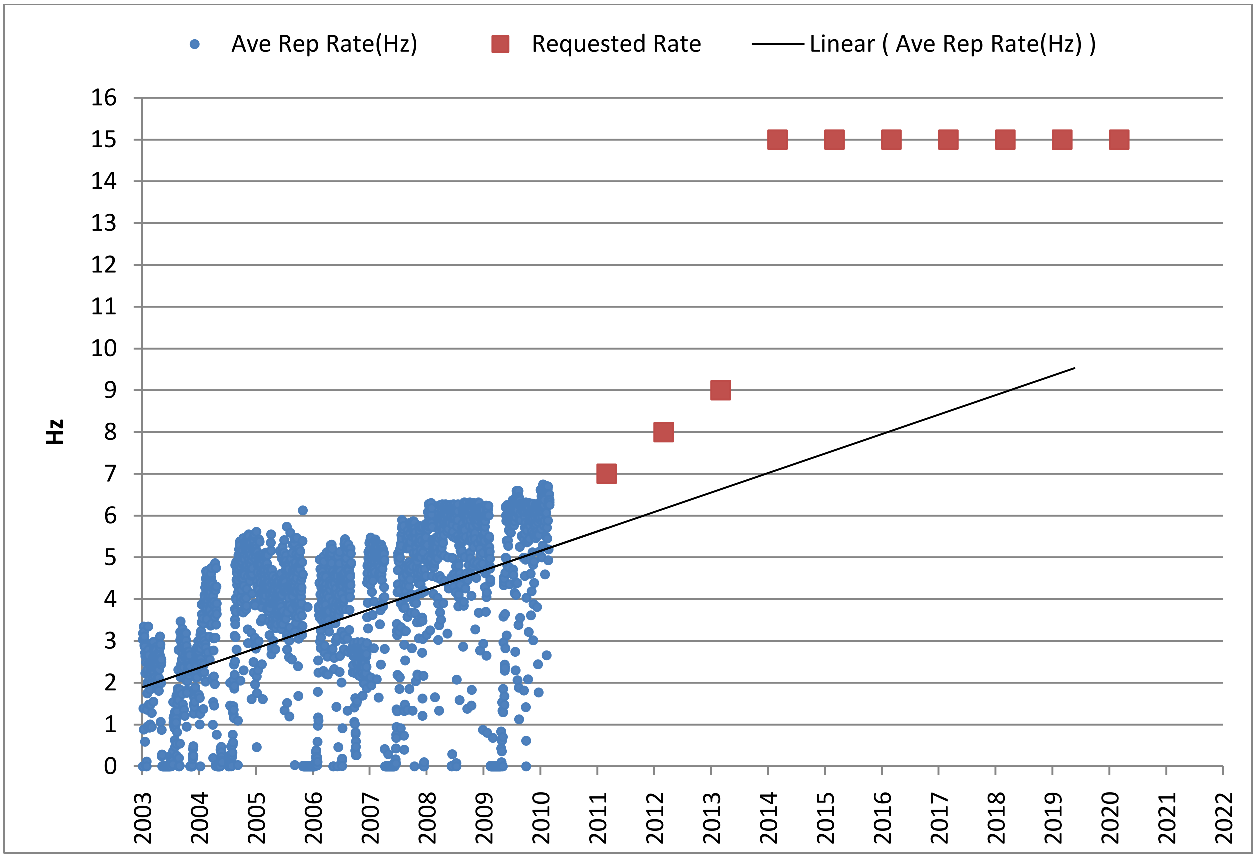
Figure 1.3 Protons Per Hour Past and Requested



60 % higher beam pulse rate (See figures 1.3 and 1.4.) and about 20% more protons above what is presently acceptable repetition and loss rates.

Shown below in figure 1.4 is the requested Booster cycle rate after the collider program. Several upgrades discussed in this task force address issues in reaching 15 Hz operation. See table i in the endnote section for more information regarding 15Hz operation and requested proton beam numbers.

Figure 1.4 Booster Cycle Rate



System Reviews and Data

Data Tables

Utilities

Table 1 LCW and Related Items

	Utilities						
	Low Conductivity Water (LCW) and Central Utility Building (CUB) Systems						
Concern	***Task/Solution***	***Details***	**QTY**	***Unit Cost***	***M&S Cost Total***	***Man-Hrs (tech)***	***Man-Hrs (eng)***
	CUB/Booster						
Low	Purchase new return pumps with proper sizing	Install new pumps with new fittings lines and valves.	2	$67,500	$135,000	FESS	
Low	Replacement of T12 iron core ballasts	A redesign will be required to allow for the use of other ballasts types which may not work well in radiation fields.			$50,000		
Medium	Replace discharge lines, and other hardware associated with the sumps. In some cases new sumps will have to be ordered.	Two of the discharge will be replaced during this summer shutdown (L9 & L12). The remaining discharge lines in Booster will have to be replaced along with fittings and valves.			$200,000	FESS	
Medium	Replace heat exchanging plates located at CUB for HE1 and HE2.		2	$90,000	$180,000	FESS	
Medium	Increase water flow to gallery power supplies by installing LCW return lines back to CUB, and separate the circuit from the tunnel return.	Install new return lines from the Booster east and west galleries back to CUB return pumps.			$150,000	FESS	

Low	Replace failing rooftop AC units, which need constant repair and are approaching the end of their lifetime. Install new ventilation duct work to improve ventilation and cooling capacity.		10	$2,000	$20,000	FESS	
Low	Increase chilled water flow to the gallery TRANE AC units. For reliability reasons purchase a spare unit since the lead time can be two months before another AC unit can be delivered.	CUB needs to figure how to supply the east and west galleries with increased water flow and cooler water.	N/A			FESS	
Low	Replace AC unit with a newer more robust AC unit that is capable of cooling the LLRF room. One that does not require continuous maintenance, and has spare parts readily available. Add a backup unit so during periods of downtime we can continue to run HEP beam without the fear of losing electronics. Improve ventilation of hot air removal.				$100,000	FESS	
Low	Replace heat exchanging plates located at CUB for heat exchangers HE1 and HE2.		2	$90,000	$180,000	FESS	
Low	Valves, piping, filtering and Strainers - Systems	(13) Strainers - Kraissl 1-1/2"	Misc		$26,875	80	
	Total				**$1,041,875**		

The Proton Source LCW systems consist of two separate systems. The Linac and Pre-Accelerator (Pre-Acc) systems use a 55° F LCW system and the Booster use a 95° F LCW system. The Booster 95° LCW system is shared with Switch Yard, an RF test area, the lower Linac power supply test room and the MuCool R&D test area and beam line. The system is over used and undersized and has no capacity to support any additional loads. There have been several recent upgrades to the 95° system in an effort to balance the loads and to support the solid state RF upgrade. As shown in the tables above, additional LCW work is still required to finish balancing the system and remedy flow constraints.

Table 2: Vacuum Systems

Concern	Task/Solution	Details	QTY	Unit Cost	M&S Cost Total	Man-Hrs (tech)	Man-Hrs (eng)
Utilities							
Vacuum Systems							
PreAcc H-							
Low	Purchase scroll pump for H- dome. This will replace a D30A Leybold Heraeus oil sealed pump		2	$7,000	$14,000	4	
Low	Purchase 1000 l/s turbo for H- ground station		1	$19,000	$19,000	2	
Low	Machine larger intake manifold for H- ground station and purchase 8"od Conflat flange add 2 3/4 intake port for instrumentation and larger hand vacuum valve for venting and purchase 8" Cf vacuum valve for I- ground station		2	$7,000	$14,000	8	
Low	Replace 450 liter turbo in Dome to 1000 liter pump station.	This was done in FY08 gate valve was removed Funded by Proton Source	1	$18,063	$18,063		
750 Line							
Low	Replace 3.25 " vacuum valve in 750 line US end, currently VRC type will not lock closed		2	$3,000	$6,000	52	
Low	*Replace 3.25 " vacuum valve in 750 line US of first RF tank, currently VRC type will not lock closed*	*No Design of valve to replace this. Will require approx. 1 man-year of engineering*	1	*$3,000*	*$3,000*	*20*	*1920*
PreAcc I-							

Low	*Replace vacuum valve to upgrade to a type that will mechanically lock when closed VRC valve in between column and vacuum box. Currently there is no design or manufacturer to allow this.*	*No Design of valve to replace this. Will require approx. 1 man-year of engineering*	1	*$3,000*	*$3,000*	*20*	*1920*
Low	Replace vacuum valves to upgrade to a type that will mechanically lock when closed VRC valve at 2nd ground station		1	$4,000	$4,000	4	
Low	Replace 450 liter turbo with new 1000 liter turbo in I-dome	Purchased by PreAcc Dept	1	$18,063	$18,063		
Low	Purchase Scroll for I- dome to replace D30A Leybold Heareaus oil sealed pump		3	$7,000	$21,000	6	
LowLow	Purchase 1000 l/s turbo for I- ground station & Machine larger intake manifold for I- ground station and purchase 8"od Conflat flange add 2 3/4 intake port for instrumentation and larger hand vacuum valve for venting		1	$19,000	$19,000	22	
Low	Linac Low EnergyPurchase 1000 l/s turbo for I- ground station two		1	$19,000	$19,000	2	
Low	Replace tank 2-5 valve (defective valve)Linac Low Energy		4	$3,000	$12,000	64	
LowLow	Replace 1397 Sargent Welch oil sealed roughing with scroll pump. This pump used to pump on tank one stem box (3 pumps on tank 1)Replace tank 2-5 valve (defective valve)		3	$7,000 $3,000	$21,000 $12,000	664	
LowLow	Roots Blower (3 locations)Replace 1397 Sargent Welch oil sealed		3	$35,000 $7,000	$105,000 $21,000	126	

	roughing with scroll pump. This pump used to pump on tank one stem box (3 pumps on tank 1)						
Medium Low	Purchase custom o-rings for low energy end bell vacuum seal. No spares, no stack available.Roots Blower (3 locations)	Unknown cost, have not found a vendor.	3	$35,000	$105,000	2412	
Medium	Linac High EnergyPurchase custom o-rings for low energy end bell vacuum seal. No spares, no stack available.	Unknown cost, have not found a vendor.	1	$5,000	$5,000	24	
Low	2 spare ion pumps for bridge couplers, no sparesLinac High Energy		2	$2,000	$4,000		48
Low	400 MeV and Dump Line2 spare ion pumps for bridge couplers, no spares		2	$2,000	$4,000		
Low	Replace Sargent Welch turbo station on 400 mev line top of chute, momentum dump Booster BD1 and Chopper400 MeV and Dump Line		4	$5,000	$20,000	8	
LowLow	Replace oil sealed roughing pump with scroll pump at momentum dump, 400mev chute, Booster BD1 and Chopper.Replace Sargent Welch turbo station on 400 mev line top of chute, momentum dump Booster BD1 and Chopper		4 4	$7,000 $5,000	$28,000 $20,000	48	
LowLow	Replace vacuum valve on Momentum dump, chopper, BD1 and Chute turbo pumpReplace oil sealed roughing pump with scroll pump at momentum dump, 400mev chute, Booster BD1 and Chopper.		4 4	$3,000 $7,000	$12,000 $28,000	644	

