AN 8 GeV CW LINAC WITH HIGH POTENTIAL BEAM POWER*

Charles Ankenbrandt[a,c], Richard Baartman[b], Ivan Enchevich[a], Rolland P. Johnson[a#],
Alfred Moretti[c], Sergei Nagaitsev[c], Michael Neubauer[a], Thomas Peterson[c], Milorad Popovic[c],
Robert Rimmer[d], Gennady Romanov[c], Nikolay Solyak[c], Vyacheslav Yakovlev[c], Katsuya Yonehara[c]

[a]*Muons, Inc., Batavia, IL, USA*
[b]*TRIUMF, Vancouver, BC, Canada*
[c]*Fermi National Accelerator Laboratory, Batavia, IL USA*
[d]*Thomas Jefferson National Accelerator Facility, Newport News, VA, USA*

Abstract

Modern technology allows us to consider operating an 8 GeV SC linac in a CW mode to accelerate a high-current H^- beam. By using appropriate accumulation rings, the linac could provide simultaneous beams for direct neutrino production, neutrino factories, fixed target experiments, and muon colliders. Several other unique accelerator applications could also be served and improved by the same continuous beam, including studies of energy production and nuclear waste reduction by transmutation, rare muon decay searches, and muon catalyzed fusion. A comparison of CW and pulsed operation is strongly dependent on the choice of accelerating gradient, and a first look at refrigeration requirements for a gradient of 20 MV/m is included in this study. Methods for accumulating the beam from a CW linac to serve the special needs of the potential future Fermilab programs mentioned above are considered. In this paper we also examine the use of a cyclotron as a source of high current beams to reduce the cost and complexity of the linac front end. Although the refrigeration system would be large for 20 MV/m gradient, a 3 mA CW H^- beam at 8 GeV looks feasible, with potential beam power up to 24 MW to access the intensity-frontier for muon and neutrino physics and also be an essential step to an energy-frontier muon collider.

INTRODUCTION

Modern proton accelerators or storage rings use multi-turn H^- charge exchange injection and strip at high energy, where the Laslett tune shift is smaller, to achieve high proton bunch intensities. This approach has been used in several new machines, and the next step that is being proposed is to provide a powerful 8 GeV H^- linac that could feed any number of accumulation rings or accelerators for planned and as yet undreamt-of purposes.

A plan for Project-X [1], to replace the aging Fermilab 8 GeV rapid cycling Booster proton synchrotron, has centered on a 1.3 GHz superconducting (SC) linac, which could also act as a string test for the ILC. The purpose of this paper is to consider a CW H^- linac as an option for Project-X, which would not be limited by any ILC constraints and, by virtue of high potential 8 GeV beam power, be best suited to the needs of any future Fermilab research program. Nevertheless, as a large-scale SRF system, it would act as a significant demonstration of many aspects of ILC technology.

Since its design in the late 1960's, the Fermilab Booster has at times been both the world's most intense proton source and almost always the bottleneck in the Fermilab research program, where proton economics have determined which experiments could be scheduled or even were possible. If the Booster is replaced as planned, it will have served in this way for about 45 years. It is quite likely that its replacement will have a similar function for a similar time.

Recent studies of proton driver requirements for muon colliders and neutrino factories [2] have indicated that the present parameters for Project-X may limit these machines because the proton beam power will be insufficient and the repetition rate too low. Even with optimistic muon collection and cooling efficiencies, at least 4 MW of 8 GeV proton power will be required for muon collider designs. The natural repetition rate for muon machines is suggested by the muon lifetime in its final storage ring. For a 5 TeV center of mass collider, for example, the muon lifetime is about 50 ms so that the natural repetition rate is about 20 Hz. For lower energy storage rings, the natural repetition rate is higher.

For the study reported here, the RF gradient G has been chosen to be low enough such that resistive losses, proportional to G^2, are not too large. In the next section we calculate the wall-plug power for the case of G=20 MV/m for ILC-like RF structures. This is to be compared to the 25 to 30 MV/m presently favored by Project-X. A gradient of 20 MV/m implies a linac that would be about 27/20 times longer than the baseline, but has the compensating virtue of easier technology for the RF cavities and klystrons.

CW CRYO POWER REQUIREMENTS

CW operation results in much higher dynamic heating in the RF cavities and input couplers and higher cryogenic cooling power requirements. Table 1 shows a comparison of the power requirements for the components of a TESLA linear accelerator operated as a pulsed machine compared to CW operation.

