FERMILAB-CONF-11-119-APC

# CONCEPTUAL DESIGN OF THE PROJECT-X 1.3 GHz 3-8 GeV PULSED LINAC*

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*Abstract*

Project-X, a multi-MW proton source, is under development at Fermilab. It enables a Long Baseline Neutrino Experiment via a new beam line pointed to DUSEL in Lead, South Dakota, and a broad suite of rare decay experiments. The initial acceleration is provided by a 3-GeV 1-mA CW superconducting linac. In a second stage, about 5% of the $H^-$ beam is accelerated up to 8 GeV in a 1.3 GHz SRF pulsed linac and injected into the Recycler/Main Injector complex. In order to mitigate problems with stripping foil heating during injection, higher current pulses are accelerated in the CW linac in conjunction with the 1 mA beam which is separated and further accelerated in the pulsed linac. The optimal current in the pulsed linac is discussed as well as the constraints that led to its selection. A conceptual design which covers optics and RF stability analysis is presented. Finally, the need for HOM damping is discussed.

## INTRODUCTION

Project-X, a multi-MW proton source, is under development at Fermilab [1]. It enables a world-leading program in neutrino physics and a broad suite of rare decay experiments. The facility is based on 3-GeV 1-mA CW superconducting linac [2]. In a second stage, about 5-9% of the H- beam is accelerated up to 8 GeV in a SRF pulsed linac for injection into the Recycler/Main Injector synchrotron complex. This fraction is directed from the CW to the to the 8 GeV linac using a pulsed dipole. The overall configuration is shown in Fig. 1

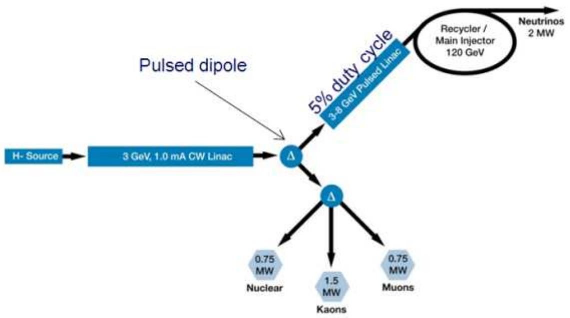


Figure 1: Project-X configuration.

## RF SYSTEM

The 3-8 GeV pulsed linac must be capable of delivering correctly formatted beam for injection into the Recycler Ring (or Main Injector) with a total charge per cycle of 26 mA-msec within less than 0.75 s. The bunch structure fed to the pulsed linac must incorporate the Recycler synchrotron RF bucket (52.8 MHz) structure to facilitate pseudo bunch-to-bucket transfer as well as the Recycler revolution (90.3 kHz) structure to provide a 200-ns extraction gap. This results in the removal of 33% of bunches during the beam pulse. The beam in the 8 GeV linac has a pulse duration of 4.3 msec with a 10 Hz repetition rate. Details of the beam structure and timing are presented in Fig. 2.

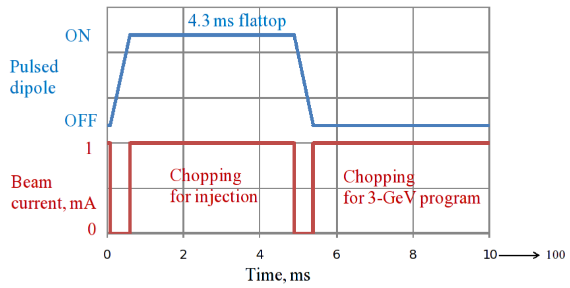


Figure 2: The beam time structure in the CW linac. The linac beam current has a periodic time structure (at 10 Hz) with two major components, one for injection to the pulse linac (4.3 msec), and the other for the 3-GeV program.

The beam velocity $\beta = 0.97$ at the pulsed linac input allows for efficient acceleration in 1.3 GHz, ILC-type $\beta_g = 1$ superconducting acceleration cavities [3]. Standard ILC-type cryo-modules containing 8 cavities and one focusing element will be used . A conservative accelerating gradient of 25 MeV/m is chosen so as to provide reliable operation in pulsed regime. The ILC cavity has $R/Q = 1036$ Ohms [3], leading to an optimal loaded $Q$ of $2.5 \times 10^7$ and a bandwidth of 53 Hz. This narrow bandwidth creates a potential problem with microphonics. In addition, the filling time is 4.2 msec and the entire RF pulse is 8.5 msec, which may increase the effect of frequency detuning from Lorentz forces. Experiments done at Fermilab [4] show that it is possible to provide active compensation of Lorentz forces and operate the cavity with a pulse width up to 10 msec at a loaded Q up to $10^7$. To mitigate both Lorentz force and microphonics, the cavity is to be over-coupled. The loaded Q is chosen to be $1.0 \times 10^7$ corresponding to a bandwidth of 130 Hz. Filling time in this case is 3 msec, and entire RF pulse is 7.3 msec and the input pulse power is 32 kW per cavity (20% higher than for optimal coupling). If one klystron excites two cryomodules, it should provide pulsed power of about 615 kW and average power of 45 kW, taking into account 20 % overhead for control and losses in the power distribution system. If the klystron feeds three cryomodules, the pulse power becomes 923 kW and the average power 67.5 kW. The klystron is to be ordered from