LowLow	Replace VLNLAM, VLNDMP, VI-LAM, VI-Q5 to a valve that will mechanically lock when closed.Replace vacuum valve on Momentum dump, chopper, BD1 and Chute turbo pump		4 4	$3,000 $3,000	$12,000 $12,000	6464	
LowLow	Purchase spare valve for 400 MEV and dump area that will mechanically lock when closed.Replace VLNLAM, VLNDMP, VI-LAM, VI-Q5 to a valve that will mechanically lock when closed.		1 4	$3,000 $3,000	$3,000 $12,000	1664	
Low	Liquid NitrogenPurchase spare valve for 400 MEV and dump area that will mechanically lock when closed.		1	$3,000	$3,000	16	
Low	Repair dewar 09 and 01Liquid Nitrogen		2	$30,000	$60,000	96	
Low	BoosterRepair dewar 09 and 01		2	$30,000	$60,000	96	
Low	Short 1-24 Replace Sargent Welch turbo Booster		24	$5,000	$124,000	100	
LowLow	Replace Roots blower station East gallery SouthShort 1-24 Replace Sargent Welch turbo		1 24	$12,500 $5,000	$12,500 $124,000	8 100	
LowLow	Replace Roots blower station East gallery NorthReplace Roots blower station East gallery South		1 1	$12,500 $12,500	$12,500 $12,500	88	
LowLow	Replace gate valve to a type that will mechanically lock when closed.Replace Roots blower station East gallery North		8 1	$4000 $12,500	$32,000 $12,500	128 8	
LowLow	Replace Sargent Welch turbo pump and roughing pump 400 mev to Injection		2 8	$6,000 $4000	$12,000 $32,000	4128	

	girderReplace gate valve to a type that will mechanically lock when closed.						
LowLow	Replace vacuum valve on 400 MEV to inj girder line, on MP02, on upstream 8 GeV line, 400 MeV to Linac.Replace Sargent Welch turbo pump and roughing pump 400 mev to Injection girder		4 4	$3,000 $6,000	$12,000 $12,000	644	
LowLow	Replace Sargent Selch turbo pump on foil box, MP02, upstream 8 GeV, 400 MeV to Linac.Replace vacuum valve on 400 MEV to inj girder line, on MP02, on upstream 8 GeV line, 400 MeV to Linac.		4 4	$5,000 $3,000	$20,000 $12,000	864	
LowLow	Replace Sargent Welch roughing pump on foil box, MP02, upstream 8 GeV, and 400 MeV to Linac.Replace Sargent Selch turbo pump on foil box, MP02, upstream 8 GeV, 400 MeV to Linac.		4 4	$7,000 $5,000	$28,000 $20,000	88	
LowLow	Replace Ion Pump bake out vacuum systemReplace Sargent Welch roughing pump on foil box, MP02, upstream 8 GeV, and 400 MeV to Linac.		1 4	$12,000 $7,000	$12,000 $28,000	8	
Low	**TOTAL** Replace Ion Pump bake out vacuum system		1	$12,000	**$674,138** $12,000	**804**	
	TOTAL				**$674,138**	**804**	

The mechanical work listed above is largely preventative but is constrained by labor and scheduled access opportunities. The cost of doing all the work however presents a challenge to the current allotted budget. With current funding and support, the above pieces of hardware will be replaced only as failures occur at the cost of increased downtime and corresponding decreased accelerator availability. It should be pointed out that the planned Pre-Acc upgrade removes most items listed under Pre-Acc and 750 KeV line and result in a cost savings of about $140,000 in vacuum hardware.

Booster High Level Radio Frequency System

Table 3 Booster High Level

Concern	Task/Solution	Details	QTY	Unit Cost	M&S Cost Total	Man-Hrs (tech)	Man-Hrs (eng)
	Booster HLRF						
	Solid State Driver Upgrade						
	Booster HLRF						
High	Power Amps		22	$74,976	$1,649,472	1760	176
High	Modulators		22	$70,334	$1,547,348	5720	1760
High	Solid State Drivers		22	$114,993	$2,529,846	5280	528
High	System Installations		22	$18,000	$396,000	1408	352
High	In House Amp		22	$40,000	$880,000	--	--
	New Solid State SUB TOTAL				$4,446,666	14168	
High	W. Gallery Bias Transformer	15 Hz Operation/Reliability	10	$17,500	$35,000	400	80
Medium	W. Gallery FBS-SCR + H. sinks	15 Hz Operation/Reliability	10	$12,500	$25,000	800	160
High	W. Gallery FBS Misc	15 Hz Operation/Reliability	10	$5,000	$50,000	400	40
High	Anode Supply Transformer	15 Hz Operation/Reliability	2	$130,000	$260,000	48	24
High	13.8 KeV VCB	15 Hz Operation/Reliability	2	$250,000	$500,000	80	40
High	Misc Anode Supply	15 Hz Operation/Reliability	2	$50,000	$100,000	320	160
Medium	Refurbish Tuner Cooling	15 Hz Operation/Reliability	19	$15,000	$285,000	304	152
Medium	84 MHz Damper Loads	15 Hz Operation/Reliability	38	$1,000	$38,000	76	0
Medium	Refurbish Tuners	15 Hz Operation/Reliability	57	10,000	$570,000	1140	40
Medium	Spare Cavity	15 Hz Operation/Reliability	1	$30,000	$30,000	120	80
	Sub Total				$1,893,000	3688	776

RF Total	$6,339,666

Items not included here, such as utilities, are included in their respective sections. While some items have been thoroughly specified (e.g. Solid State items), others – like spare cavity, are only rough estimates. Operations and reliability are listed in the table as one item due to the concern that running at 15 Hz may not be done reliably without recommended work. The spare cavity work is in progress but funding and manpower severely limit the pace of the work. One high level RF topic not listed above is the replacement of all the present cavities. This item will be discussed in the following 'concerns' section of the report.

Magnet Systems

Table 4 Booster Magnets

	Magnet Systems						
	Booster Magnets						
Concern	***Magnet / Status***	***Associated Power Supply / Status***	**QTY**	***Unit Cost***	***M&S Cost Total***	***Man-Hrs (tech)***	***Man-Hrs (eng)***
	400 MeV Line						
Low	Chopper: 1 spare HV terminal, unit is designed to be repaired in place. 15 Hz capable **No spare	Uses commercial DC HVPS. FNAL built thyratron pulser, thyratrons and HV cable commercially available.	1				
Low	Lambertson: New spare stored in Linac enclosure	Uses commercial DC PS.	1				
Low	Loma Linda Quads: 3 spares	Uses commercial DC PS.	8				
Low	Green Quads: 6 spares	Uses commercial DC PS.	8				
Low	MH1, MH2: 3 spares, one mounted on stand	Uses commercial DC PS.	3				
Low	MV0: 1 spare	Uses commercial DC PS.	1				
Low	MV1, MV2: 4 Spare coils plus complete spare magnet is being rebuilt from old MH1 (requires new pole tips, beam pipe and LCW	Uses commercial DC PS.	2				

	manifolding.) Coils can be replaced in place, has Been done.						
Low	Trims: Spares exist	FNAL build supply system, can/will be replaced by new Booster trim style supplies	12				
	Booster						
High	Gradient Magnets: Prepping of spares -- Short term: 1 of each class of magnet to be electrically tested and put under high vacuum. Long term: prep, test and put under high vacuum as many as can be made into operational spares, 11 magnets maximum. 15 Hz capable.	Uses FNAL built supplies, in house repairable, all new power transformers, 15 Hz capable (no spare filter spare choke coils are in storage) 96 operational/ very old/ rad damaged? Only failure modes to date are vacuum and LCW leaks. No coil insulation failures. Before 1973 there were some two ceramic insulator failures and some magnets were changed out.	96		$80,000		
Low	Chokes: 2 spares, can and have been rebuilt or repaired by TD		48				
Low	Capacitors: ~ 60 spares and replacements are commercially available, present caps are second generation.		~800				
Low	Trims: All new, 14 spares, 15 Hz capable.	All new supplies, FNAL built, in house repairable, 15 Hz capable	48				
	Injection / Extraction						
Low	Orbump Magnets: 2 operational spares under high vacuum, a third ready to be put under vacuum, 15 Hz capable.	FNAL built, 15 Hz capable	3				
Low	Extraction Septa, MP02 & MP03: 2 tested spares, 1 under high vacuum, the 2nd	FNAL built, 15 Hz capable PS polarities reversed as a	2				

	will be put under high vacuum, 15 Hz capable.	preventative measure.					
Low	Dogleg Dipoles: 8 spares in storage	Uses commercial DC PS.	4				
Low	VBC0: Tested spare in storage	Uses commercial DC PS.	1				
Low	VBC1: Rebuilt spare has completed magnetic field measuring at IB1 and is ready for storage.	Uses commercial DC PS.	1				
Low	EDWA dipoles: 1 spare in storage	Uses commercial DC PS.	4				
Low	Quads: Pbar SQA - SQE style, spares exist	Uses commercial DC PS.	9				
Low	Kicker Magnets: 7 new spares, TD ready to build more, primary failure mode is radiation damage to HV insulating material. 15 Hz capable.	Uses commercial DC HVPS. FNAL built thyratron PFL type pulser, thyratrons and HV cable commercially available.	11				
	Total				$8,0000		

Note: Future costs for Booster corrector magnets and all pulsed magnets are minimal since we have enough spares. **The cost to replace the gradient magnets is not considered. A new gradient magnet would basically mean a redesign of the Booster and is considered outside the scope of this task force.** If failures were to start to occur the first task would be to understand the failure mode with rebuilding the failed magnets the likely option. It may be useful to have engineering look at a design replacement in the event that failed magnets are too hot or can't be rebuilt. Not shown in table is labor estimates to repair or replace a dipole gradient magnet. An estimate for replacing a gradient magnet and the retuning of orbits to stable operations is about 1 month. The estimate(s) depends largely upon location. The hardware to replace a magnet has recently been assembled but can't be fully tested.

Table 5 Linac Magnets

	Magnet Systems						
	LINAC Magnets						
Concern	***Magnet / Status***	***Associated Power Supply / Status***	**QTY**	***Unit Cost***	***M&S Cost Total***	***Man-Hrs (tech)***	***Man-Hrs (eng)***

750 KeV							
Low	Triplett Ends Q1/Q2 Magnet: N/A New Injector	Power Supply: N/A New Injector	6				
Low	Triplett Centers Q1/Q2 Magnet: N/A New Injector	Power Supply: N/A New Injector	3				
Low	Triplett Ends Q3 Magnet: N/A New Injector	Power Supply: N/A New Injector	2				
Low	Triplett Centers Q3 Magnet: N/A New Injector	Power Supply: N/A New Injector	1				
Low	Long Quads Centers Magnet: N/A New Injector	Power Supply: N/A New Injector					
Low	Short Quads Ends Magnet: N/A New Injector	Power Supply: N/A New Injector					
Low	Trims Magnet: N/A New Injector	Power Supply: N/A New Injector					
Low	45 and 90 bends Magnet: N/A New Injector	Power Supply: N/A New Injector					
Linac Low Energy							
Medium	Tank Quads Type I Magnet: Repair on Failure	Power Supply: Upgraded/Spares	8/0				
Medium	Tank Quads Type II Magnet: Repair on Failure	Power Supply: Upgraded/Spares	10/0				
Medium	Tank Quads Type III Magnet: Repair / Replace	Power Supply: Upgraded/Spares	18/0				
Low	Tank Quads Type IV Magnet: Repair / Replace	Power Supply: Upgraded/Spares	22/1				
Low	Tank Quads Type V Magnet: Repair / Replace	Power Supply: Upgraded/Spares	125/3				
Medium	Tank Quads Type VI Magnet: Repair / Replace	Power Supply: Upgraded/Spares	25/0				
Low	Linac Trims Magnet: Repair on Failure		16/ Unknow n				
Linac High Energy							

Low	HE Linac Quads	See 400 MeV Section	See 400 MeV				
	400 MeV						
Low	Spectrometer Magnet	Magnet: Switch to alternate coils Power Supply: Upgrade/Spares	1/Built In Coils				
Low	Super Trims						

The Linac magnets can be divided into two sections: internal (in the DTL tanks) and external elements. The internal elements are quadrupoles and have failed several times in recent years. The repair process can vary substantially quadrupole to quadrupole and due to limited spares a rebuild is the only option. A re-tune of the line while the repair or access time becomes available is the current procedure. All external elements have spares and are accessible. The 750 KeV line elements have been listed as not applicable due to their planned retirement in 2012.

