A CONCEPT: 8 GeV CW LINAC, STAGED APPROACH*

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Abstract

This paper describes a concept for a CW Proton Linac on the Fermilab site. Except for the RFQ, the linac is based on superconducting technology. The linac has three segments that accelerate to 1 GeV, 3 GeV, and 8 GeV, respectively. It is located near the existing Fermilab Proton Source so that each section of the linac can be used as soon as it is commissioned. The whole design is based on the designs suggested for the Proton Driver and Project X. The suggested site and linac segmentation allow for the construction to start as soon as approval is granted. Additional benefits come from the fact that the present linac (the oldest machine in the Fermilab complex) is replaced, and the functionality of the existing Proton Source is preserved for the future.

INTRODUCTION

In order to create more opportunities for beam-based experiments using existing Fermilab infrastructure and in light of the expressed interest in a proton source capable of delivering multi-megawatt beam, a linac similar in design to Project X[1], but located near the existing linac, is proposed. The proposed linac, when completed, would be used to feed the existing 8 GeV program with increased intensity. Additionally, the proposed staged scenario would allow make use of some of the existing infrastructure.

The energy profile of the beam as suggested for Project X is shown in Figure 1.

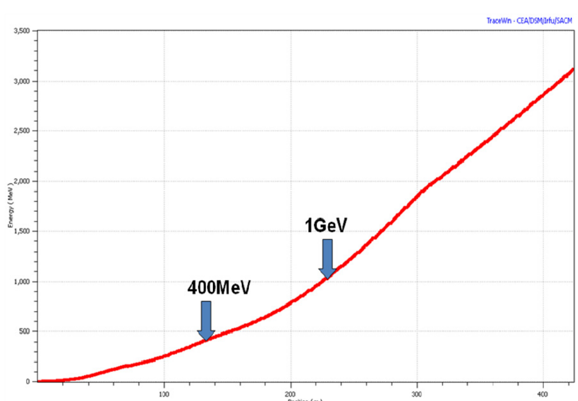

Figure 1: The arrows show the energies of the beam at the indicated distances from the ion source.

The proposed location of the new linac is indicated in Figure 2. The present 400-MeV linac (indicated by the blue line in Figure 2) is ~150 meters long and will be replaced with the new linac starting ~90 meters further upstream (as indicated by the red line in Figure 2). This will allow use of the existing tunnels for the linac and the beam transport line to inject 1-GeV beam into the Booster.

The injection can be bunch to bucket, as shown later. As in the case of the 400-MeV linac upgrade, the increase in injection energy will decrease the space charge tune shift in the Booster. For example, for typical present-day beam intensity and normalized transverse emittances, the space charge tune shift will decrease from 0.33 to 0.18. That in turn will allow more intense Booster beam at 8 GeV. This will also reduce the needed frequency swing of the RF cavities, allowing an increase of the total RF voltage per turn. The second blue line in Figure 2 indicates a CW linac from 1 to 3 GeV, and the long yellow line directed toward MI30 (the left side of Figure 2) shows the position of the 3 to 8 GeV linac.

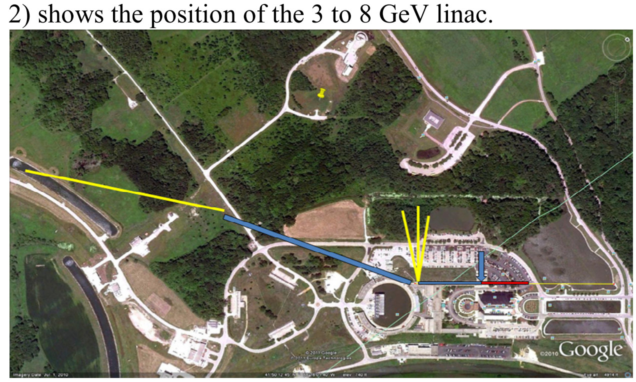

Figure 2: Proposed layout of the new linac on the Fermilab site.

In the rest of this note, a plan for staging of the new linac and the resultant effect on operation of the complex at each stage are described.