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#rol@muonsinc.com

Table 1: cryogenic power loads per 8-cavity cryomodule for a CW versus Pulsed TESLA-style linac.

Cryomodule	TESLA		CW	
	Static	Dynamic	Static	Dynamic
Temperature Level	2K			
Static, dynamic sum	1.1	7.6	1.3	159
2K Sum [W]	8.8		160	
	5K - 8K			
Static, dynamic sum	11.7	7.0	10.6	58
5K Sum [W]	18.7		68	
	40K - 80K			
Static, dynamic sum	91.5	82.7	59.1	2870
40K Sum [W]	174.1		2930	

The basic parameters to estimate the dynamic losses in the RF cavities at 2 K in Table 1 are:

1.	Beam energy	U	8 GeV
2.	Beam power	W	20 MW
3.	Gradient	G	20 MV/m
4.	Quality factor	Q	~2×10^{10} (ILC-like structure, 2K)
5.	Number of cavities	N	350
6.		R/Q	1050 Ohm/cavity

A simple estimate of the total RF load for the high energy part of the linac (from 1 to 8 GeV) at 2 Kelvin is:

$$P = \frac{G^2}{Q \times (R/Q)} N = 19W/cavity \times 350 = 6700W.$$

Note that 8 cavities/cryomodule implies 152 W at 2 K of dynamic heating per cryomodule just due to the RF load.

Table 2: Cryogenic system power requirements

Temperature level	40 K to 80 K	5 K to 8 K	2 K
Total cryomodule heat load (W)	2930	68	160
Number of cryomodules	44	44	44
Total linac heat load (kW)	129	3	7
Conversion factor to wall plug power	16.5	200	700
Power at each level (MW)	2.1	0.6	4.9
Total operating power (MW)	7.7		
Cryogenic system margin	1.5		
Total installed power (MW)	11.5		
Installed 4.5 K equivalent (kW)	52.3		

Dynamic heating at the 5 K to 8 K and 40 K to 80 K temperature levels is dominated by the input coupler. A rough estimate of those heat loads comes from scaling experience with TTF-III input couplers. However, the TTF-III input coupler would not actually handle CW loads; the 40 K heat may be overestimated here. For CW operation, a different design such as that from Cornell [3] would be used. A 1.3 GHz, CW coaxial-type TW coupler for ERL was developed and tested up to 61 kW at Cornell. This coupler may be a prototype for a cavity of the CW linac.

Table 2 provides an estimate of total cryogenic power required for the linac, 11.5 MW, equivalent to 52.3 kW of cooling at 4.5 K, which would require two very large cryoplants, each about the size of that of the LHC.

The power required for one ILC – like cavity is more than 50 kW for an acceleration gradient of 20 MV/m. Fifty kW is required for acceleration, and about 20% is overhead for the feedback system, etc. One of the possible options is to use CW IOT tubes to feed each 1 m ILC-like cavity. There are 1.3 GHz 30 kW, CW IOT available, developed by CPI [4]. The CPI Company has offered to examine technical feasibility of a CW operating 1.3 GHz tube providing output power of 60 and 120 kW. Very preliminary modeling shows no fundamental technical difficulty to build such a tube [4].

ACCUMULATORS AND BUNCHERS

In both the pulsed and CW linac options, the basic idea is that an 8 GeV accumulator ring would be used to strip the H$^-$ ions to store sufficient proton charge. The protons would then be bunched either in the accumulator ring or in a second ring where short bunches can be extracted for muon production. Additional relatively inexpensive accumulator rings could be added as new opportunities arose for new experimental programs. Present plans for uses of the Project-X beam at Fermilab have considered the recycler ring, the present pbar accumulator and debuncher rings, and the Main Injector as places where the H$^-$ ions could be used to form intense proton beams.

The baseline Project X plan is to inject from a pulsed linac into the Recycler via a stripping foil for a total of 3 ms. To facilitate the creation of intense short bunches in a multi-megawatt driver for a neutrino factory or a muon collider, a much smaller accumulation ring with much larger transverse acceptances is preferable. Filling such a ring from a CW linac implies a longer injection time, raising the issue of multiple passages of circulating protons through a stripping foil. Ideally that issue ought to be addressed by simulations. For now a numerical example may suffice to suggest that the issue is not a show-stopper.

