A MULTI-MISSION 8 GEV INJECTOR LINAC AS A FERMILAB BOOSTER REPLACEMENT

G. W. Foster and J. A. MacLachlan
*Fermi National Accelerator Laboratory, Box 500, Batavia IL 60510-0500**

Abstract

Fermilab is currently conducting design studies and cost estimates for both an 8 GeV synchrotron[1] and an 8 GeV superconducting linac[2] as possible replacements to the Booster injector to the Fermilab Main Injector (FMI) and the Tevatron. The main goal of the project is a five-fold increase in the proton intensity of the Fermilab accelerator complex. The 8 GeV linac option will be able to accelerate electrons and muons as well as H^- and protons. It will therefore be a capable driver for an XFEL, for pulsed sources of muons, neutrinos, antiprotons, and spallation neutrons, in addition to its primary mission of direct 8 GeV H^- injection into the FMI. The main issue is cost. The present design uses superconducting cavity designs from SNS, RIA, and TESLA, but repackaged in cost-effective and low heat leak TESLA-style cryomodules. The cost-effective TESLA rf distribution, with one 10 MW klystron driving many cavities, requires electronically controlled ferrite phase shifters to provide phase and amplitude control on individual cavities. This capability also provides the ability to re-phase the cavities to accelerate electrons or H^-/protons on a pulse-by-pulse basis. In addition to a near-term physics mission of the 8 GeV injector linac, it also represents a ~ 1 % scale demonstration of the possible economics of a linear collider.

1 8 GEV LINAC CONCEPT

The fundamental tactic for building an economical 8 GeV linac is to adopt designs from existing machines or proposals with few changes, even using the original engineering drawings and making follow-on orders for complete subsystems from original vendors where possible. The general scheme is to copy the SNS linac to 1.2 GeV with a change to TESLA-style cryostats and to use TESLA-like cryomodules and cavities from 1.2 to 8 GeV. In adapting the SNS model, we have kept the single-pulse beam parameters of 25 mA in 1 ms but reduced the repetition rate from 60 Hz to 10 Hz to match the capabilities of the TESLA cryogenics and Multi-Beam Klystrons. The reduction in average beam current results in significant cost savings, particularly in the warm copper front end. The goal is an H^- linac which can saturate the space charge limit of the FMI ($\sim 1.5 \cdot 10^{14}$) in a single injection every 1.5 s, retaining the majority of the 10 Hz pulses as a springboard to any of several outstanding physics opportunities.

Benefits from such a high brightness injector should accrue to practically all of the physics program, present and projected. The FMI could operate at higher current with low loss and smaller emittances. A 1 ms macropulse at 25 mA gives ~ 2.3 A. At lower current, injected emittances could be preserved; for higher currents phase space painting is a clear necessity. The supply of 8 GeV protons would improve dramatically, from $\sim 10^{17}$/h to $> 5\cdot 10^{18}$/h. The practically instantaneous injection from the linac permits the rapid cycling of the FMI to lower beam energies so that the 2 MW maximum beam power can be delivered at any energy between 8 and 120 GeV. This unprecedented flexibility will permit the neutrino program to evolve in response to the results of future experiments.

Ultimately, there could be important contributions to the development of a major new facility. For example, the proposed linac represents a 1.5 % scale demonstration of TESLA economics without directly confronting the obstacles to linear collider funding. It would inform the choice of linear collider technology and establish a stronger US position. It can also contribute to μ collider and ν factory prospects by establishing a cost basis for Proton Driver and μ acceleration. As the first element in the injector chain for a VLHC[3] it could sufficiently reduce the emittance compared to existing proposals to allow reducing the beam current by a factor of four. For stage 1 (1.9 T magnets), this would mean reduced instability and smaller required aperture. For stage 2 (9.8 T magnets), injection could be at emittance close to the radiation damped equilibrium.

In the following we demonstrate that such an undertaking is technically reasonable and, just as importantly, that it should be cost effective. Even where it is necessary to improve on the archetypes, existing technology can serve. We do not question that the capital cost of a synchrotron injector should be less, but, without attempting detailed arguments, endeavor to show that required design effort, performance capability, simplicity of operation, and versatility all favor the linac approach as the more promising investment of time and resources.