LOW ENERGY LINAC-CONCEPT

The low energy portion of the linac complex consists of ion source(s), LEBT, RFQ, MEBT, and linac up to some energy. For a high power CW machine with multiple users, redundancy in the form of multiple ion sources is needed. Also needed to provide the various required beam time structures is a wideband low energy beam chopping system. All these elements are indicated in Figure 3 and will be described in the following sections

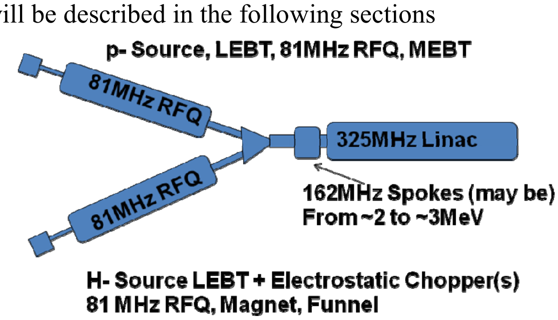

Figure 3: Low energy section of proposed linac. Details of components are described below.

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RFQ

One of the requirements of Project X is the ability to feed several experiments in parallel with flexible bunch structures. The highest beam repetition rate is expected to be ~ 20-30 MHz for kaons with a maximum bunch intensity up to 1.9E+8 protons. Following these requirements and the desire to have bunch separation long enough to make bunch by bunch kickers possible, we consider 81MHz RFQ. For input energy to the RFQ we chose 30 keV, beam energy from the existing D-Pace ion source and for the output energy, to stay below neutron production, we chose 2 MeV. Figure 4 shows graphical outputs from the Parteq simulation code

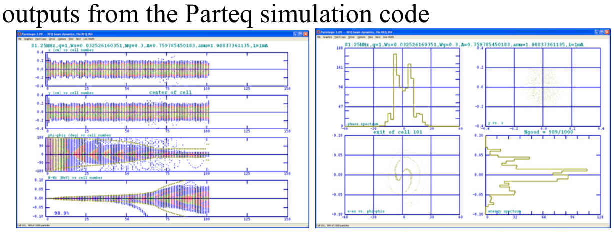

Figure 4: Horizontal, Vertical, Phase and Energy envelopes. The beam profiles at 2MeV.

The lists below show basic design parameters of RFQ.

Using the following parameters to create Parmteq input file

Particle symbol	= H-
Frequency	= 81.25 MHz
Beam current	= 1 mA
Normalized RMS emittance	= 0.2 pi mm mrad
Input energy	= 0.02752616 MeV
Shaper energy	= 0.03252616 MeV
Shaper phase	= -81.2368007 deg
Gentle-buncher energy	= 0.3 MeV
Gentle-buncher phase	= -30 deg
Final energy	= 2 MeV
Final synchronous phase	= -30 deg
Vane voltage	= 0.106381129 MV
Accelerating efficiency	= 0.75978545
Focusing parameter	= 13.4765212
Number of radial matching cells	= 4
Transition cell with no m=1 section	

Section lengths

Radial matching section	= 5.64955674 cm
Shaper	= 41.5701789 cm
Gentle buncher	= 83.9719811 cm
Accelerating section	= 265.101211 cm
Transition region	= 10.3606282 cm
Total	= 406.653556 cm

Power estimates

Copper power	= 78.4952518 kW
Beam power	= 1.97247384 kW
Total power	= 78.4678412 kW
Capture	98.6%

z	B	phi	m	V	W	A	a	psi
-5.650	0.674	-90.000	1.000	0.106	0.028	0.000	4.704	360.000
0.000	13.477	-90.000	1.000	0.106	0.028	0.000	1.070	360.000
10.393	13.477	-87.809	1.032	0.106	0.028	0.010	1.053	319.624
83.560	13.477	-59.562	1.186	0.106	0.071	0.104	0.982	187.142
91.766	13.477	-53.441	1.235	0.106	0.090	0.142	0.959	166.056
97.821	13.477	-48.860	1.293	0.106	0.109	0.163	0.935	150.795
102.621	13.477	-45.276	1.360	0.106	0.128	0.228	0.907	139.091
106.590	13.477	-42.375	1.437	0.106	0.147	0.276	0.877	129.749
109.994	13.477	-39.966	1.525	0.106	0.166	0.326	0.844	122.066
112.957	13.477	-37.924	1.628	0.106	0.185	0.382	0.808	115.605
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
120.090	13.477	-33.276	2.070	0.106	0.243	0.500	0.679	101.035
122.053	13.477	-32.068	2.292	0.106	0.262	0.624	0.627	97.279
123.863	13.477	-30.982	2.586	0.106	0.281	0.691	0.568	93.912
125.542	13.477	-30.000	3.000	0.106	0.300	0.760	0.500	90.873
390.643	13.477	-30.000	3.000	0.106	2.000	0.794	0.481	90.873