Controls and Instrumentation

Table 6 BPM Systems

	Instrumentation						
	BPM Systems						
Concern	***Task/Solution***	***Details***	**QTY**	***Unit Cost***	***M&S Cost Total***	***Man-Hrs (tech)***	***Man-Hrs (eng)***
	Linac Low Energy						
Low	Low Energy: 14 BPMs						
		Cabling	yes		$6,000	160	
		Transition Mod	1	$1,500	$1,500	120	
		Timing Board	8	$4,000	$32,000	120	
		VME Crate	1	$7,000	$7,000	120	
		VME uP	1	$3,800	$3,800	120	

		Digitizer (8ch)	8	$2,000	$16,000	160	
		Sum $66300.00			$66,300	800	
	Linac High Energy						
Low	High Energy: 30 BPMs						
		Cabling	yes		$6,000	120	
		Transition Mod	15	$1,500	$22,500	120	
		Timing Board	1	$4,000	$4,000	120	
		VME Crate	1	$7,000	$7,000	120	
		VME uP	1	$3,800	$3,800	120	
		Digitizer (8ch)	15	$2,000	$30,000	300	
		Sum $60,300.00			$73,300	900	
	400 Mev						
Low	400 MeV: 18 BPMs						
		Cabling	none				
		Transition Mod	9	$1,500	$13,500	120	
		Timing Board	1	$4,000	$4,000	120	
		VME Crate	1	$7,000	$7,000	120	
		VME uP	1	$3,800	$3,800	120	
		Digitizer (8ch)	9	$2,000	$18,000	160	
		Totals			$63,500.00	640	
	Booster						
Low	Booster: 48 BPMs						
		Cabling	none				
		Transition Mod	24	$1,500	$36,000	420	
		Timing Board	4	$4,000	$16,000	420	
		VME Crate	4	$7,000	$28,000	420	

		VME uP	4	$3,800	$15,200	420	
		Digitizer (8ch)	24	$2,000	$48,000	380	
		Totals			$110,400	2060	
	TOTALS				**$329,100**	**4400**	

The present Linac BPM system is difficult to maintain and discussion has been underway to replace much of the hardware outside of the actual BPMs. Upgrades to the 400 MeV and Booster have been done over the years. For example new cabling has been installed for the 400 MeV BPM system. However all systems need new frontend hardware since the analog frontend cards are no longer made and contain obsolete hardware.

Table 7 Controls

	Controls						
Concern	***Task/Solution***	***Details***	***QTY***	***Unit Cost***	***M&S Cost Total***	***Man-Hrs (tech)***	***Man-Hrs (eng)***
	Linac						
Low	SRMs: Replace Hi Energy SRMs with HRMs; SRMs to be used as spares for Low Energy End	About 75 SRMs with discontinued/obsolete parts			$166,000	640	480
Low	BPMs: A new system should be designed by Instr. Dept. which would require some interface…	Already missing hardware so that not all BPMs are instrumented.			See Instrumentation estimates		
Low	Misc. IRMs: Upgrade from MVME162s to MVME5500s	IRMs have MVME162 cards which are discontinued by Motorola			$26,000	80	40
Low	Motion Control: Replace with modern controllers similar to wire scanners	Emittance Probe are antiquated Fermilab built modules			$7,000	120	40
Low	Test Bench: Upgrade with HRMs	IRMs have MVME162 cards which are discontinued by Motorola			$20,000	120	80

	400 MeV							
Low	BPMs: Upgrade digitizers, crates, processors	Comet Boards discontinued, replacement parts expensive or unavailable, RF Modules scarce and hard to maintain			$25,000	480	640
	Booster							
Low	MADCs: Upgrade to HRMs	Old equipment hard to maintain, crosstalk prone (12-190s, 13-290s)			$75,000	320	80
Low	BPMs: Upgrade - new digitizers, crates, processors & trigger generators (this does not address the RF Module maintenance issues)	Comet Boards discontinued, replacement parts expensive or unavailable, RF modules and trigger generators hard to maintain, NOT capable of true 15 Hz operation			$60,000	640	640
Low	HLRF: Upgrade IRM from MVME162s to MVME5500s or HRMs; purchase spare local control touch pad interfaces	IRMs have MVME162 cards which are discontinued by Motorola and are difficult to keep up with system improvements. Local control touch pads are wearing out.			$120,000	640	640
Low	Misc. IRMs: Upgrade IRMs from MVME162s to MVME5500s	IRMs have MVME162 cards which are discontinued by Motorola and are difficult to keep up with system improvements.			$10,000	80	40
Low	Clock and Camac Links: Upgrade to Fiber system	Outdated electronics - maintenance issues			$94,500	320	160
Low	Vacuum System: Should be ok	PLCs front ended by BOOVAC					
Low	Loss Monitors: Upgrade IRMs with MVME5500s or replace IRMs with HRMs … could retire the 290 inputs	These are monitored both by 290s and by IRMs with MVME162s.			$63,000	160	40
Low	BLLRF1: Over time replace GPIB connected devices with Ethernet devices	This has lots of GPIB Connections					
Low	BLLTEK: PC with						

	Labview™						
Low	GMPS : This presumably will be changed only if EE support modifies the supply.	Camac cards					
Low	Multiwire : We have adequate spares and these modules have been dependable in the past… no upgrade required by the dept.	192 Camac cards					
	TOTALS				**$666,500**	**3600**	**2160**

There are no spares of the analog I and Q modules to keep the present LINAC BPM system operational. The new electronics consists of a transition module which contains a band-pass filter that is activated by a passing LINAC pulse. The filter ring frequency is down-converted to an intermediate frequency (IF) which is digitized at 125 MHz and stored in memory for position and intensity computation. The digitizer is an eight channel FPGA-based VME 64X board which has been designed, built and tested in the instrumentation department. Each BPM crate would have a microprocessor board MVME5500 acting as a crate controller, a timing board providing an injection/extraction trigger and IF frequencies in addition to N number of digitizer-down converter boards all contained in a VME64X crate connected to the Control System through ACNET.

Table 8 Diagnostics

	Instrumentation						
	Diagnostics						
Concern	***Task/Solution***	***Details***	**QTY**	***Unit Cost***	***M&S Cost Total***	***Man-Hrs (tech)***	***Man-Hrs (eng)***
	Multi-Wire Systems						
Low	Multi-Wire System: Pre-Acc	1,000	3	$3,000	$120		
	Multi-Wire System: Linac Low Energy	1,000	3	$3,000	$120		
	Multi-Wire System: 400 MEV	TBD	12				
	Multi-Wire System: Booster	TBD	2				

	BLM Systems						
Low	Low Energy Linac BLM System		40	$222.00	$8,880.00	160	8
	Digitizer Card		10				
Low	High Energy Linac BLM System		40	$222.0	$8,880.00	160	8
	Digitizer Card		10				
Low	400 MeV BLM System		12	$222.00	$2,664.00		
	Digitizer Card		3			80	4
Medium	Booster BLM System Upgrade						
	Digitizer Card		92				
	TLM Systems					400	20
Low	TLM System						
	7/8 in Heliax		800 ft.	$9	$7,104		
	TLM Chassis		4	$4,000	$16,000		
	Connectors				$1,500		
	Total				**$45,028.00**		

Toroids

The proton source uses 35 toroids and all of them would get upgraded partially or completely. Twelve locations would maintain the present Pearson CT and twenty three would get a new Pearson CT model 3100 1.0 V/A.

The electronics would be placed at three different locations along the LINAC (?). The toroid system would consist of

1) MVME5500 Processor acting as crate controller. Timing board.
2) Calibration boards with 8 independent analog outputs.
3) Digitizer Down-Converter boards to handle up to 10 toroid signals and calibration signals.

4) VME64X crate

Cabling consisting of two ¼ inch heliax cables per toroid system, one for calibration and one for signal. The crate would display raw data and processed data via ACNET.

Multiwire System

Presently the instrumentation department maintains multiwire systems along the 8 GeV line starting at NW800 up to NW852 for a total of 18 multiwire systems. There is a request to replace a multiwire system with a new one and installed at MWIRE5 downstream of the spectrometer as well as a second system upstream of the dump.

The new multiwire system will have 2 Axis vacuum can. Stepper motors would control the X and Y position of the 16 wire plane array. The standard SWIC scanner electronics provided by the Accelerator Division controls department would be used. Costs are yet to be determined.

The present wire scanners in the proton source consist of a fork with a single wire along the X axis, a second wire along the Y axis and a third wire at a 45 degree angle. The wire scanner is driven diagonally into the beam, during a measurement, then driven backwards to remove it from the beam. The analog signal is reported back to ACNET through the control system.

The number of wire scanners and their location are:

1) 400 MeV line has 12 wire scanners.
2) MTA line has 7 wire scanners.
3) High Energy LINAC section has 16 wire scanners.
4) Low Energy LINAC has 3 wire scanners.
5) 750 KeV line has 2 wire scanners.

Total Loss Monitors (TLM)

A total loss monitor system based on 7/8 inch Andrews heliax air dielectric coaxial cable (HJ5-50) flooded with a standard gas (%80 Argon, %20 CO2). The system is divided into four segments along the LINAC, each segment is biased with 2,100 VDC and the center conductor is read out into a standard loss monitor chassis capable of integrating and differentiating the signals.

Cost: As noted in the above table;

The chassis is supplied by the Instrumentation department at a cost of $ 4,000.00 per chassis. This includes the voltage bias source and the daughter cards required by each TLM segment.

7/8 inch Air Dielectric Coaxial cable $ 8.88 per foot.

Booster Low Level (Cost and time estimates for upgrades to the Booster Low Level RF)

The upgrades are intended to improve the reliability of the Low Level system and to also provide more flexibility of function. Improved Low Level control will help the Booster reach higher rep rates and maintain acceptable losses. Two modules are currently in development, a new frequency source, which also provides control of the RF reference phase, and a new triple phase detector module. These two modules will replace ten modules currently used for Booster acceleration phase lock and phase lock to Main Injector. A description of how these modules will be integrated into the current system is outlined in "Configuring the LLRF System for Testing New Frequency and Phase Control Components", December 2009, Beams-doc-3604-v1.

The improvements we expect to achieve with the new system are:

1. A reduction in the number of hardware modules we must maintain and the amount of cable congestion in the racks.
2. Greater flexibility to control the Main Injector phase-lock process.
3. More precise and flexible control of RF phase.
4. Greater flexibility in testing modifications to the control algorithms.

The table below outlines the recommendations.

Table 9 Booster Low Level

	Booster Low Level RF Controls						
Concern	***Subsystem/Module***	***Status***	**QTY**	***Unit Cost***	***M&S Cost Total***	***Man-Hrs (tech)***	***Man-Hrs (eng)***
	Low Level Freq / Phase Reference						
Medium	Triple Phase Detector Module	Printed circuit design fabrication and testing. Currently 70% complete			$5,000	480	480
Medium	VME DDS Frequency/Phase Reference	Central module of the Frequency/Phase Control Upgrade. Upgrade needed to eliminate phase shift modules and improve the Main Injector phase-lock process. Currently 50% complete.			$15,000	960	1920

Low	Freq./Phase Control: Resistive Wall Beam Pickup at L18	Spares available					
Low	Freq./Phase Control: Resistive Wall Beam Pickup at L16	Spares available					
Low	Freq./Phase Control: ENI 3W RF Amplifier	Spares available					
Low	Freq./Phase Control: AM Detector/Beam Gate Generator	Included in Phase Detector Upgrade. Possible component obsolescence.					
Low	Freq./Phase Control: Manual Phase Shifter	No Concern					
Low	Freq./Phase Control: Fast Phase Detector / Mode Controller	Included in Phase Detector Upgrade. Possible component obsolescence.					
Medium	Freq./Phase Control: Booster Digital Frequency Source / Bias Curve Generator Upgrade	Upgrade needed to eliminate phase shift modules and improve the Main Injector phase-lock process. Possible component obsolescence.					
Medium	Freq./Phase Control: Phase Shifter	Included in the Frequency/Phase Control Upgrade.					
Medium	Freq./Phase Control: Paraphase Control Module	Included in the Frequency/Phase Control Upgrade.					
Medium	Freq./Phase Control: Paraphase Curve Generator Module	Included in the Frequency/Phase Control Upgrade.					
	Radial Position Control						
Low	RPOS Control: Phase Shift Controller	New layout with current components or functions integrated into new Frequency/Phase Control Upgrade. Possible component obsolescence.			$10,000	480	960

Low	RPOS Control: AC RPOS Damper Module	Possible component obsolescence. New layout with current components or functions integrated into new Frequency/Phase Control Upgrade					
Low	RPOS Control: BPM RF Module (dwg. EE-37626)	Possible component obsolescence.					
Low	RPOS Control: VXI Cogging Module						
	Timing Modules						
Low	Timing Modules: Divide by 84 Module	Timing modules can be integrated within a single new module. Possible component obsolescence.			$10,000	480	480
Low	Timing Modules: Beam Sync Module	Possible component obsolescence.					
Low	Timing Modules: Gap Detector / Gate Generator	Possible component obsolescence.					
Low	Timing Modules: Fast Sample and Hold #1	Possible component obsolescence.					
	MI Phase Lock						
Low	MI Phase Lock Modules: Gate Sync Modulator						
Low	MI Phase Lock Modules: ENI 3W RF Amplifier						
Medium	MI Phase Lock Modules: Timing Generator	Component Obsolescence / Desire more flexibility of MI phase-lock process. Included in Phase Detector Upgrade and Frequency/Phase Control Upgrade.					
Medium	MI Phase Lock Modules: 32 Countdown Module	Included in Phase Detector Upgrade and Frequency/Phase Control Upgrade.					

