FERMILAB-PUB-08-698-AD

A Staged Approach to a High Intensity Proton Source

Dave McGinnis

October 15, 2008

Abstract

By combining a 2 GeV linac with rapid cycling synchrotron, a 200kW, 8 GeV proton source can enable a 2.1 MW, 120 GeV beam from the Main Injector. This source can be built with standard accelerator technology and little technical risk. This source can then be upgraded in a straight forward manner with more advanced accelerator technology such as an 8 GeV superconducting linac and a super-ferric, medium energy Booster to provide enough beam for 10.4 MW at 120 GeV in the Main Injector. In addition, the upgraded source can provide 1.7 MW at 8 GeV and 4.7 MW at 22 GeV. This staged approach avoids the "all-or-nothing" pitfalls of the current Project X concept.

Introduction

Recently, multiple review committees have suggested that Fermilab re-examine the design of Project X in relation to the design of ILC cryo-modules. Removing the constraint of using low beam current ILC cryo-modules lessens the need for using the Recycler as an accumulation ring.

The main advantage of a superconducting linac is beam flux while the main figure of merit for a neutrino program is beam power. Beam power is the product of energy and flux. Since synchrotrons can reach higher energies than linacs, a synchrotron can also be used to produce large beam powers.

The optimum crossover point between using a high energy linac or a rapid cycling synchrotron is not very well defined. Superconducting RF technology might be able to push this point to the few GeV range. However, since superconducting RF technology is not as mature as synchrotrons, a high intensity proton source that consists of a combination of a high energy linac plus a rapid cycling synchrotron should be considered.

This accelerator complex could be built in stages. The construction of a project in well defined stages in which at the end of every stage a substantial increase in performance is obtained is very attractive in these times of tight budgets. The first stage is characterized by an investment in civil construction and standard accelerator technology. The second stage is characterized in an investment in more advanced accelerator technology such as a high energy superconducting linac and a super-ferric, medium energy booster synchrotron. This note will examine such a staged approach to Project X.

Current Project X Design

The current concept of Project X inserts an accumulation ring in between the superconducting linac and the Main Injector. The accumulation ring provides two functions. First, the ring accumulates multiple linac pulses while the Main Injector is ramping so that the required amount of linac charge per pulse is reduced. Second, the linac is used to provide beam to other users while the Main Injector is ramping because the H- stripping foil is located in the accumulation ring instead of the Main Injector.

Originally, Project X was proposed to be built with a staged approach. In the first stage, the energy of the linac is much less than the Main Injector injection energy and the accumulation ring functions as a booster accelerator that accelerates beam from the final linac energy to the Main Injector energy. In the second stage, as more linac cryo-modules become available, the linac energy is raised until the linac energy matches the Main Injector injection energy. At this point, the booster accelerator functions as an accumulation ring as in the current Project X configuration.

Later, as a cost saving measure, it was proposed that the Recycler could function as the accumulation ring. Since the Recycler is constructed from permanent magnets, the first stage concept of a booster accelerator was no longer viable. While the cost of the final configuration of Project X using the Recycler is less, the technical risk is significant. First, before Project X can be of any use, the final energy of the linac must equal the Recycler energy of 8 GeV. This requires about 40 cryo-modules in the linac which requires a large upfront cost. The production of the cryo-modules has been problematic. Second, the transport and stripping of H- ions at 8 GeV is about an order of magnitude higher in energy than has currently been achieved.

First Stage

The primary goals of Project X is to produce a proton beam in excess of 2MW at 120 GeV in the Main Injector for a long baseline neutrino program and provide an 8 GeV proton beam on the order of 100kW to other users. This can be done with considerably less cost and less technical risk with a proton source that includes both a linac and synchrotron than a source that consist only of a high energy linac.