These lists are outputs of the design code RFQuick and the tracking code Parmteq. The full lists are included for completeness. However, the key parameters to note are: the total RFQ length is around 4 meters, the capture efficiency is ~98% and the beam is fully bunched at 200 keV. The total RF power (to copper and the beam) is ~80 kW. This means that the RFQ can be made of copper and run as a CW device. The power source can be one of the existing RF power vacuum tubes, and the removal of 80 kW of heat from a four meter long object does not seem to be a very challenging task.

MEBT

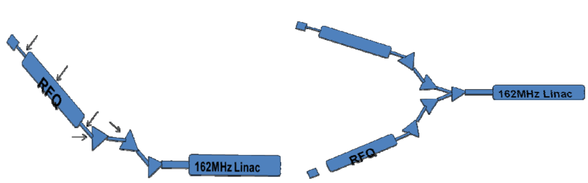

Figure 5: Figure on the left shows a single arm, and the arrows indicate possible laser ports.

Once this configuration of LEBT and MEBT is adopted, there are several options that we can choose from:

- A single arm, with a single 81 MHz RFQ. In this case there is no redundancy, and it must be possible to change the ion source quickly.
- Two identical 81 MHz RFQs, with one in standby for fast switching. This assumes that both systems have H^- sources.
- Two identical 81MHz RFQs, with one arm having an H- source and other a proton source so that the two systems can be switched fast depending on the user's needs.
- Two identical 81 MHz RFQs, with both arms having H^- sources and the last dipole in the MEBT made as a funneling system so that the linac gets 162 MHz structure from the beginning, if there is a need for such a beam.

The dipoles in the MEBT have edge focusing, the straights do not have to be long, and the bending angles can be from 30-70 degrees depending on how much dispersion is needed for momentum collimation. Simulations show that, depending on the focusing channel in the 162-MHz linac, output from the RFQ and the MEBT can be made to match the input to the 162 MHz linac. Figure 6 shows the quadrupole and solenoid matched beam.

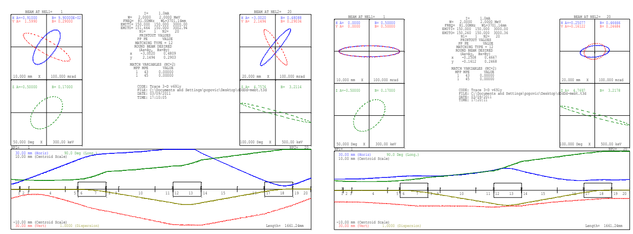

Figure 6: Three dipoles systems with zero dispersion for quad as well as the solenoid based 162 MHz linac. This simulation shows that the bunch structure is preserved and the beam can be injected in the 162 MHz accelerating structure.

1 GeV LINAC

Beam is accelerated from 2 MeV to 1 GeV in structures whose total length is shorter than 240 meters. The acceleration from 2 to ~10 MeV is achieved using superconducting 162 MHz quarter-wave structures. One option is the five-cavity cryomodule with a total length of ~ 5 meters that was suggested by P. Ostroumov as shown in Figure 6.

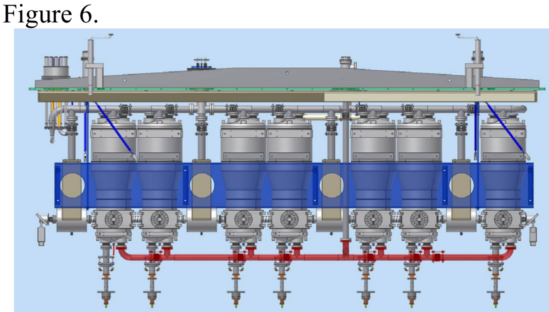

Figure 6: ANL cryomodule with five cavities and focusing solenoids.

From 10 MeV up to 1 GeV acceleration is based on the 325 and 650 MHz superconducting cavities as described in the Project X document [ref?].