Medium	MI Phase Lock Modules: High Stability Phase Detector	Included in Phase Detector Upgrade and Frequency/Phase Control Upgrade.					
Medium	MI Phase Lock Modules: Program Generator	Included in Phase Detector Upgrade and Frequency/Phase Control Upgrade.					
Medium	MI Phase Lock Modules: Parabola Zero Box	Included in Phase Detector Upgrade and Frequency/Phase Control Upgrade.					
Medium	MI Phase Lock Modules: Fast Sample and Hold #2	Included in Phase Detector Upgrade and Frequency/Phase Control Upgrade.					
	Environmental						
Low	Air Conditioner for LLRF Room	New AC unit			$100,000		
	TOTAL				**$140,000**		

High/Low Energy Linac RF Systems

60 KW Modulators

Currently there are 8 PFN-based modulators operating in the high energy end of the Linac (7 + 1 hot spare). The modulator topology is divided into two sections, a charging supply and a pulse forming network (PFN) which includes a pulse transformer and a klystron.

The charging supply has two sets of magnetic components, a 480V delta-wye rectifier transformer and a 2.4 Henry choke which charge twelve 27 microfarad DC NWL capacitors.

The second component is a PFN that is charged from the charging supply through an 24 SCR based switch. The main components of the PFN are twenty six 1.0 microfarad 22 KV Maxwell pulse capacitors and twenty six 7 microhenry chokes.

The PFN transfers its energy to the primary of a 1:20 turn Stanganes pulse transformer using a 24 SCR switch, in turn the secondary of the transformer modulates the cathode of a 12 MW klystron.

Klystrons and Focusing Solenoids

The proton source requires seven operating klystrons plus a hot spare. The current klystron was designed by Litton Industries for Fermilab. Litton sold their Power Tube division to L3 Communication who now produces klystrons. We currently have a business order agreement with L3 Communications that they will repair a fixed number of klystrons at a fixed cost. This agreement lasts for three years and can be renewed. In the event they don't want to renew the agreement it could be an indication they are going out of business and at that time we should buy seven new klystrons for our LINAC.

Our current experience with all the Litton klystrons show a Mean-to-failure time of 80,000 hours. Two of the original tubes are still in operation, four klystrons failed in storage due to corrosion (they were redesigned by L3 Communication to prevent this from happening again).

The tubes can be repaired at a cost of $225,000.00 and a new tube costs $375,000.00.

We also need a new focusing solenoid for the klystrons; these are manufactured by Stangenes Industries. We have two spares on hand. Of the ones in operation one sprung a water leak and it has been repaired.

Long term Modulator Operation Requirements:

We should have three sets of magnetics on hand, the hot spare modulator components would count as one available set. This means we need to purchase:

1) 1 Delta-Wye rectifier transformer from Stangenes Industries
    a. XFMR S/N 7690-5/R-3551
2) 1 2.4 Henry choke from Stangenes industries
    a. SI-6704
3) 1 1:12 150 microsecond pulse transformer from Stangenes industries
4) 24 14 KVDC 21.7 capacitors from NWL
    a. #10881
5) 26(52) 22 KV 1.0 microfarad capacitors from Maxwell industries
    a. #36167
6) 40 SCRs for the PFN and/or Charging Supply switches
7) 7 Ignitrons
8) 1 pulse XFMR SI-6545

Table 10 Klystron Systems

Klystron Systems							
Concern	***Task/Solution***	***Details***	**QTY**	***Unit Cost***	***M&S Cost Total***	***Man-Hrs (tech)***	***Man-Hrs (eng)***
Low	Delta Wye XFMR		1	$45,625	$45,625		

Low	Charging Choke		1	$20,700	$20,700		
Low	21.7uF Cap		24				
Low	1.0uF Cap		26	$1,540	$40,040		
Low	Pulse XFMR		1	$64,750	$64,750		
Medium	Klystrons L-5859*		1	$375,000	$375,000		
Medium	Klystron Repair L-5859*		1	$225,000	$225,000		
Low	Klystron Repair VKP-7955		1	$135,000	$135,000		
Low	SCR		48				
Low	Fc Solenoid		1	$90,000	$90,000		
Medium	Ignitron 7703LP		7	$1,475	$10,325		
	TOTAL				**$1,006,440**		

*Klystrons – The table below provides additional tube information. The lifetime issue and/or an early failure may require one additional spare or rebuild (if possible) at some latter date (see table below.) Miscellaneous electronics components purchased on an as need-basis, to maintain continuous operation of the seven systems.

Present L-5859 Status

- Current inventory on these tubes is the following:
- Active: 7
- Spare: 8
- Stand by: 1
- Conditioned: 1
- Unconditioned: 6
- Being Rebuilt: 0

  Total: 15 tubes

The table below shows the current number of years each Klystron station has been operational and the estimate of how many more years there are left for each system assuming a lifetime of 20 years.

Table 11 Klystron Hours

Klystrons	Years of Operation	Remaining # of years
K1	6.0	14

K2	16.1	3.9
K3	14.3	5.7
K4	6.3	13.7
K5	16.5	3.5
K6	9.4	10.6
K7	14.5	5.5

Present VKP-7955 Status

We have been using this klystron for the high RF power drive for the Buncher, Vernier and the Un-buncher cavities of the HE linac. They have been in continuous operation for over 16 years and we have had zero failures. The average life time of the klystrons has reached 135,200 hours. This klystron is made by CPI.

Low Energy Tube Status

Electronics components purchased on an as need-basis, to maintain continuous operation of the five low energy Linac systems are not listed below.

Table 12 Low Energy Linac Tubes

Tube	Details	Spares	Cost (new/rebuild)	Concern
7651 Tetrode	Burle, 5 in use, Lifetime 4.8 years	8	2,402	Low Might be replaced with solid state, Burle makes about 24/year
4616 Tetrode	Burle, 5 in use, Lifetime 3.3 years	6	53,740	Low Burle makes about 20-25/year
7835 Triode	Burle, 5 in use, Lifetime .93 year	14 3 others being rebuilt and 7 more ready to be rebuilt	208,640	High Only used by FNAL, LANL, BNL. Burle makes about 10/year, Quality Control and Cost are going the wrong way LANL looking to replace
F-1123	Discontinued –Rebuilds by two companies: CPI and Kennetron 15 in use, Lifetime 2 years	44 1 being rebuilt 17 in processing 6 possible rebuilds	3,000	Medium Recent quality issues

ML-6544	CPI, 15 in use, lifetime 1.6 years,	13	12,400	Low High Production Tube
8613 Thyratron	Richardson, 5 in use, Lifetime 4 years	9	1,245	Low
NL-37248 Ignitron	Richardson, 5 in use, Lifetime 5.7 years	6	2,580	Low/Medium Mercury issue
4E27A15	Richardson, 5 in use, Lifetime 7 years	6	550	Low
3CX3000F1 Triode	Richardson, 5 in use, Lifetime 7 years	5	1,590	Low
GL-7703 Ignitron	Richardson, 5 in use, Lifetime 10 years	5	2,166	Low

LINAC and BOOSTER Power Distribution Systems

Both machines have aging power distribution systems with elements that are no longer manufactured and have limited repair options from industry. Some of these elements include the circuit breakers in the house power transformers, the house power transformer and Motor Control Center, MCC buckets. To reduce the exposure to any single point failure that would cause extended down time ONE each of the systems can be replaced to increase the availability spare parts.

Table 13 Power Distribution Systems

Power Distribution							
Concern	***Task / Issues***	***Details***	**QTY**	***Unit Cost***	***M&S Cost Total***	***Man-Hrs (tech)***	***Man-Hrs (eng)***
Medium	LINAC 480vac breaker panel:	Procure new equipment to improve the availability of spare parts for other equipment in the lower gallery.	1	$65,000	$65,000		80
Medium	LINAC 13.8kvac line side breaker and cabinet:	Procure new line side breaker equipment to create spare equipment for the remaining equipment in the lower gallery.	1	$50,000	$50,000		80

Medium	LINAC Transformer:	Procure a new transformer that has a lower temperature rise on the coils. Change from 150 Deg C rise to 80 Deg C rise to reduce the gallery heat load and free up one transformer for spare.	1	$200,000	$200,000		80
Medium	LINAC line filter:	Design and procure a new 480vac line filter to improve the line voltage during NTF operation.	2	$35,000	$70,000		320
Medium	LINAC Motor Control Center:	Procure a replacement MCC to free the present equipment for spare parts.	1	$30,000	$30,000		80
Low	LINAC 480vac breaker panel: installation.	One week of down time to remove the present system and install the new panel as a unit.	1	$20,000	$20,000		40
Low	LINAC 13.8kvac line side breaker and cabinet: Installation	Two days of down time to remove the present system and install the new gear.	1	$10,000	$10,000		40
Low	LINAC Motor Control Center: installation.	One week of down time to remove the present system and install the new MCC as a unit	1	$10,000	$10,000		40
	TOTAL				**$455,000**		560

Concerns and Solutions

The following section will describe systems found to be a high concern and detail possible solutions. A more complete analysis and cost scoping process will need to be done on all the concerned systems. This first pass is an attempt to provide guidance for further planning.

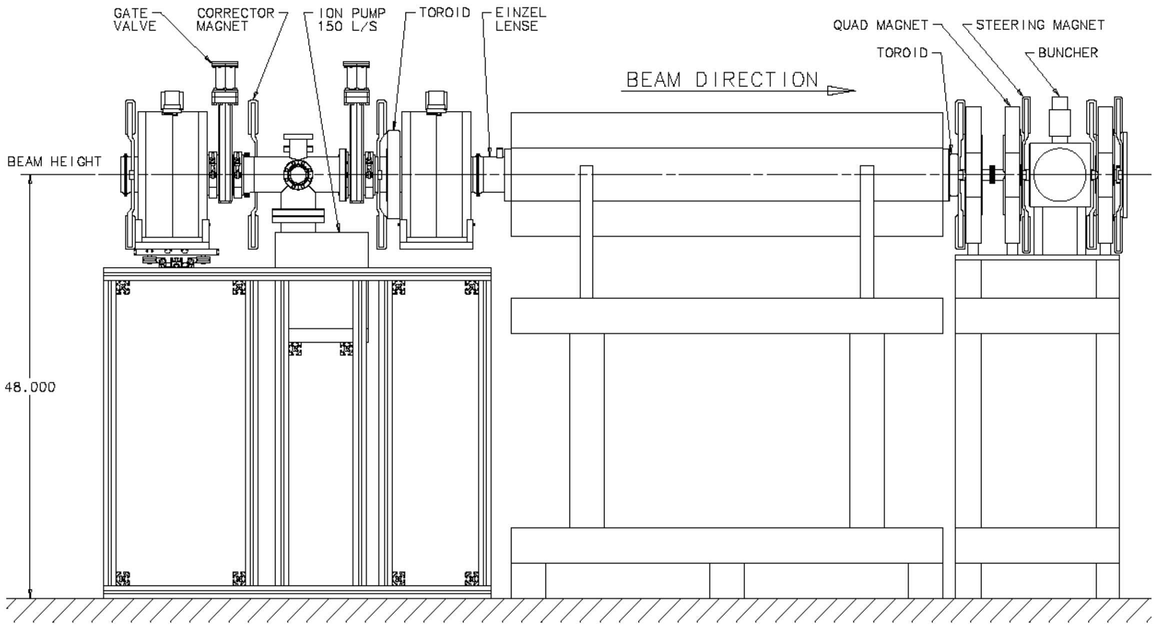
Linac and Pre-Accelerator High Level Concerns

Cockcroft Waltons/750 KeV Line

The Pre-Acc and Linac have several high concern systems. The first concern area is the two Cockcroft-Waltons. The CW's have been in service since about 1970 (the H- source was added several years after the I-) with only minor changes to the original components and design. Over the past 40+ years of operations the sources have had high up time due to the fact that there are two sources and variations in current do not contribute to downtime. However the sources have had several major failures two of which have resulted in repairs that took about one year. With greater proton throughput demands, variations in output current have become more of an issue. Another issue is that the maintenance required keeping the sources operating at suitable levels are substantial and becoming more difficult. The sources have many unique components that are difficult to maintain and may require substantial engineering to replace. The solution that the Accelerator Division has chosen is to replace the CWs with a RFQ based injector. The new design has progressed quickly and in May of 2010 an RFQ order was placed. The other components in the design will be ordered this Fall with the goal of being in a test stand in early 2011. The funding of this project has been an issue and will need to be addressed if the installation goal of 2012 is going to be met. The removal of the old 750 KeV line and Source components and installation of the new RFQ injector system will require approximately three month shutdown. The installation is planned to correspond with the planned 2012 shutdown. The initial design document can be found in the public document database #Beams-doc-3646-v1. The design is based upon the experience at BNL with additional research/testing done at FNAL (HINS and source upgrade design studies.) The plan is to replace the present injector with a round (dimpled) magnetron 35keV source followed by a 750keV RFQ. The design uses conventional technology such as solenoids, buncher cavity and steering elements to match into the present drift tube linac (DTL). For a small additional cost of adding a second magnetron, solenoid and steering elements, uninterrupted maintenance and repair can be carried out. The design intends to reuse as much of the present power sources, beam line hardware and infrastructure in order to keep cost at a minimum. Required new items are a buncher cavity, three solenoids and a 1.2 m long RFQ, several trim magnets, (beam pipe and the associated hardware will require mechanical labor), three quadrupoles and a new electrostatic (Einzal) lens.