2 PRIMARY PARAMETERS

The performance goals are given in Table 1. In the context of existing machines, this seems an immodest proposal; however, as an emulator of SNS it is but an exploitation of prior developments with some incremental developments and a step back in average beam current. Table 2 gives a highly condensed summary of the machine technical parameters. Additional detail appears below in the description of selected subsystems.

* Operated by the Universities Research Association under contract number DE-AC02-76CH03000 with the U. S. Department of Energy

Table 1: Performance goals

Linac		
kinetic energy	8	GeV
particles	H^-, p, $e^\pm$	
length	671	m
repetition rate	10	Hz
macropulse duration	1	ms
beam current (1 ms average)	25	mA
beam intensity	$1.5 \cdot 10^{14}$	pulse^{-1}
	$5.4 \cdot 10^{18}$	h^{-1}
average beam power	2	MW
peak beam power	200	MW
FMI + Linac		
kinetic energy	120	GeV
beam power	2	MW
repetition rate	0.67	Hz
injection period	90	turns
beam current (average)	2250	mA
beam intensity	$1.5 \cdot 10^{14}$	cycle^{-1}
	$3.6 \cdot 10^{17}$	h^{-1}

Table 2: Technical parameters

	Cu	SC1	SC2	
kinetic energy	87	1305	8000	MeV
length	41.21	144.8	502	m
number of modules	6	12	36	
number of quads	147	54	72	
radio frequency	402.5	805	1208	MHz
klystron count	7	10	24	
klystron peak power	2.5	5	10	MW

3 TECHNICAL SUBSYSTEMS

The front end linac is a 402 MHz, 87 MeV DTL fronted by an RFQ; it could be a clone of the SNS design. However, the lower average current in the 8 GeV proposal opens the possibility of using a turn-key commercial product.[4] The 87 - 173 MeV segment is realized with $\bar{\beta} = 0.47$ superconducting cavities designed for the RIA proposal[5] in place of the CCL in the SNS design. The SNS designers also considered using superconducting rf in this range but chose to avoid additional development.[6] In the meantime, much of the necessary development has occurred. It is intended to employ the $\bar{\beta} = 0.61$ SNS cavities between 173 and 386 MeV and $\bar{\beta} = 0.81$ SNS cavities from 386 to 1305 MeV. The 1.3 GeV to 8 GeV portion is modeled closely on the TESLA proposal.[7] However, it is necessary to scale the klystrons and cavities to 1208 MHz to mate with the 805 MHz SNS rf. A block diagram layout is shown in Fig. 1. The transverse focusing is considered in a separate paper.[8]

The superconducting cavities either exist as specified or are in an advanced stage of development. Notwithstanding the strong motivation to exploit existing technology, there are two fundamental departures from the models driven by economics, *viz.*, cryostat design and rf distribution. In both we are pulled toward the economy of the TESLA solution, but for both we need to make substantial adaptations. For an H^- linac with $\bar{\beta}$ fixed in coarse increments, it is necessary to phase the rf separately for each cavity. SNS obtains maximum control for this by feeding each with a separate klystron, an impossible luxury for the 8 GeV machine. We propose to use the TESLA approach of large klystrons with power divided to several cavities. The required modulators have been developed at Fermilab and in service at TTF since 1994.[9] In place of TESLA's three-stub tuners, the 8 GeV linac will use ferrite loaded phase shifters and circulators at each cavity.[10] A schematic of this system is shown in Fig. 2. The phase and power adjustment is made with a so-called E-H tuner, which consists of a magic T with two of its arms loaded with biased ferrite. A commercial quote has been obtained for this crucial component. Anticipated insertion loss is ~ 0.2 dB.

For the sake of beam availability to users, the CEBAF cryostat design adopted for the SNS specified a one shift replacement time for a cryomodule. This resulted in a design with warm to cold transitions at the end of every cryomodule, a separate cryogenic distribution pipe with bayonet disconnects, and an integral cold box, J-T valve, and heat exchanger in each cryomodule. The price for this is extra hardware, high heat load, and lower rf packing factor. The TESLA proposal quotes a 25 day replacement time.[11] For the 8 GeV linac the replacement, will take about two days. The difference from TESLA results from a cryo sector length of about 300 m instead of 2.5 km. The basic concept of the TESLA cryostat is adopted with such changes as necessary to accommodate the SNS cavities and power couplers of KEK/SNS design.