Space charge tune shift is one of the major intensity limitations for synchrotrons. This is the main motivation for the high energy linac of Project X. The space charge tune shift is given as:

$$\Delta Q = \frac{r_o}{2\pi}\frac{1}{\beta\gamma^2}\frac{R \cdot B}{F_L}\frac{N}{\varepsilon_n} \tag{1}$$

where r_o is the classical radius for a proton ($1.53\text{x}10^{-18}$m), N is the number of particles, R is the transverse form factor, B is the longitudinal bunching factor, F_L is the longitudinal filling factor (which includes spaces for kicker rise time and abort gaps), and ε_n is the 95% normalized transverse beam emittance. It was shown in the initial Project X report that a value of R=1 and B=2 could be achieved using phase space painting techniques.

The main features of the space charge tune-shift is that it rapidly decreases with energy, it is dependent on the total number of particles, and it is independent of the circumference of the accelerator. These features of the space charge tune-shift formula can be exploited by taking multiple injections from a small rapid cycling booster into a large high energy ring. This was the design strategy for increasing the intensity at the Brookhaven AGS complex.

The current Fermilab Booster has injection energy of 400MeV and runs a tune shift well in excess of 0.2 for an intensity of $5\text{x}10^{12}$ protons/cycle. If the injection energy was raised to 2 GeV and phase space painting techniques are used, then intensity of over $40\text{x}10^{12}$ protons per batch can be accelerated with a tune shift less than 0.09 for a 25 π-mm-mrad normalized 95% transverse emittance. A 2 GeV linac is only twice the energy of the SNS linac so much of the linac and H- stripping technology used at SNS could most likely be extended to 2 GeV.

A new Booster is built following the 2 GeV Linac. The circumference of the Booster should be harmonically related to the Main Injector or the Recycler. It will also be assumed that the 53 MHz RF frequency is to be used in the Main Injector (although this is not a rigid constraint). The harmonic number of the Main Injector for 53 MHz RF is 588. The harmonic number has the following factors:

$$588 = 2 \cdot 2 \cdot 3 \cdot 7 \cdot 7 \tag{2}$$

Too small of a Booster circumference places severe constraints on the magnetic field ramp rate. Also, the second stage of this concept proposes raising the extraction energy of the Booster to above the transition energy in Main Injector (~ 20GeV). Again, too small of a Booster circumference places a burden on the strength of the Booster magnetic field in the second stage. Too large of a circumference increases the cost of the Booster unnecessarily. A reasonable compromise is to have the new Booster circumference one fourth of the Main Injector circumference.

If the bending magnets occupy about 60% of the Booster circumference and constraining the magnetic field ramp rate to 2 T/s, the new Booster can ramp from 2 GeV to 8 GeV with a cycle time of 4Hz. A magnetic field ramp of 2 T/s and a cycle time of 4 Hz is significantly less than the present Booster parameters of over 10 T/s and 15 Hz cycle time so the magnet technology of the new Booster can be considerably less complex.

The slow cycle rate of 4 Hz is compensated by the use of the Recycler as an accumulation ring following extraction from the Booster at 8 GeV. The main advantage of the Recycler as an accumulation ring is to remove the time it takes to load the Main Injector at injection with multiple Booster batches. This accumulating of multiple Booster batches takes place in the Recycler while the Main Injector is busy ramping and then the Recycler transfers to the Main Injector in a single turn when the Main Injector is ready for injection. Since the accumulation of multiple Booster batches is done at 8 GeV, space charge tune shift in the Recycler is much less of an effect. Four Booster batches at an intensity of 40×10^{12} protons per batch have a tune shift of less than 0.04 in the Recycler. The four Booster batches are transferred to the Main Injector in a single turn and then accelerated in the Main Injector. An intensity of 4 x 40×10^{12} protons every 1.5 seconds provides a beam power of 2.1MW at 120 GeV. A parameter table for the first stage is shown in Table 1.

The Linac-Booster duty factor shown in Table 1 is the percentage of the total cycle time that is used for accelerating beam for the Main Injector. The rest of the remaining time can be used to service other experimental programs. The accumulation of four Booster batches at a Booster cycle rate of 4 Hz requires 1.0 seconds of cycle time. This leaves 0.5 seconds of cycle time or two Booster cycles available for other users. The Booster running at 40×10^{12} protons/batch with a cycle rate of 4Hz provides 208 kW of beam at 8 GeV. Two thirds of this power is used to fill the Main Injector, the other third (70kW) is available for other 8 GeV users.