Below is the basic line layout.

Side View



Top View

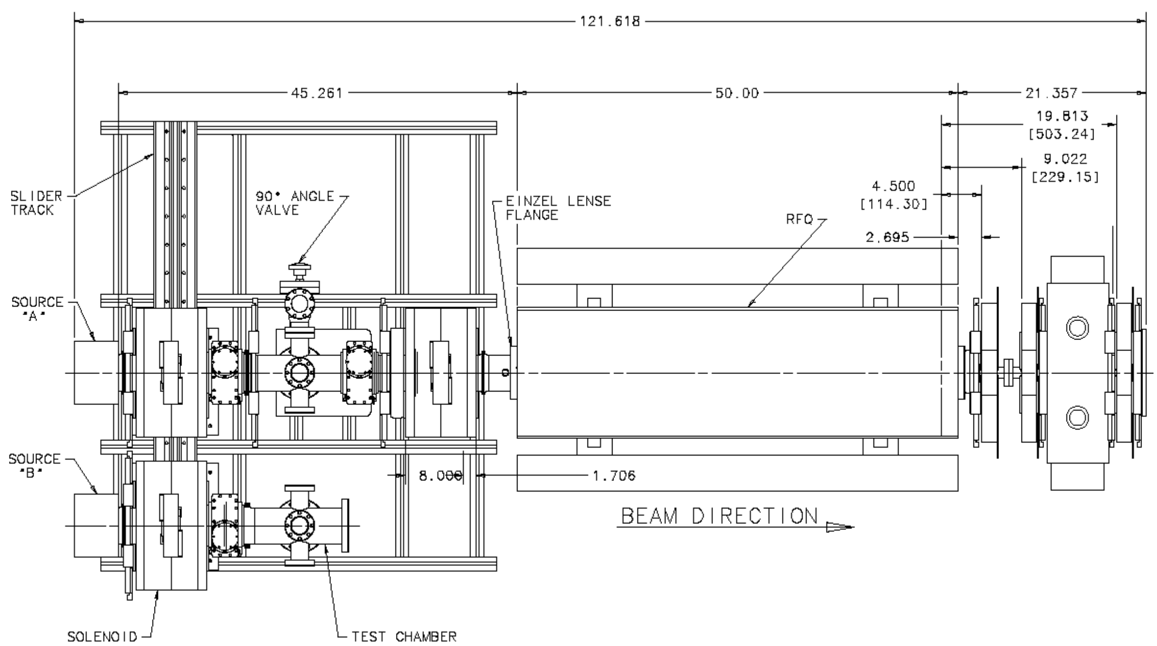


Table 14 Pre-Acc RFQ Work

Item	Number	Cost/Item	Cost	Concern	Notes
Sources	2	15,000	30,000	Low High Voltage Issues	
Solenoid	3	45,000	135,000	Low Time	Drawings Done
Quads	3	45,000	135,000	Medium Cooling/Size	Tech Div still working design
Trims	6 - 7	?	?	Medium Time - Simple Trim	Tech Div still working design
Buncher	1	?	?	Medium	Just received first design
RFQ	1	220,000	220,000	Low Time	Being Built
Parts & Labor			500,000	Medium Time and Funding	Engineering underway
Total			~1,000,000		Install 2012

Low Energy Modulators

The next item of high concern is the Drift Tube Linac modulators. Built in the late 1960's the technology, components, diagnostics and knowledge base has become difficult to find. The experts who have and are continuing to investigate this system will require additional time to complete a thorough review. A basic overview of the issues and possible solutions are as follows:

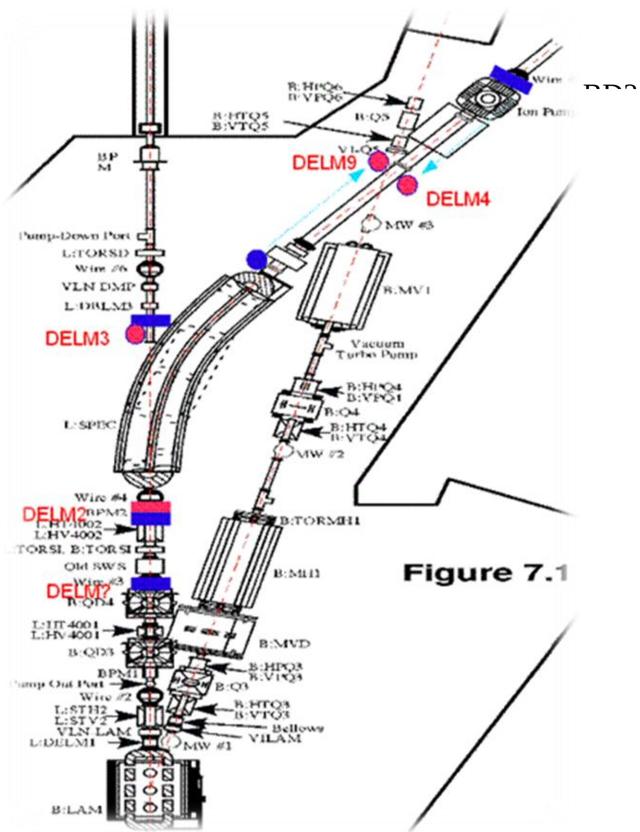
Options that are being considered are:

1) Replace the present RF amplification system with a new design that is being built at LANL. It would replace the 7835 socket and all upstream RF amplification systems. The cost is estimated at 1.1 million per station. This system is undergoing initial testing and will have results in early FY11.
2) We have been in contact with Continental Electronics Inc. about building a new modulator. They are looking at the possibility of finding a manufacturer who will make switch tubes or finding a tube that will replace the F1123 as the primary tube in our modulators. If a replacement is found then it may be possible to rebuild our present modulator based upon the new switch tube. We should have more information and a possible estimate by FY11.

3) A new modulator based on Marx Generator technology and combining switched cells with linear cells and including a bouncer circuit. This is in the early stage of research and no estimate on possible cost and delivery can be given.
4) Evaluate a proposed modulator design made by DTI Corporation to a specification similar to our own. This is also early in the review cycle and so have no estimate on time or cost.

Linac Momentum Beam Dump

In December 2007 the 400 MeV beam dump number two (BD2) (Figure 1) developed a vacuum leak underground where repair is not practical. In order to resume operations in a timely matter, Mechanical Group installed a 10 mils Ti window, separating the roughing vacuum at the dump



(almost 0.5 torr) and the good vacuum of the beam line ($\sim 10^{-7}$ torr). A roughing pump was installed which continues pumping down the momentum dump area in order to renew the air inside the vacuum chamber and inhibit the production of acids.

The current running mode is not considered to be a permanent fix. There has already been a vacuum problem at the window January 14th, 2009. A working group to formulate a long term solution for the Linac Dump #2 area was begun. The working group decided upon the following options.

1 Replace the dump.

2 Insert a sleeve that mimics the inside shape of the dump.

Dump Replacement

Replacing the dump is not the optimum choice because it would:

- Be expensive (see table 1)
- Potentially involve a large radiation dose.
- It would take many weeks to complete the project[1]
- Disposing of the old dump with a possible dose rate of 50 R/hr.

Table 15 Rough Cost estimate with Schedule Estimate

Activities	Cost Estimate	Time
Build a new dump	~ $ 70,000.00	Unknown
Civil installation	~ $ 50,000.00	6-8 weeks

2.2 Sleeve Insert

Inserting a sleeve is the option that the working group is recommending as the best solution. A design has been generated by mechanical engineering. The insert is made of OFHC copper, grade **C-19400**. Calculations show that it will withstand the mechanical and thermal stresses it will be subjected to. The sleeve will be 177.05 inches long with 82.5 inches sloping at an angle of 3 degrees to match the old dump surface.

Current Situation

Problems with the copper insert are mainly concerned with the copper material. The C19400 copper is the only alloy we have found that has good enough thermal properties and meets the strength criteria set forth in CGA (SF=2) or ASME (SF=3) when heated by the beam. The problem is that the thickest plate forged in this alloy is only forged in up to 1/8th inch thickness. We require a one inch thick plate for dissipating the heat generated by the beam.

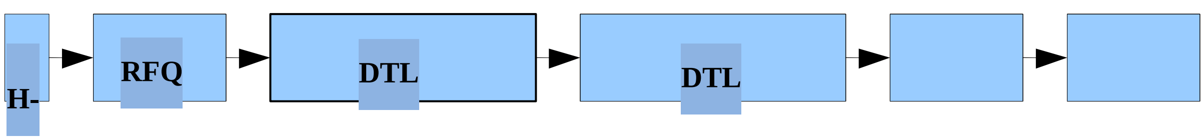
[1] The 11 months shutdown in 2012 was announced Oct/2009, 10 months later then initiation of the working group.

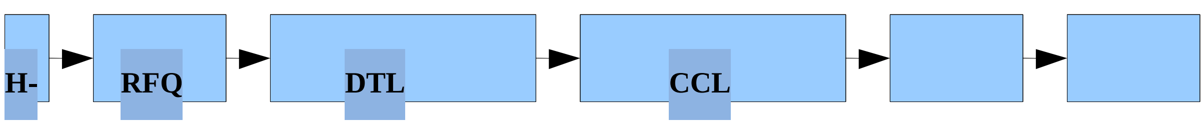
We are looking at an alternate design that uses a softer copper and a stainless steel vacuum pipe. We believe that this sandwich will provide enough strength to prevent the insert from collapsing due to the heat generated by the beam. Structural details are being studied. The cost difference is not known at this time.

Linac Drift Tube Front End

The next item on Linac high concern list is the low energy front end. The modulators, already discussed above, are only part of the issue. The entire low energy system, which consists of 5 drift tube linac (DTL) structures, can be considered a high concern. The DTL front end has been in operations for over 40 years. The DTLs are driven with high power RF tubes designed in the 1950s and the cavities themselves were built with 50 year old technology. The tuning, cooling and diagnostics of the cavities are either not working properly or require constant attention to keep operational. The lattice design if done today would improve capture and reduce emittance dilution. Tank one of the low energy Linac was a prototype and not intended for operational use. There is no spare tank one and a major failure would require a repair as the only option. The DTL tanks all show moderate to severe water damage due to numerous water leaks and condensation issues. Many of the drift tube quadrupoles are run above their power supply limit to achieve proper focusing. Given the problems we have with the RF power sources, aging DTLs and beam requirements using today's technology a new front end should be considered.