The choice in the TESLA proposal to put the klystrons and instrumentation electronics in the tunnel has not been adopted. The klystron gallery is located underground near the linac tunnel but shielded by intervening earth as shown in Fig. 3. The civil construction costs could be reduced substantially by a single-tunnel design. However, the risk of degraded reliability seems too great.

4 COST ESTIMATE

The primary issue for the 8 GeV proposal is affordability rather than technical feasibility. Top-down estimates have been based on scaling the SNS and TESLA models and some relevant Fermilab experience. Preliminary bottom-up estimates have been done for cryostats, cryosystems, and some crucial components. The naive scaling from the costs in the TESLA proposal and from the SNS is laid out in Table 3.

There are many reasons why the TESLA linac should be cheaper. But how much? Detailed breakdowns are needed to bridge the disconnect between SNS and TESLA costs.

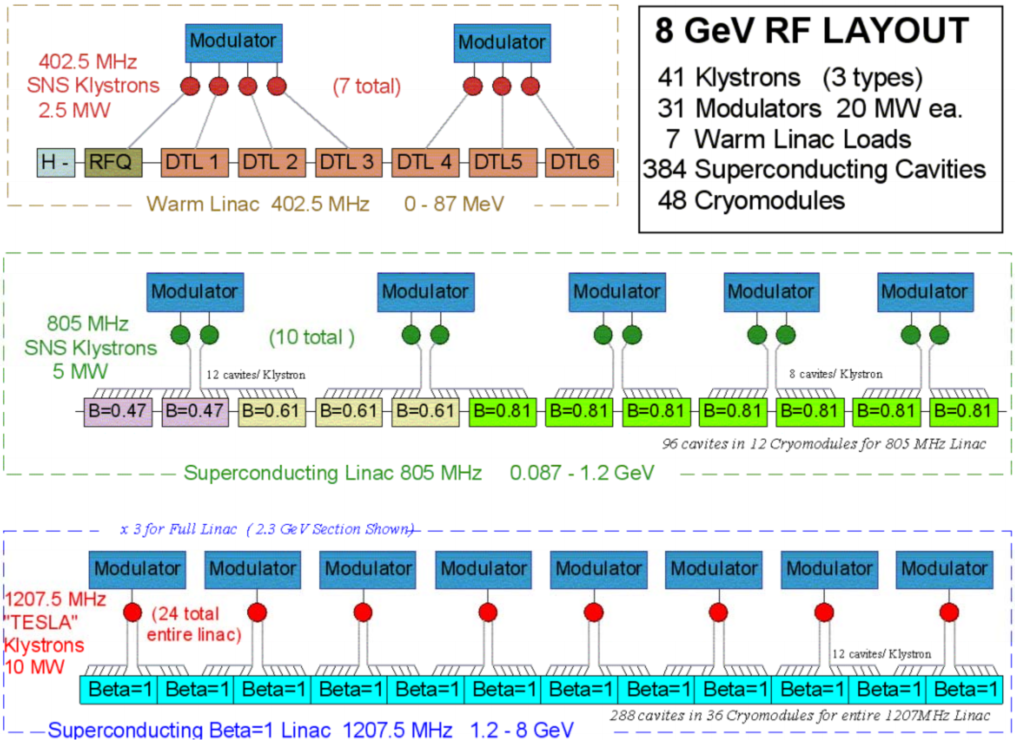

Figure 1: The module layout and rf distribution.

Table 3: Naive cost scaling from TESLA and SNS

TESLA project cost (European)	\$3 B
less damping rings, IR, injector	\$2.5 B
US basis (2x) for bare linac	\$5 B
scale to 7 GeV	\$70 M
reverse TESLA quantity discount $\left(\frac{7}{500}\right)^{-0.074}$	\$100 M
add fixed project cost ($\sim$ \$50 M)	**\$150 M**
SNS project cost	\$1.3 B
linac cost (appx., incl. civil)	\$250 M
scale by energy gain in scrf (7.6/0.8)	**\$2.5 B**