A repetition rate of 100 Hz implies an injection time of 10 ms compared with 3 ms in the Recycler. If the accumulation ring is ~5 times smaller than the Recycler, then the circulating beam passes through the injection region 5*10/3~17 times more than in the Recycler. However, the multi-megawatt accumulation ring must have transverse acceptances ~10 times larger than the Recycler in order to control transverse space-charge effects. Painting into both transverse planes then implies 100 times more phase-space volume to work with. So the number of times that each circulating proton passes through the stripping foil might be lower than in the Recycler by a factor of ~100/17~6. Alternatively, the development of magnetic plus laser stripping may solve the problem [5].

LINAC FRONT END

Conventional Front End

Front end schemes for high-power CW proton accelerators are already well established [6,7]. Typically they have four parts in series: 1) normal conducting (NC) 50-75 keV proton or H$^-$ minus source, 2) Radio-Frequency Quadrupole (RFQ), 3) low- and intermediate-energy section containing the NC to SC transition, and 4) (SC) high energy section.

The proton beam out of the source is a continuous beam that needs to be bunched at (a subharmonic of) the frequency used for the intermediate and high energy sections of the accelerator. This task, and an initial acceleration boost up to a few (5 to 7) MeV is performed by an RFQ. Several CW proton RFQs have been built or designed recently [8,9,10].

While there is a wide international consensus on the use of an Electron Cyclotron Resonance (ECR) H$^-$ source and RFQ for energies up to 5 to 6 MeV, different ideas have been pursued for the intermediate energy section up to approximately 100 MeV. Many projects have used different combinations of traditional normal conducting RF systems such as classical Drift Tube, Coupled Cavity Drift Tube, and Coupled Cavity Linacs. However, the use of SC cavity technology seems to be most promising in terms of the needed accelerator plug power efficiency. Some projects have investigated the possibility of extending the SC part of the accelerator down to low energies with independently phased low-velocity SC cavities, where the most promising are spoke and re-entrant SC cavities because of their simplicity and good RF parameters. The choice of NC or SC technology for the intermediate acceleration stages may be an issue for pulsed machines, but for CW beams the intermediate velocity SC structures are favored. Also a very big advantage of CW operation is the absence of Lorentz force detuning problems, which are especially severe for low-beta SC cavities in pulsed mode.

Cyclotron Front End

A somewhat unorthodox alternative choice for the front end of the CW linac is a cyclotron. An H$^-$ cyclotron with peak magnetic field of just over 1T can safely achieve 100 MeV without significant Lorentz stripping. Such cyclotrons exist or are being built, but since they use a stripper foil to extract, the common varieties are wrong for this application. We would like to retain intact the H$^-$ ions, so a separated turn scheme is required. This can be achieved with sufficient RF voltage. A good example of such a machine is the PSI Injector 2 [11], which accelerates up to 2 mA of protons to 72 MeV. Compared with bare protons, single turn extraction of H$^-$ ions is technically simpler because the ions that would be intercepted by the septum can be pre-stripped and thus re-directed to a beam dump.

It is projected that such a cyclotron can accelerate over 3 mA average current [12] from an injected current of as little as 9 mA. DC H$^-$ ion sources have provided as much as 20 mA into a normalized rms emittance of 0.4 microns [13]. The width at extraction resulting from this emittance is only about 3 mm. The space charge effect in an isochronous machine is to create round bunches; this means bunch lengths are also about 3 mm, allowing them to fit easily into the 325 MHz linac buckets.

The most delicate region of the cyclotron is the center. If the RF frequency is too high and the injection energy too low, it is not possible to launch circular bunches cleanly matched to the focusing structure. For this reason, the beam frequency would be a relatively low 54 MHz (=325 MHz/6), and the injection energy a relatively high 1 MeV.

Since the energy spread tolerated by the cyclotron is very small, the cyclotron injector should not be an RFQ but a DC device as exists at PSI.

NEXT STUDIES

From the standpoint of an accelerator that will be the Fermilab workhorse for the next four or five decades and will take several years to build, the existence of immediately available off the shelf components is not the most relevant question. Nevertheless, it is useful to look at the components such as power couplers, klystrons, and SC RF that are available and to imagine which devices could be improved with an appropriate amount of R&D.

To extend the studies reported here, all linac system parameters (RF frequency, and other cavity, klystron, and coupler choices, refrigeration system, the conventional construction and infrastructure, etc.) will be examined as a function of accelerating gradient to arrive at a CW system to compare to the pulsed option for Project-X. Other, more speculative approaches are also being considered, such as the use of a Jefferson Lab style recirculating linear accelerator, the use of lower energy protons for muon and neutrino production, and the possibility to use the proton accelerator to simultaneously accelerate cooled muons [14].

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