A replacement plan would be to follow the example of the Spallation Neutron Source (SNS) and replace our system with a copy of their front end klystron systems. One possible Linac front end would have a 400 MHz DTL section and then an 800 MHz CCL section. Another would have only a 400 MHz DTL and then a new 800 MHz Klystron section. The new front end would feed into our present 800 MHz klystron cavities. Understanding the parameter space and cost would require some significant time but very little effort on technology research and development. The design should consider whether to run the low energy Linac at 15 Hz or 30 Hz. The additional pulses could be used for Linac studies, MTA or NTA at no burden to HEP.





Cost estimates for the replacement is currently estimated at 27 million for the cavities and about 30 million for the RF power section. Since this is a copy of the SNS facility, engineering cost would mainly be for retrofitting the system. A more detailed cost breakdown of SNS systems being considered can be found in the attached references.

Booster High Level Concerns

Since October of 1970, the Booster has delivered over 1E24 protons. In the mid 1970s, Booster went to a multi turn injection and higher proton throughput. After almost thirty years of running less than 1E19 protons per year the demand increased due to FNALs Neutrino programs. Today, the Booster accelerates about 15 times more protons per day then 10 years ago, about 1.5E20 protons per year. The dramatic increase in proton throughput has required intensive retuning and several upgrades. The improvements made to the Booster, have allowed higher throughput while keeping the activation levels less than 1 watt per meter (outside the collimation region.) The operational requirements to run the Booster for another 15 years will require a better understanding of radiation damage issues as well as exposure issues to workers. However, an increase in throughput will most likely require additional improvements to the Booster accelerator if activation levels are to remain at the present level.

Gradient Magnets (system)

The Booster synchrotron lattice uses combined function gradient magnets. Designed in the late 1960's, based upon Cornell synchrotron magnets, approximately 114 magnets were built with 96 magnets installed. The magnets were design to accelerate single turn high intensity Proton beam from 200 MeV to 10 GeV at 15 Hz. It is estimated that many of the magnets have received over 1Mgrey of dose in the 40 plus years of operations. The magnets have been very reliable with only a few ceramic feed through failures in the early years of turn-on. (See Endnotes **iii Copy of Gradient Engineering Note**)

The Booster has never lost a gradient magnet due to coil failure. Yet this remains a source of concern since some of the magnets have seen very high levels of beam loss and the losses around the extraction region and collimator regions continue to be very high. Figure 4 below is an excerpt copied from the original coil specification. (See Endnotes iii **Copy of Insulation System Note)**

Insulation specifications - Engineering Specification -- 0322-ES-2157-A

Figure 3 Copy of Magnet Specification Insulation - Epoxy

4.5 Desired Coil Characteristics

Radiation resistance (10% drop in flexural strength) 10^{+10} rads

A study by Eric Prebys in 2003 included extensive modeling of the gradient magnets. The concluding paragraph is below.

‘ Radiation issues In the Fermilab Booster Magnets*

E. Prebys#, Fermilab, Batavia, IL 60510, U.S.A.

2003

Conclusions

Our studies indicate that the epoxy resin used as an insulator in the magnets of the Fermilab Booster may have received integrated radiation doses as high as 100 kGy over the life of the machine. The increased proton flux needed by the neutrino program could mean that some areas will receive as much as 1 MGy over the next ten years.

While these numbers are within the range where epoxy resins have been shown to work in the past, they are definitely at a level which causes some concern, particularly given our lack of details about the exact epoxy used. It is therefore extremely important to keep beam loss at a minimum in the coming years and to try to keep it as uniform as possible to avoid excessive localized dosage.

Further study is warranted, and should a magnet fail for other reasons, it will be important to inspect the condition of the epoxy. ‘

The solution the department has decided upon is as follows:

1. Locate all remaining Booster combined function magnets.
2. Determine the condition of the magnet
    a. Vacuum
    b. Ceramic feed through
    c. Outer skin
    d. Bellows and magnet face
    e. Electrical
3. Magnets are categorized
    a. Repairable
    b. Use for testing/Spare parts

4. Build up inventory of usable magnets
    a. Two D style of both end configuration (4 total)
    b. Two F style of both end configuration (4 total)
5. Store magnets in new storage area under monitored vacuum system
6. Goal is to have 8 spares total under vacuum by end of 2011
7. Build up apparatus for magnet change out
8. Write up procedure for changing magnet at all the various locations

At present we have two magnets electrically certified and under vacuum. Work is ongoing to repair the minimum number as stated above. The limited amount of spares and parts may require changes to this plan. If a magnet were to start to fail the first step would be to analyze the failure and determine if the magnet is repairable. Activation issues will be a concern and may determine viability of repairs. If multiple magnets were to fail and repairs not possible a retro fit designed magnet may be needed in short order. Areas near the collimators and extraction where the magnets have been and will continue to receive high doses of radiation will be of greatest concern.

Figure 15 Spare Gradient Magnets (Under Vacuum)

Booster High Level Radio Frequency (system)

The Booster high level RF system consist of two outdoor 30 kV anode supplies, 19 modulators, 19 bias supplies, 19 double gap transmission style cavities utilizing fast ferrite tuners, control systems, and utilities. The systems have remained largely unchanged for 40 years except that one station has been updated using a Main Injector RF type modulator, a new 150KW cathode driven RF power amplifier, and a 4KW solid state driver amplifier. Station 19, added in 2005, also has an updated modulator, 150KW PA, and 4KW solid state driver amplifier. The remaining 17 stations use the original 100 kW power amplifier (PA) mounted on top of the cavity in the tunnel. These systems have several high concerns.

1. The first high concern is the power amplifiers that have driver stages built into the tunnel-mounted amplifier module. Twenty individual tubes drive the cathode of each power amplifier. These tubes are becoming difficult to maintain, have a limited lifetime (9 to 12 months), and are supplied solely from a single manufacturer; no second source is available. The quality of tubes now delivered is variable but the trend is for shorter service life. Repetition rate and radiation levels greatly affect the tube lifetime and both have increased to meet the HEP program.
2. The next high level concern is the accelerating cavities themselves. Built over 40 years ago, there have been issues with cooling water leaks at weld joints and connections, but now erosion of the copper tubing itself is to the point of causing water leaks. For the first time in 40 years, two RF cavities have this year experienced ceramic window failure. Damage to the ceramics and other hardware components due to sparking, radiation, and thermal cycling have and will result in reduced reliability.
3. The third high level concern is the ferrite bias supply transformers. These transformers in half the stations are not rated to run at 15 Hz; they must be changed to run the Booster at 15 Hz as the program will demand.
4. The fourth high concern is conventional high power electrical system components, including the anodes supplies, transformers, and 13.8 kV vacuum circuit breakers.
5. Although not specifically meeting the criteria for high concern, a spare cavity should be considered from the machine availability perspective. A failed RF cavity, pulled from the tunnel for repair, will result in a period of reduced intensity (several months based on recent failures – two in this past year) due to limited RF power. The addition of a spare cavity will mitigate this risk.

Solid State (system)

The present Booster power amplifiers consist of 3 major sections, the distributed amplifier, the cascode amplifier, & finally the power module, all located on top of the accelerating cavity in the tunnel. When a failure occurs in any one of the 3 sections of the present power amplifier, a tunnel access is required to make repairs. The life expectancy of the present Booster Power Amplifier varies depending on the section of the amplifier. The Distributed Amplifier uses 6 water-cooled 4CW800F tetrodes (800 watt plate dissipation), which typically last about 12 months. The cascode amplifier uses 14 water-cooled 4CW800F tetrodes (800 watt plate dissipation), which also last about 12 months. Note that when tubes are changed in either the distributed amplifier or cascade amplifier, they are replaced with a complete set of new tubes, 6 or 14 respectively; at a cost of $1200.00 per tube. After a 12-month service life, the tubes become emission limited and will not supply the current needed to support the minimum power requirements. The proposed upgrade with a Solid State Driver amplifier will eliminate these tubes. Presently our annual tube budget for the small 800 watt tetrodes is $500,000. Premature failures do occur due to various mechanisms ranging from power outages to water leaks. These failures, though small in number, further reduce the average life expectancy for a amplifier. Typical repair time for a present Booster power amplifier is about 60 man-hours or more, to be compared to the proposed new power amplifier which can be serviced in less than 16 hours. This is due to the three sections of the present Booster amplifier. Each section must be independently rebuilt and tested before assembly into a complete power amplifier unit. The assembly is then tested to meet predetermined acceptance specifications. Each amplifier is run for a minimum of 4 hours on our test station to catch premature failures. The complexity of these devices, along with their age, makes the repair process very labor-intensive.

The present series tube modulators use technology from the 50's. Some of the tubes used in the high-voltage deck amplifier chassis are becoming difficult to procure. These and other parts may soon have to be replaced with "newly designed" components. The modulators use very few printed circuit boards but contain G-10 boards with point-to-point wiring. This makes troubleshooting difficult and time consuming. Failures come in many ways but typically require several days to a week or more to repair and test, especially if the failure involves high voltage arcing.

Figure 16 Inside of Booster Modulator

The upgrade plan calls for building 22 new modulators, 150 Kwatt power amplifiers, and solid state driver amplifiers. All major components would be procured from commercial vendors on a build-per-print basis; final assembly of components would be done in-house. This technique proved very successful in keeping costs to a minimum for the assembly of the Main Injector's RF equipment. Twenty-two of each will be sufficient for 19 stations with 3 spares.

The installation can be divided into two parts: station preparation & actual component installation. Once the preparation of each station is complete (could be done on down days), conversion of a single station could be done on a two-day shutdown. Stations would be converted one at a time as down time permits. No long shutdown is needed for this upgrade. All cabling would be prefabricated and RF cables phase matched ahead of time. Water taps are already installed at all station locations for the solid state driver. However, some modifications to the LCW return piping header in each gallery is necessary to reduce the return pressure. This upgrade is essential for reliable Booster RF operation over the next 10 years. Demands on the RF system to increase the repetition rate from the present 7 Hz to 9 Hz and then possibly to 15 Hz are not compatible with increasing reliability for much of the existing RF equipment. The new equipment will go far toward improving reliability while at the same time reducing radiation exposure to our technicians.

Power Tube Amplifier

Solid State Amplifier

Cost and timeline for the solid state upgrade is constrained by two issues: manpower and funding. Given the currently available funding level and manpower, two stations are scheduled to be converted in 2010 and four more stations by 2012. The remaining eleven stations would be converted in the following two years. The impact of this schedule is that Booster will not run above 9 Hz until the end of 2014. Delays in funding or changes in technician support will delay this date further. The total required funding, given in the tables section, is $**4,446,666** to complete the project at today's prices.

This cost, as seen in the tables, can be greatly reduced by moving the amplifier to an in-house project. Additional details on this project can be found in the given reference Beams Document 2883-v1.

Anode Supply and 13.8 kV Hardware

Booster presently is operating with two large outdoor 35KV high power (1700KVA) Anode Power Supplies (APS). The west gallery APS provides high voltage for 10 RF stations. The east APS provides high voltage for 9 RF. These large power supplies are the original units that were installed in 1969. They contain the following major functional blocks:

1. A 13.8KV fused disconnect – replaced with a new unit in 2008.
2. A specialized 13.8KV step start vacuum circuit breaker – original from 1969.
3. 1700KVA rectifier transformer – Rebuilt in 1970.
4. A DC cabinet containing the rectifier, filter capacitors, electronic crowbar, and individual station disconnect switches, etc. – mostly original from 1969.

Figure 1 is a picture of the West Booster Anode Power Supply.

Since it is not practical to replace and rebuild the Booster Anode Power Supplies as we did in Main Injector and Tevatron with an air conditioned block build, a selective approach to replacing major components is the preferred path to upgrading these 40 year old supplies. Looking at the key building blocks from above, the first is the 13.8 KV fused disconnect. This has already been replaced with a new unit so no upgrade is needed.

The second major block is the 13.8KV step start vacuum circuit breaker (VCB). These are the original units from the 1969 and are nearing their end of life (EOL) service. Troubleshoot is very difficult due to a number of the wire labels have either fallen off or the number are eligible due to age and weathering of interconnecting control wires. In addition, these units have a number of old obsolete relays that once our spares run out would require circuit redesign in order to preserve operational functionality. We propose to upgrade these special step start vacuum circuit breaker assemblies with modified Ross Engineering components that would make them very similar to what is now in service in Main Injector's RF system.