We begin this by using actual SNS costs for niobium and finished cavities, cavity tuners, rf couplers, assembly labor *etc*. We also have actual costs for klystrons, circulators, water loads, *etc*. We have drawn on Fermilab experience to cost TESLA-style cryostats and labor. We have US vendor pricing for TESLA-style rf distribution; it is much cheaper from offshore sources. Fermilab estimates for cryogenics and cryoplant agree with actual SNS costs. The modulator costs, the single largest component of rf cost, are known from the virtually identical Fermilab-built units for the Tesla Test Facility. Estimates for civil construction, controls, and project management are based on the recent Main Injector costs. The result has not been reviewed or exhaustively error checked. It could easily change by 10 – 20 % by the time of a final report, but we think it adequate to make the point that the 8 GeV superconducting injector linac is a project on the scale of the Main Injector. Figure 4 shows a high level breakdown of a total estimated cost of \$238 M without contingency. The technical risks are considered moderate, so an overall 30 % contingency is applied, bringing the final estimate to \$369 M.

5 OTHER MISSIONS

The principal mission of the 8 GeV linac is to raise the intensity in the FMI to 1.5×10^{14} protons/cycle, so-called super beams. Interestingly, as a factory machine, the linac produces an average beam power of about 2 MW, about the same power as the 120 GeV super beam from the FMI. This enormous beam power could serve a number of secondary missions which could be high priority in the future. For example

1. 8 GeV ν program
2. 8 GeV spallation n source
3. 8 GeV fixed target program
4. ν factory front end
5. electron linac
6. XFEL
7. recirculating linac (pseudo CEBAF)
8. $\overline{\mathrm{p}}$ deceleration
9. TESLA damping ring preaccelerator . . .

The list is not exhaustive, and perhaps some of the suggestions seem improbable. One can hope that the potential of such an accelerator promotes other improbable suggestions, among which will be the key to a major experimental program.

There are certain applications where a given beam power at medium energy is better than the same at high energy. For example, neutrino production at high energy yields a long tail stretching from the peak production at rather low energy out to something like half or more of the production energy. Lower energy with the same beam power gives essentially the same event rate, and the peak energy is not shifted down by much. The advantage is that the energy spread in the beam is greatly reduced.

6 CONCLUDING REMARKS

An 8 GeV injector linac will be highly useful at Fermilab regardless what other machine is built later. There are no technical obstacles to an early start, but important optimizations must be finished to establish the economic justification. Many existing designs can be copied or even purchased from the original sources. The big linac should be less problematic than a linac-synchrotron combination with the same final energy. Both in the project and operational phases the manpower requirement is smaller, making the complex simpler to run and freeing scarce talent for other activities. Perhaps surprisingly, the cost is similar to that of the recently commissioned Main Injector or the original Fermilab Proton Driver at 12 GeV. In comparing it to the Proton Driver II proposal for an 8 GeV synchrotron, one finds that when that proposal is augmented by the cost of a suitable 600 MeV injector, the cost margin in favor of the synchrotron does not seem compelling balanced against the beam performance and operational simplicity of the 8 GeV linac. The versatility and adaptability to future uncertainties argue decisively for the linac as the strategic choice for a Fermilab injector upgrade.

7 REFERENCES

[1] "Proton Driver Study II, Part 1", Fermilab TM-2169 (May 2002) `http://www-bd.fnal.gov/pdriver/8GEV`

[2] `http://tdserver1.fnal.gov/project/8gevlinac`

[3] "Design Study for a Staged Very Large Hadron Collider", Fermilab TM-2149 (June 2001) `http://tdserver1.fnal.gov/tddoc/DesignStudyReport/upload/`

[4] AccSys Technology (www.AccSys.com) estimates $20 M for a suitable turn-key 87 MeV DTL based on systems previously delivered for medical facilities and synchrotron injector

[5] C. C. Compton *et al.*, "NIOBIUM CAVITY DEVELOPMENT FOR THE HIGH-ENERGY LINAC OF THE RARE ISOTOPE ACCELERATOR", US PAC 2001 (Chicago), `http://accelconf.web.cern.ch/AccelConf/p01/PAPERS/MPPH116.PDF`

[6] "Preliminary Design Report: Superconducting Radio Frequency Linac for the Spallation Neutron Source", Y. Cho, ed., SNS-SRF-99-101 (December 20, 1999)