* Work performed under DOE contract DE-AC02-76CH03000.
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Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.

the industry. Note that the cryogenic load in the cavities is close to the one envisioned for the ILC (20 W/CM). This load is what permits the use long cryomodule strings in the ILC design (the ILC rf pulse is shorter, but additional load of up to 16 W/CM takes place because of HOM excitation). A standard TTF3 coupler, designed for the DESY XFEL and ILC for 250 kW of peak power and 4 kW of the average power [3] would likely work for Project-X parameters as well, but it looks complicated and expensive. For the 8-GeV Project X linac one only need 30 kW of peak power and 2.3 kW of average power. Accordingly, a simple 1.3 GHz coupler compatible with the Type-IV ILC cryomodule is being designed for the Project X linac parameters [5]. The coupler design with flat window and no internal bellows is shown in Fig. 3.

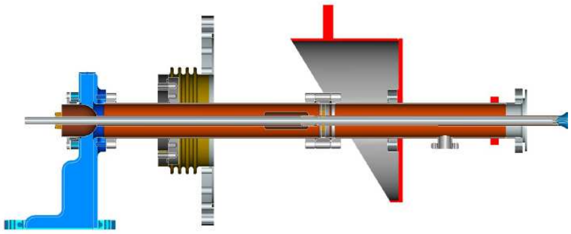

Figure 3: 1.3 GHz coupler for Project X; preliminary mechanical design.

## LATTICE DESIGN

The lattice has a simple regular FODO structure, with 8 cavities in the open space between quadrupoles. One cryomodule encompasses a quadrupole and 8 cavities, a quadrupole in the center, 4 cavities upstream and 4 cavities downstream of the quadrupole. It is assumed that cryomodules would be assembled in a single cryogenic string cooled by one cryo-plant, similarly to the XFEL and ILC designs. Synchronous rf phases in cavities vary along the linac from $-16^\circ$ at the linac entrance to $-10^\circ$ at the end of linac to accept bunches emerging from a 50 m transfer line downstream of the CW linac. The design of this transport line will be discussed elsewhere. The beam is accelerated from 3 to 8 GeV in a total of 28 cryomodules. Both lattice design and beam tracking were performed using the CEA TraceWin/Partran code. The beam rms envelopes and phase advances in the pulsed linac are shown in Fig. 4. Space charge is a small perturbation in the 3-8 GeV energy range; emittances are well-preserved an no special issue arises in the error-free nominal lattice. While a detailed analysis of the impact of misalignments and rf errors has not yet been done, no major problem is anticipated. The most serious issues are microphonics and Lorentz force detuning (LFD) in long pulses ( 8ms) given the high loaded Q of the cavities. As mentioned above, the baseline approach for the Project-X pulsed linac is to use one rf source for a few cryomodules (16, 24 or 32 cavities per rf station) in conjunction with feed-forward compensation for LFD and microphonics and feedback control of the cavity voltages vector-sum . The required hardware components, algorithms and software are under development at Fermilab [4].

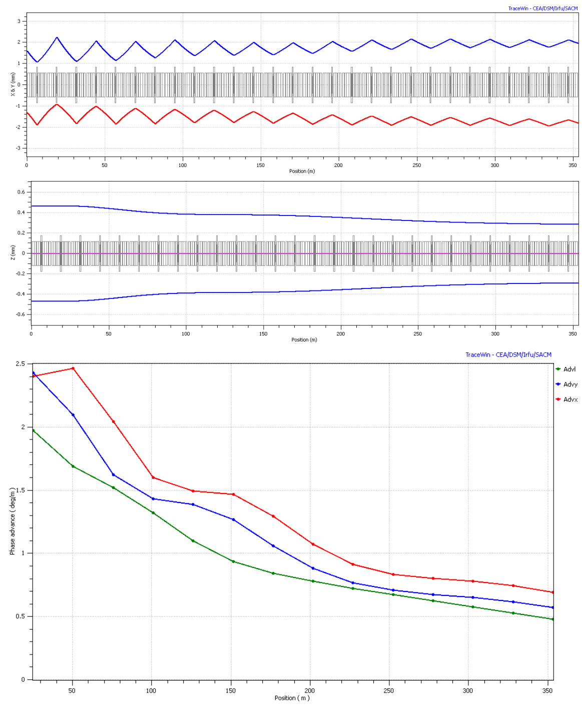

Figure 4: RMS envelopes. top: transverse; bottom: longitudinal and phase advances in the 3-8 GeV pulsed linac.