This structure is to be housed in the existing linac tunnel and is to be built as indicated in Figure 1. One of the ways how this can be staged with minimal interruption of existing High Energy Physics (HEP) program will be described in a separate section.

Table 1. The acceleration options up to 8 GeV.

Section	RF	Energy (MeV)	C/mag/ CM	Type
SSR1(β_G=0.22)	325	10-42	20/20/ 2	SSR, sol.
SSR2(β_G=0.4)	325	42-160	40/20/4	SSR, sol.
LB(β_G=0.61)	650	160-460	36 /24/6	5-cell ell, doublet
HB(β_G=0.9)	650	460-3000	160/40/2 0	5-cell ell, doublet
HB(β_G=0.9)	650	3000-8000	224/56/2 8	5-cell ell, doublet

The next section describes how the existing Booster can use the new linac.

BOOSTER OPERATION

Presently, the 400 MeV H^- beam from the linac is transported along a ~40 meter transfer line to the Booster tunnel, and about $5x10^{12}$ protons are injected per Booster cycle. The peak current of the linac beam is ~30 mA, and injection lasts for twelve Booster turns or 26 µs (total injection time 12*2.2 µs).

The present line has two twelve-degree vertical bending magnets and two ten-degree horizontal bending magnets that would be replaced in order to minimize H^- stripping in the beam at 1GeV.

The new linac would have a peak current of 5 mA, that would require an injection time longer then 180 µs in order to inject more beam in the Booster than is currently possible.

To keep H^- stripping smaller than $5x10^{-5}$, the two vertical dipoles have to be replaced with 3.5 meter long magnets having a magnetic field of 0.35 T. The horizontal magnets would require a field of 0.35 T and length of 2.8 meters.

The rest of the transfer line can be used as is, with the exception of the injection dogleg system. The middle magnet would need to run with 88% more current, alternatively it could be replaced with a 50% longer magnet. Another possibility is to use correctors for additional displacement and painting during injection.

To avoid field swing dB/B bigger than $1x10^{-4}$,the injection time should not be longer than 240 µs. For the linac current of 5mA, this corresponds to $7.5x10^{12}$ protons injected in the Booster. This also insures that space charge tune shift will be half of the value that we have right now at Booster injection. This gives 150 kW of beam power from the Booster at 8 GeV and from the Main Injector, 0.5 MW at 120 GeV without slip stacking.

With the present 400 MeV injection energy of the Booster, the RF frequency swings from 38 MHz to 53 MHz. For injection at 1GeV, this swing is reduced to an interval from 46.5 to 53 MHz. With such a small frequency swing, the cavities can be tuned with just two tuners, and the third tuner can be removed from the cavity, Figure 7. At present, the cavity beam pipe has a diameter of just 2.25 in, the same as the gap in the main magnet. A shorter frequency tuning range will allow the beam pipe to be increased to 3.5 in, thereby significantly decreasing the beam loss on cavities and activation.

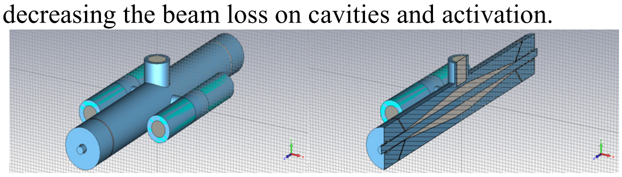

Figure 7: CST model of Booster Cavity with two tuners.

STAGING FROM 400 MeV TO 1GEV

The project can start with the building of 90 meters of tunnel, as indicated with a red line in Figure 2. As soon as a new 400 MeV linac is finished, a transfer line along the present linac tunnel can be built and the present 200 & 800 MHz systems can be decommissioned. Existing linac buildings can be used to house new support equipment, and a new accelerating structure can be installed in the present tunnel. The rest of the linac up to 8 GeV can be built along straight lines (as illustrated in Figure 2) with 8 GeV injection to the Main Injector at MI30. The initial configuration of the 3-8 GeV linac section will be pulsed with a tunnel long enough to accommodate additional RF needed for CW linac.

ACKNOWLEDGMENT

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REFERENCES

[1] S. Holmes et al., “Project X Reference Design Report,” Project X Document 776-v1 (2010), http://projectx-docdb.fnal.gov