The third item is the 1700KVA rectifier transformers that are nearly 40 years old. These existing transformers have all been rebuilt at least once in the very early 1970's due to internal electrical short circuits. Having to run at a 15 Hz rate increases the likely hood of these transformers failing sometime in the future. Replacement transformers have already been designed, purchased, and installed for Main Injector's 53 MHz system. We recommend that new transformers (identical to the ones purchased for MI's 53 MHz RF system) be purchased for the booster. These transformers were specifically designed to operate at 15 Hz and are rated at 2000KVA and cost ~$ 131,000 each.

The forth item is all the DC cabinet components that are mostly original to the 1969 installation. We propose to upgrade the rectifier stacks, electronic crowbar, inter-phase reactor, and control circuitry.

On completion of this upgrade the Anode Supplies would be capable to operating the Booster RF system reliably at a 15 Hz continuous rate for at least 15 years. Total estimated cost for the Anode Supply upgrade is ~ $860,000.

Spare Cavity

The process of pulling a cavity, radiation cool down, investigation and repair takes several months. This has resulted in reduced proton intensities and repetition rates during the repair cycle. Booster runs at an acceptable efficiency when the RF accelerating voltage is above 900 MV; a missing cavity reduces the voltage overhead needed to compensate for weak or faulted stations. After RF 19 was installed, the Booster no longer had a spare cavity. A review of materials on hand found that the quickest solution to obtain a spare is to re-assemble the original 1969 prototype. Required parts are all available and require about three weeks of two technicians for assembly. This would also require machine shop time (estimated at about 60 hours) to replace and repair sections with newer cast pieces. The engineering required would be very little and the total cost is estimated to be less than $60,000. The work is currently not proceeding due to lack of available labor.

Bias Supply

Each Booster RF station has three ferrite tuners powered by a bias supply. The parts used in the bias supplies are in need of redesign. But of most concern are the bias supplies transformers. The bias supplies in the Booster East Gallery were designed with larger transformers that allow for 15 Hz operation. However, the ten West Gallery Bias Supply transformers, subject to overheating, have not proven their ability to run at rates greater than 10 Hertz. It is necessary to replace all of these transformers to reliably support 15 Hertz operation. The cost given in the tables section to replace the 10 bias transformers is about $175,000. Additionally, the supplies need to have upgraded heat sinks and SCR’s at a total cost of $125,000. The cost to upgrade additional obsolete parts is $50,000 for all ten supplies. The sum total for the ten Booster West bias supplies is then $350,000.

Radiation/Activation and Related Issues

Already discussed above were issues regarding radiation damage to the Booster gradient magnets. That is just one issue in many in regards to Booster and Linac radiation concerns. The following section can be divided into two areas: Equipment and Exposure.

The Accelerator division follows strict safety guidelines and radiation related issues are monitored by various groups inside and outside the laboratory. Radiation issues related to worker and environment are primarily controlled and monitored by our labs Environmental and Safety Group. The current Booster radiation shielding (SA) limits the allowed intensity to 1.35E17 pph. To achieve, for example, 5E12 ppp at 15 Hz would require this limit to be increased by a factor of 2 to 2.7E17 pph.

Nowhere in the Booster is there sufficient shielding to handle an undetected loss at full intensity. Consequently, the bulk of the Booster ring is protected by radiation detectors. This means that the beam intensity limit for these areas is determined by the allowable dose per trip. This of course depends on how much beam can be lost in the time it takes the detectors to trip off the beam. Assuming a 1 second response time, there needs to be sufficient shielding to protect against an accident condition involving 15 pulses with 5E12 ppp at 8 GeV. This means that controlled areas with unlimited occupancy will require about 13 ft of earth equivalent shielding to ensure that the dose per trip is below the 5mrem FRCM limit. For minimal occupancy areas 9 ft of shielding will be required to keep the dose per trip below the 100 mrem FRCM. There is only one location in the Booster that does not meet this requirement. It is in the CUB utility tunnel at the point where it crosses over the Booster near the Short-19 straight section. There is no way that extra shielding can be added at that location, but it may be possible to repost it as a Radiation Area.

An important ingredient to the current Booster SA is the assumption that the pattern radiation generated is determined by the locations of the main magnets. This assumption was verified by loss studies documented in the SA, and is thought to be a consequence of the fact that the main magnets are combined function magnets powered by a 15 Hz resonant circuit. This means that main magnets cannot be individually tuned and that the beam lattice function is roughly independent of energy. These factors combined to cause beam losses to occur at fixed locations with respect to the Booster straight sections and allowed the ring to be protected with a finite number of appropriately placed detectors; one for each of the 48 plus a few additional ones to handle special cases such as the extraction areas. Since the time the SA was written, the Booster has been equipped with high field correctors that allow the operators to adjust the high field beam tune. Tests need to be done to check if these correctors are capable of invalidating this key assumption about loss patterns.

In addition to ES&H guidance and the SA limits, there are concerns regarding radiation effects on equipment. The following high concern section will focus on equipment related issues, and the impact on operations.

Cable Failure – Cable failure due to radiation damage has been an on-going issue for a number of years. Most severely impacted are those cables that terminate close to the beam line. An example is the HV cables for the ion pumps. Virtually all of the cable ends have had to be spliced or replaced and the ion pump HV connectors have been rebuilt using radiation hardened parts. Similarly, many other cables have had to be re-terminated or spliced. Typical BNC style connectors simply crumble. Efforts are being made to find vendors of cable connectors made of radiation hardened materials, ex, peek. However, unless the cables themselves are made of rad hardened materials the connectors don't accomplish much.

Implications -- For years, out of fear of precipitating a cascade of failures, the rule has been to never pull out old cables. This has resulted in cable trays being overloaded. These cables are frequently tie wrapped to others and attempting to pull out the old cable will in fact also pull on other cables. This leads to bending and stretching of those cables which will damage and break the brittle insulation causing shorts.

Of particular concern are cables that were installed early in the machine construction and are buried in the bottom of the cable trays. These cables include interlock and equipment safety sensor lines and power cabling for turbo pumps and the Booster gradient magnets.

Remediation efforts underway

The idea of running 15 Hz and higher throughput can only be achieved with beam loss control. Effort on this front has gone on for 40 years and will continue as long as there are losses. Listed below are just some examples of the ongoing work and concerns for bema loss control.

- Power Loss Monitoring and Standardized Radiation Surveys -- Standardized surveys have been in use for several years. This allows continuous monitoring for changes in the loss patterns in the machine. Additional beam loss monitors have been added as well as software that continuously monitors machine operations and losses.
- Candy cane tubing -- Plastic tubing on the Gradient magnets has been replaced with radiation hardened materials
- Rad-hard connectors -- We have been able to find vendors for certain connectors. Ex. SHV connectors on the BLM ion chambers replaced with peek versions.
- Replaceable cable ends -- New installations are done with splice connectors and replaceable ends already in place.
- Dosimetry to baseline present rad dose rate -- Measurements are going to be made to baseline the present dose rates at various locations in the machine.
- Collimator region -- The machine components in the collimator regions are undergoing loss levels at rates higher for longer time than have ever been experienced in the machine before. It is expected that if gradient magnet fails due to radiation damage it will happen in this area. We also expect that all cabling in this region will eventually have to be replaced.
- Extraction regions -- The Booster presently has only one extraction region. Removal of the Long 13 extraction system has increased the acceleration efficiency and dramatically lowered losses in that area. The Long 3 extraction losses are actually less now, even though the machine through put is higher, because of improvements to the extraction system. However, continued improvements to the extraction process will be necessary to reduce extraction losses required to run higher throughput. Scaling our present losses at extraction to 1.8E17 protons per hour would raise the activation levels above our present limit. Ideas being worked on include a fast kicker, additional high field orbit bumps and modifications of the extraction trajectory. The fast kicker would prevent clipping of bunches outside the notched region. The fast kicker design is basically a half length Booster kicker designed to fit two such devices into the place of a single Booster kicker. The doubling of the number of kickers would require doubling the number of PFN and switches. The orbit modifications being looked at are made possible because of the new correctors. Orbit control will allow beam to enter the extraction area with an angle that more closely resembles our extraction angle. The angle correction will reduce some scrapping and may help reduce kicker voltage. Modifications to the extraction trajectory have been ongoing and have helped reduce losses. More work is required to maximize the extraction aperture without compromising the circulating beam aperture. Items being considered include lowering the extraction septa, modifying the alignment of the extraction beam pipe and additional steering elements.
- Orbit Control and alignment -- The new Booster correctors have vastly improved orbit control and harmonic tuning but work is still ongoing. Software being developed will be used to measure and correct beam dynamics. Items like tune, chromaticity, coupling, beta bumps, angles and positions are all being investigated into making their control an automated process. In addition to the correctors, software has been written to better understand how to increase the Booster aperture by making corrections to the combined function magnets

positions. This has been done in the past with success but does require dedicated study time as well as shut downs to make the necessary alignment moves. The process of moving the gradient magnets and then correcting the orbits is easier with the new correctors and orbit software.

Power Distribution

While no system listed here is actually listed as a high concern in the above table section, the sum total issue of the aging power systems merits special concern. The present repair upon failure that is performed becomes ever more difficult with the obsolete 40 year old power systems. If done correctly, cost and downtime can be minimized. Waiting for failure to occur and then ordering needed parts will increase the downtime to the entire Accelerator complex. Below is a breakout of the systems listed in the power table above with more details and solutions.

Linac Transformers

The LINAC house power transformers a located in the lower gallery and consist of 1500kva 13.8kvac-480/277 dry transformers with 5.42% impedance and designed for 150 Deg C rise on the coils. These transformers are custom made for this installation but are not a unique design. They are standard dry transformer design distribution class however they were built with the insulation technology of the time. Each transformer 3 (Y0178, Y0179 & Y0180) consists of a line side breaker and a 2500 amps secondary breaker panel. The 480/277 breaker panel consists of a main a breaker with three distribution breakers. Both the line side and 480vac load side breaker panel can be replaced independent of the transformer. So we can pursue procurement of replacement panels for one transformer system with a long term goal to change out this equipment on one of the transformers. This will then free up spare parts for the other two transformers. The breakers and support equipment can then be refurbished either in house for possibly by a breaker repair center then would allow for enough parts on hand to manage any flash over and operating problems that may occur. Procuring switch gear of this type would take on the order of a few months and the replacement in the gallery would take a few days.

The transformer itself is a large source of heat in the lower gallery. If a replacement of one of the transformers is considered we could procure a transformer design that would change from 150 Deg C rise on the coils to an 80 Deg C rise design. This is a common practice in modern closed space applications to reduce the heat loading on HVAC systems and extend the life of all equipment in the area. The major design changes in new transformers are the use of NOMEX insulation material which has a higher temperature margin and the windings would be changed from aluminum to copper to reduce heat. We have one spare on hand for the three units installed in the LINAC, also this transformer design is used to power Wilson Hall and share the spare. There has been one failure over the life of these transformers that occurred approximately 10 year ago.

Power for the 32 Deg and 58 Deg bend supplies used by NTF are connected to the Y0180 transformer in the center of the LINAC. When these supplies are used the line distortion caused by the supply operation chopping the line voltage can be seen on most equipment in the LINAC gallery. To reduce the line distortion and therefore reduce the voltage stress on the existing equipment we should design and install a 480vac line filter for this equipment. This can be a standalone device added to the present system near the supplies. We have some history using these types of filters on the house power to improve the line when the large supplies are in operation. It may be more economical to find a power supply solution that is not a 12 pulse type of supply for these magnets rather than add more equipment to patch the problem.

Motor Control Centers LINAC:

The MCCs in the LINAC lower gallery run pumps and HVAC blowers. They consist of four bays with 15 buckets and an additional 15kva transformer and low voltage breaker panel. The centers are of the older design that are hard wired in place and take extended time to replace a failed element. Modern design MCC use a quick disconnect system that allows for easy removal of a failed element without exposure to the line voltage for the maintenance personnel and allows for replacement without taking down the entire MCC. This is the type of MCC installed in the Main Injector pump rooms that control the cooling systems. Replacing one of the MCC in the lower gallery would then free up spare parts for the other control centers.