In summary, the first stage consists of:

- A 50kW, 2 GeV Linac operating at 4 Hz based on SNS technology.
- H- stripping at 2 GeV based on SNS technology.
- A 200kW, 2 GeV to 8 GeV Booster that is one fourth the size of the Main Injector with a cycle rate of 4 Hz based on 2T/s magnet technology.
- Accumulation of four Booster batches at 8 GeV in the Recycler.

- Transfer from the Recycler and acceleration in the Main Injector of 160×10^{12} protons every 1.5 seconds to provide 2.1MW of beam power at 120 GeV.
- 70kW of beam power at 8 GeV to other users.

Parameter	Value	Units
Linac Beam Current	10	mA
Linac Pulse Length	0.65	mS
Linac Energy	2	GeV
Booster Energy	8	GeV
Booster Circumference	825	m
Booster Cycle Rate	4.0	Hz
Booster Magnetic Field Ramp	2.0	T/s
Booster Magnetic Filling	61	%
Booster Max. Magnetic Field	0.33	T
Booster Batch Intensity	41	$\times 10^{12}$
Booster Beam Fill	90	%
Booster Normalized Emittance	25	π-mm-mrad
Booster Tune Shift	0.09	
Main Injector Tune Shift	0.04	
Total Cycle Time	1.5	S
Available Linac Beam Power	52	kW
Available Booster Beam Power	208	kW
120 GeV Beam Power	2.1	MW
Linac-Booster duty Factor	67	%

Table 1. Parameters for the first stage of a high intensity proton source

Second Stage

The first stage achieves Project X goals using standard linac and synchrotron technologies. However, a 120 GeV beam power of 2.1 MW is only a factor of three greater than the planned Fermilab Accelerator Nova Upgrade (ANU). While a factor of three increase in intensity is impressive and the project opens the door to other 8 GeV experimental programs, it could be argued that running the Nova program three times longer might be an alternative strategy. Therefore, it is important that any proton source built at Fermilab have future goals that are at least an order of magnitude greater than ANU. There are two intensity bottlenecks for achieving higher beam powers; space charge tune-shift at injection in the Main Injector and transition crossing in the Main Injector. It was for these two reasons that the current Project X design limited the maximum beam current circulating in the Main Injector to less than 2.5 Amperes which limits the Main Injector beam power at 120 GeV to be less than 2.3 MW.

Both of these intensity bottlenecks are eliminated by raising the injection and extraction energy of the new Booster. If the linac energy is raised to 8 GeV, the space charge tune-shift is

kept below 0.08 with almost a nine-fold increase in intensity in the Booster over the first stage. Raising the linac energy to 8 GeV is a substantial project that includes the industrialization of superconducting RF cryo-modules and H- stripping at 8 GeV. However, if the linac tunnel in the first stage is built long enough to accommodate the 8 GeV linac in the second stage, then the cryo-modules are added incrementally as they become available. While building a long linac tunnel in the first stage increases the cost of the first stage, the added civil construction is not technically risky and provides flexibility in the second stage.

In the first stage, the space charge tune-shift in the Main Injector for the accumulated batches is a manageable 0.04 at 8 GeV. However, if the Booster batch intensity is increased by a factor of nine, then the space charge tune-shift at an injection energy of 8 GeV into the Main Injector becomes unreasonable. The only alternative is to increase the injection energy of the Main Injector. The Main Injector has transition energy of 20.4 GeV. It is very desirable to inject at an energy above the transition energy so intensity effects at transition in the Main Injector are avoided. A Main Injector injection energy of 22 GeV gives about 8% of head room above the transition energy. At an injection energy of 22 GeV, the space charge tune-shift is less than 0.05 for a nine-fold increase in intensity over the first stage Main Injector beam current.