[7] "TESLA Technical Design Report", DESY 2001-11 (2001) or `http://tesla.desy.de/new-pages/TDR_CD/start.htm`

[8] J. A. MacLachlan,"Envelope Matching for an 8 GeV Multi-Species Superconducting Linac", this conference

[9] H. Pfeffer *et. al*, "A second Long Pulse Modulator for TESLA Using IGBTs", EPAC '96, `http://accelconf.web.cern.ch/AcelConf/e96/PAPERS/MOPG/MOPG048G.PDF`

[10] Alfred Moretti and David Wildman, Fermilab, priv. comm.

[11] S. Wolff *et al.*, "THE TESLA CRYOGENIC DISTRIBUTION SYSTEM", TESLA REPORT 2001-37, `http://tesla.desy.de/new_pages/TESLA_Reports/2001/pdf_files/tesla2001-37.pdf`

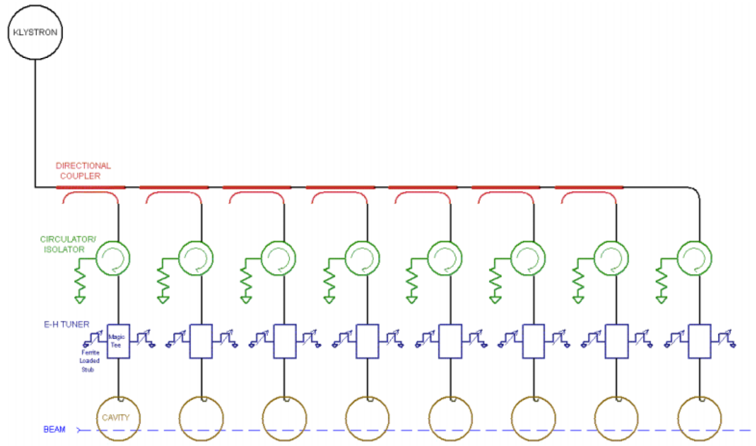

Figure 2: The rf power distribution scheme using directional couplers and fast ferrite phase shifters

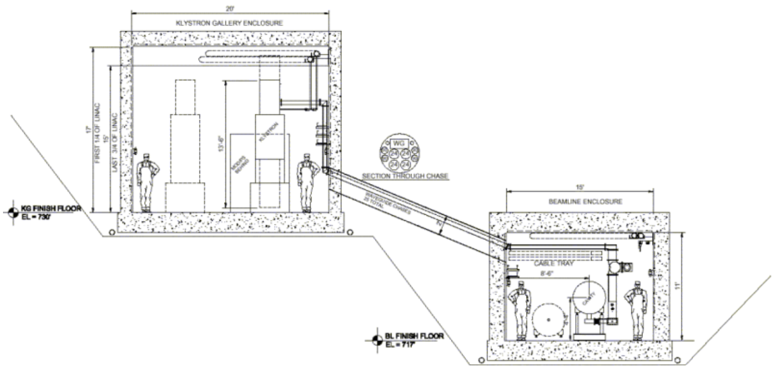

Figure 3: Tunnel cross-section.

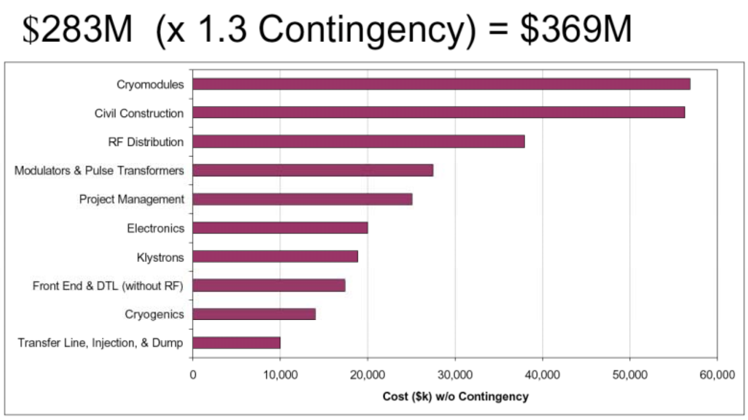

Figure 4: Major cost elements in the 8 GeV superconducting linac