Transformers Booster:

The house power for Booster is supplies from transformers Y-BW2 and Y-BE2. Each transformer is a 1000kva oil filled device with a 480vac secondary breaker panel installed. This equipment has the same concerns as the LINAC secondary panel equipment; the breakers do not have spare parts. In addition there is an oil containment issue that is still outstanding. Due to close proximity to the occupied booster galleries without a fire rated wall increases the oil fire hazards. Replacing both of the house power transformers and secondary panels with either dry or cast coil type transformers would remove the oil containment hazard and provide modern equipment freeing the present breakers in the panels for use as spare equipment for the LINAC.

In working with FESS on feeder issues to the booster it was brought up that the duct that contains the feeders that power the Booster has been collapsed for some time and will not allow us to replace a failed feeder without extensive effort if the failure is in the collapsed section. The present plan for the Booster will not increase the needed power and therefore not increase the heating on these cables. There is no clear plan for dealing with this issue and will need to be reviewed.

In addition to the transformers mentioned above there is one other transformer that has a potential large impact on operations. Transformer Y-CG1 that powers the cross gallery and therefore the MCR failed in the recent past taking down the entire accelerator complex. The transformer installed as a replacement is even older that the one that failed. This should be replaced with a new transformer with new high voltage breaker and new secondary main breaker. The present pad has a containment dam that could allow for the use of an oil type as a replacement but a new dry or cast coil type could be installed as a replacement. Replacing the high voltage breaker compartment with gear that is compatible with the Main Injector equipment (SEIMENS GM series breakers) would improve our spare parts. We presently have 50 GM series breakers installed in the Main Injector power supplies, KSS, F sector supplies and Tevatron supplies. This transformer system has as high of risk to operations as any other single element because of the uniqueness of the installation. Choosing an installation type that can better make use of other spare 1500kva transformers we have in the MI and Tevatron would reduce the risk and reduce the down time if a failure occurs.

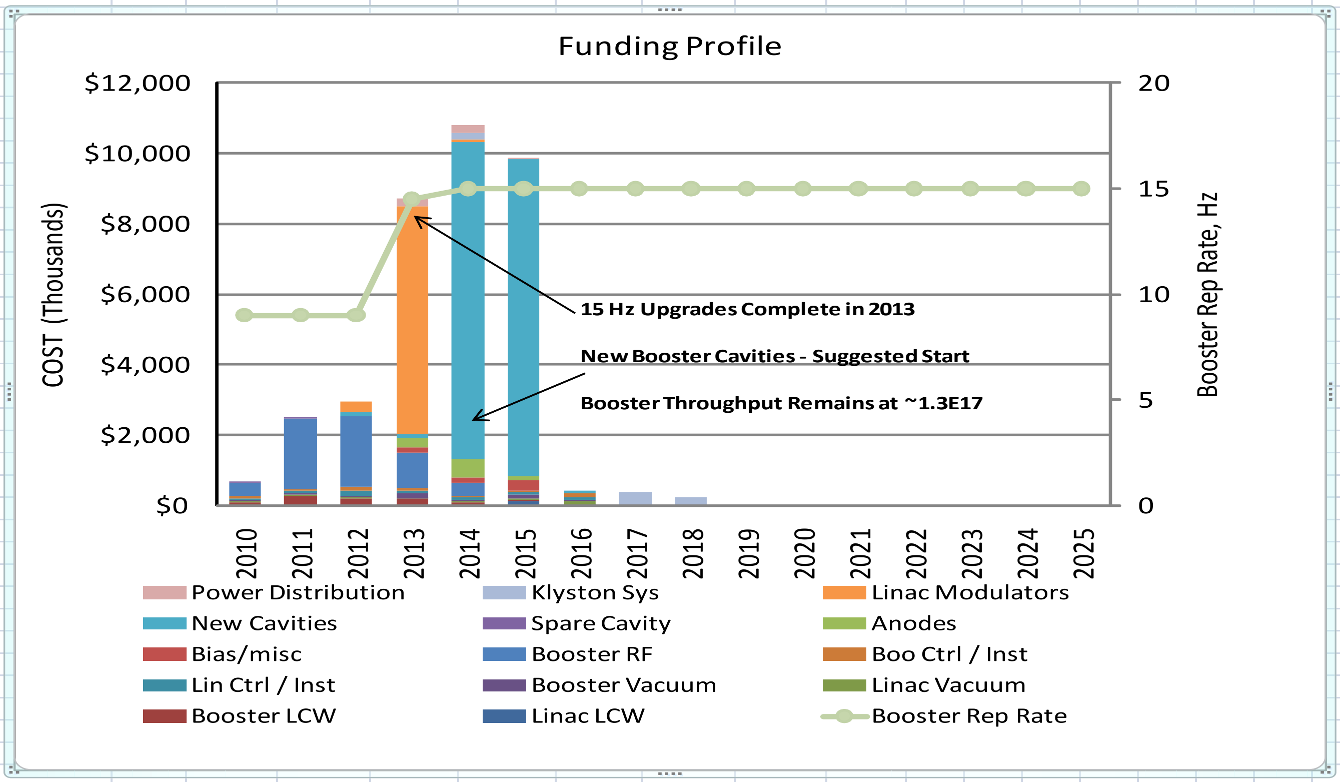
Motor Control Centers Booster:

The MCCs in the both the east and west fan rooms run pumps and HVAC blowers. They consist of four bays with 12 buckets and an additional 15kva transformer and low voltage breaker panel. The centers are of the older design that are hard wired in place and take extended time to replace a failed element. Modern design MCC use a quick disconnect system that allows for easy removal of a failed element without exposure to the line voltage for the maintenance personnel and allows for replacement without taking down the entire MCC. This is the type of MCC installed in the Main Injector pump rooms that control the cooling systems. Replacing one of the MCC in the LINAC lower gallery or in one of the booster fan rooms would then free up spare parts for the other control centers.

Funding Profile

In this section, a suggested funding profile is given. Costs given in the above tables were analyzed and broken into appropriate blocks to produce a funding schedule to meet the Task Force goal. Reaching 15Hz operations and then operational reliability and long term viability was used as the yearly funding guidance.

Booster LCW	$100k	$285k	$200k	$180k	$100k	$25k											$890k
Linac Vacuum	$17k	$20k	$20k	$35k	$35k	$40k	$90k										$257k
Booster Vacuum	$45k	$55k	$55k	$125k	$40k	$125k	$40k										$485k
Lin Ctrl / Inst	$50k	$50k	$160k	$80k	$50k	$60k	$90k										$540k
Boo Ctrl / Inst	$50k	$50k	$100k	$80k	$50k	$60k	$90k										$480k
Booster RF	$400k	$2,000k	$2,000k	$1,000k	$385k												$5,785k
Bias/misc				$150k	$150k	$285k											$585k
Anodes				$260k	$500k	$100k											$860k
Spare Cavity	$3k	$57k															$60k
New Cavities			$100k	$100k	$9,000k	$9,000k	$100k										$18,300k
Linac Modulators			$300k	$6,500k	$100k												$6,900k
Klyston Sys					$180k			$375k	$225k								$780k
Power Distribution				$200k	$200k	$55k											$455k
Year Totals	$665k	$2,517k	$2,935k	$8,710k	$10,790k	$9,875k	$435k	$375k	$225k								$36,527k
Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	
Booster Rep Rate	9	9	9	15	15	15	15	15	15	15	15	15	15	15	15	15	



The table shows that to reach 15 Hz operations, the solid state upgrade and associated system work need to be completed. The schedule shows that in 2013 with suggested funding and manpower that goal could be reached. Funding for other systems to maintain operational reliability is less rigid and will need to be more thoroughly planned. A large item, Linac modulators is not yet complete and will change the funding profile guidance given below. The cost of new Booster RF cavities is also a rough estimate and one that needs to be better understood in terms of laboratory goals.

Endnotes: [i] **Requested Proton Beam**

[ii] **Copy of Booster Lamination Note**

[iii] **Copy of Insulation System Note**

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[i] **Proton Beam Requested Spreadsheet**

Expt	Start	End	Energy	Total	Year	P/Cycle	MI rate	Pulse/MI	Boo Cyc	Up Weeks	Yearly Sum
NOvA	Feb, 2013		120	20-32	1	4.3	1.33	12	12	40	9.3857684
	2014				2	4.3	1.33	12	12	42	9.8550568
	2015				3	4.3	1.33	12	12	40	9.3857684
	2016				4	4.3	1.33	12	12	42	9.8550568
	2017				5	4.3	1.33	12	12	40	9.3857684
	2018				6	4.3	1.33	12	12	42	9.8550568
	Jul 2019				7	4.3	1.33	12	12	40	9.3857684
	2020				8	4.3	1.33	12	12	40	9.3857684
SY120	Oct, 2011	Sep, 2021	120		10			~5% time line			76.494013
E-906	Oct, 2010	Jul, 2013 ?	120	0.07	2 to 3	2		~5% time line			
Test Beams	NOW	Sep, 2021	120	~0	Years	~0		~5% time line		Up-Weeks	Yearly Sum E20
MicroBooNE	Feb, 2013		8	6	1	4		3	3	40	2.1827368
	2014				2	4		3	3	42	2.2918737
	Sep,2015				3	4		3	3	40	2.1827368
	2016				4	4		2	2	40	1.4551579
G-2	Oct, 2014		8	4	1	3		1	1	42	0.5729684
	2015				2	4		1	1	40	0.7275789
	2016				3	4		3	3	42	2.2918737
	Sep,2017				4	4		1	1	40	0.7275789
	2018				5	0		0	0	40	0
Mu2e	Oct, 2017		8	7.2	1	3		3	3	40	1.6370526
	2018				2	3		4	4	42	2.2918737
	2019				3	3		4	4	40	2.1827368
	2020				4	3		4	4	40	2.1827368
						BCYC/min	joules/e12				
	Plan 1	Plan2 (NC)	Boo Eff	Boo Hz	sec/h	0.06666	15				
year	p/hour E17	p/hour E12	0.96		3600	Boo Watts					
2012		172150	179036	8.25		550.881	20				
2013		172150	179036	11.25		550.881	20				
2014		180270	187481	12		576.866	20		BLEng	Const.	
2015		182977	190296	12		585.527	20		6.00E+08	1.60E-19	
2016		172150	179036	12.75		550.881	20				
2017		174857	181851	12		559.542	20				
2018		172150	179036	12		550.881	20				
2019		172150	179036	12		550.881	20				
2020		172150	179036	12		550.881	20				

ii **Copy of Insulation System Note**

Insulation System

The insulation system shall consist of epoxy impregnated fiberglass with integrated mica glass on the tape wrapped individual turns. The following epoxy impregnation formulation is specified.

Dow' 332 or CIBA 6005 resin	100 parts by wt
Nadic Methyl Anhydride (NMA)	90 parts by wt
DMP-30	1 part by wt

Mica glass tape (.007" x 1" half lapped) as a binderless tape or with B-staged epoxy is to be used as turn insulation. In the latter case BF_3 MEA epoxy would be acceptable but only if fully cured before the final impregnation. Also, a separater from layer-to-layer to be replaced after the initial cure with fiberglass would have to be used. This is to insure complete impregnation between layers. The .025" layer insulation shall consist of one piece of cloth cut to size or two layers of 3" or 3½" tape overlapped by at least 2".

The outer ground wrap shall consist of four layers of .010" x 1" fiberglass tape. Each double layer shall be half-lapped and wound with the opposite spiral. All fiberglass shall be Volan "A" or an A-1100 finish treated

At the end cross-over N.E.M.A. Grade G-10 epox fiberglass laminant, which has been well sande or sandblasted and cleaned, may be used. The resin system is relatively brittle, therefore, exceptional care must be taken to tightly fill all of the volume of the mold. "Resin rich" areas exceeding .015" thick may crack.

The coil is to be completely vacuum impregnate into a monolithic void free structure. The coil and mold shall be outgassed at 50° C to 90° C at 200 microns measured at the end away from the pump before introducing the epoxy. The components are to be thoroughly mixed and outgassed at 45° C to 60° C. The coil and mold shall be maintained at 45° C and 60° C during impregnation. Atmospheric pressure or preferably higher pressure shall be applied to complete the impregnation.

The coil is to be cured at 75° C to 85° C for 8 hours. ______________________________ The coil shall be slowly cooled to minimize distortion. In no case shall the outside of the coil be painted with epoxy or other materials after impregnation.

[iii] **Copy of Insulation System Note**

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