The disadvantage of injecting at 22 GeV into the Main Injector is that the Recycler is no longer available for accumulating Booster batches (unless the Recycler is re-fitted with electro-magnets). Thus, the Main Injector must hold at the injection energy of 22 GeV while four Booster batches are accelerated and accumulated in the Main Injector. This places a premium on Booster cycle time. If the Booster magnetic field ramp rate is kept at 2T/s, then the Booster cycle rate would have to be dropped to 2Hz to accommodate the 8 GeV to 22 GeV energy ramp and the Main Injector would have to wait 2 seconds at 22 GeV while the Booster batches are accelerated. A more optimum situation is to raise the Booster magnetic field ramp rate to 4T/s. At a Booster magnetic field ramp rate of 4T/s, the Booster cycle time is back at the first stage value of 4 Hz and it takes 1 second to load the Main Injector with four Booster batches.

A magnetic field ramp rate of 4T/s is about double the current Main Injector ramp rate but is much less than the current Booster ramp rate of over 10T/s. The cost of magnet system at 4T/s is substantially larger than the cost of a 2T/s system. An alternative technology is to use super-ferric magnets that where proposed for the VLHC. The current state of the art for these magnets meets the 4T/s requirement. The maximum field required at 22 GeV for a Booster that has a circumference that is one fourth the Main Injector circumference and has a filing factor of 70% is about 0.8T. This field could be accommodated with a fairly large aperture magnet of about 100mm[1].

A parameter table for the second stage is shown in Table 2. The 120 GeV beam power for the second stage is over 10 MW. This beam power is a tradeoff between the increase in Booster intensity due to the higher injection energies and the dwell time for accumulating beam in the Main Injector. The positive side of the injection dwell time in the Main Injector is that the Booster and Linac are completely available to provide beam to other users while the Main Injector is ramping. The amount of beam power available to other users at 8 GeV is over 1 MW or the amount of beam power available to other users at 22 GeV is over 2.8 MW while still providing 10.4 MW to the 120 GeV program.

In summary, the second stage consists of:

- A 1.7 MW, 8 GeV Linac operating at 4 Hz based on extended ILC technology.

[1] Private communication with Henryk Piekarz

- H- stripping at 8 GeV.
- A 4.7 MW, 8 GeV to 22 GeV Booster that is one fourth the size of the Main Injector with a cycle rate of 4 Hz based on 4T/s magnet technology (possibly super-ferric technology).
- Accumulation of four Booster batches at 22 GeV in the Main Injector.
- Acceleration in the Main Injector of 13.5×10^{14} protons every 2.5 seconds to provide 10.4 MW of beam power at 120 GeV.
- 1 MW of beam power at 8 GeV or 2.8 MW of beam power at 22 GeV to other users.
- The Recycler ring available for a slow spill program with available duty factors up to ~100%

Parameter	Value	Units
Linac Beam Current	20	mA
Linac Pulse Length	2.7	mS
Linac Energy	8	GeV
Booster Energy	22	GeV
Booster Circumference	825	m
Booster Cycle Rate	4.0	Hz
Booster Magnetic Field Ramp	4.0	T/s
Booster Magnetic Filling	71	%
Booster Max. Magnetic Field	0.79	T
Booster Batch Intensity	338	$\times 10^{12}$
Booster Beam Fill	90	%
Booster Normalized Emittance	25	π-mm-mrad
Booster Tune Shift	0.08	
Main Injector Tune Shift	0.05	
Total Cycle Time	2.5	S
Available Linac Beam Power	1726	kW
Available Booster Beam Power	4746	kW
120 GeV Beam Power	10.4	MW
Linac-booster duty Factor	40	%

Table 2. Parameters for the second stage of a high intensity proton source

Summary

By combining a 2 GeV linac with rapid cycling synchrotron, a 200kW, 8 GeV proton source can enable a 2.1 MW, 120 GeV beam from the Main Injector. This source can be built with standard accelerator technology and little technical risk. This source can then be upgraded in a straight forward manner with more advanced accelerator technology such as an 8 GeV superconducting linac and a super-ferric, medium energy Booster to provide enough beam for 10.4 MW at 120 GeV in the Main Injector. In addition, the upgraded source can provide 1.7 MW

at 8 GeV and 4.7 MW at 22 GeV. The projected 120 GeV beam power at each stage is shown in Figure 1.

The construction of a project in well defined stages in which at the end of every stage a substantial increase in performance is obtained is very attractive in these times of tight budgets. The first stage is characterized by an investment in civil construction and standard accelerator technology. The second stage is characterized in an investment in more advanced accelerator technology such as a high energy superconducting linac and a super-ferric, medium energy booster synchrotron. This staged approach avoids the "all-or-nothing" pitfalls of the current Project X concept.

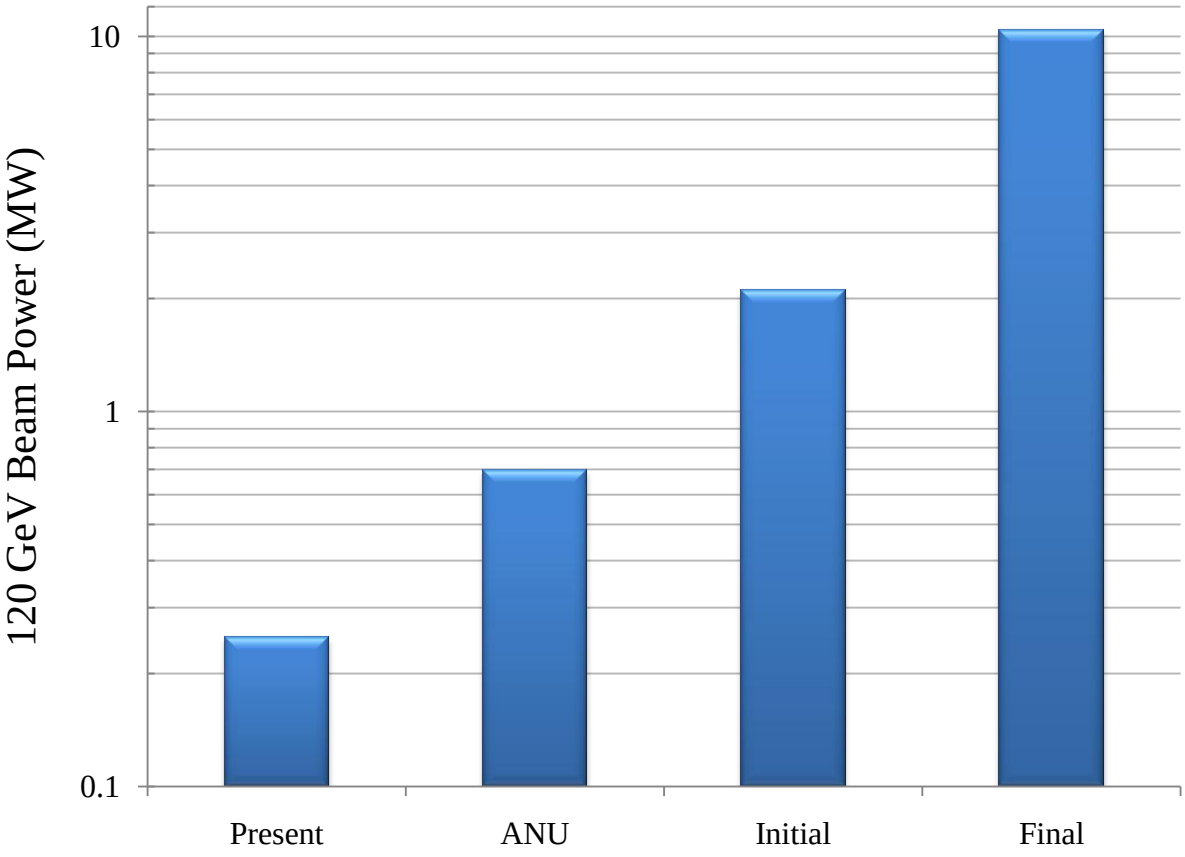

Figure 1. Projected 120 GeV Beam Power for a staged version of Project X.