## VECTOR SUM STABILITY REQUIREMENTS

Without special measures, beam loading jitter coupled with klystron rf errors and cavity detuning due to microphonics and Lorentz forces would result in intolerable variation of the beam output energy. In SC electron linacs, a dedicated LLRF control system is key for stabilization of the beam parameters. Such a system was developed and successfully demonstrated, for example at the FLASH facility, where one klystron feeds a few cryomodules. The basic method is to control the vector sum of the voltages from all the cavities fed by a single klystron. In a proton linac where the beam velocity is not ultra-relativistic, the beam loading dependence on energy may limit the performance of LLRF system. To better understand requirements for vector-sum (VS) control, a set of simulations were performed. Random rf phase ad amplitude errors were generated for groups of 16 cavities assumed to be powered by a single klystron. The vector-sum $V_S$ is defined for each group as $V_S = \sum_{n=1}^{N} A_n \mathrm{e}^{i\phi_n}$, with $A_n, \phi_n$ representing respectively the voltage amplitude and phase of cavity $n$ and $N$ the number of cavities per klystron. We also assumed the vector-sums $V_S$ are affected by independently generated errors. For each set of generated errors, the beam was tracked through the linac and the energy spread was recorded. The results confirmed that provided $V_S$ can be controlled exactly (no error), the output energy spread remains below 1 MeV, even with large rf errors in the cavities (up to 10% and $10^\circ$). The energy spread is, on the other hand, very sensitive to errors in the vector-sum. This is illustrated in Fig. 5, where each plot represents statistics for 30 linacs. Assuming a maximum acceptable 10 MeV energy spread for injection into Recycler ring, the results indicate that vector sum errors should be less than 0.5% and 0.5° in amplitude and phase respectively.

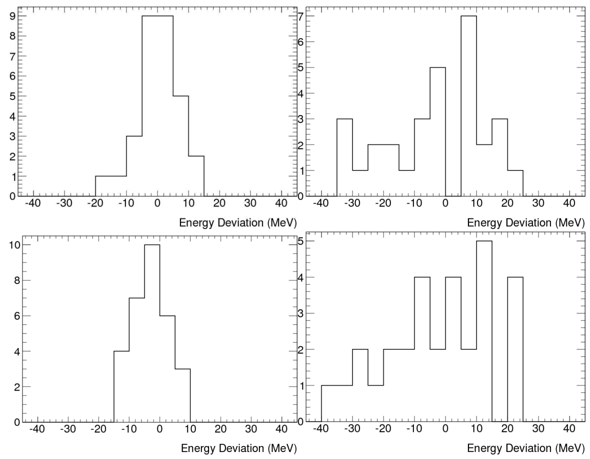


Figure 5: Vector sum stability requirements. (a) $V_S$ : (0.5% , 0.5°) (left) and (1%, 1°) (right). Cavity errors: (5%, 5°) (b) $V_S$: (0.5%, 0.5°) (left) and (1% ,1°) (right). Cavity errors (10% , 10°) . All errors are rms.

## LLRF CONTROL SIMULATIONS

Further studies were performed using the LLRF simulation code SCREAM, modified for our purposes. This time domain code includes longitudinal dynamics (w/o space charge), beam loading and models for fast and slow microphonics, LFD and feedback control. The result of a simulation for the first rf station is presented in Fig.6, where the green lines show dynamics of accelerating gradient during 4.2 ms pulse in each cavity (from 1 to 16) and blue line is calculated VS. No errors were assumed in this simulation. The total variation of the output energy is defined by non-linear effect from different beam loading typically not exceed 120 keV in the pulse. Switching Lorentz force detuning ON dramatically changes the results. We assume that active LFD compensation by piezo-tuner will reduce detuning by up to 10-20% of its nominal value. Therefore, in our simulation model we used reduced LFD coefficients, varying from 0.1 to 0.5 Hz/(MV/m)$^2$ rather than the typical value of about 1 Hz/(MV/m)$^2$ quoted for an ILC/TESLA cavity. The results of the simulations with and without feedback are shown in Fig. 7. On the left plot the gradient for all 16 cavities (in green) and $V_S$ (in blue.) are shown during the rf pulse. LFD changes the gradient from a nominal 25 MV/m to about 10-20 MV/m. There is almost no beam acceleration in the linac in this case. On the right plot one can see the result with feedback control. Here, the gradient variation in cavities and $V_S$ is much smaller (note the different scale). The intra-pulse output energy spread is 130 keV, which is close to the spread calculated for an ideal cavity, without LFD.

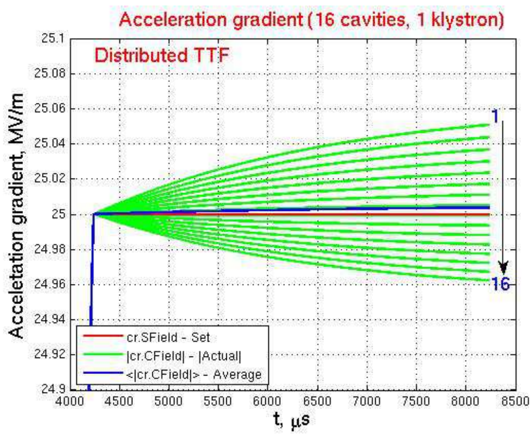


Figure 6: Accelerating gradient (green), $V_S$ (blue) and $V_S$ Set-point (red) vs. time in first 16 cavities for ideal case (no errors, no LFD, no microphonics).

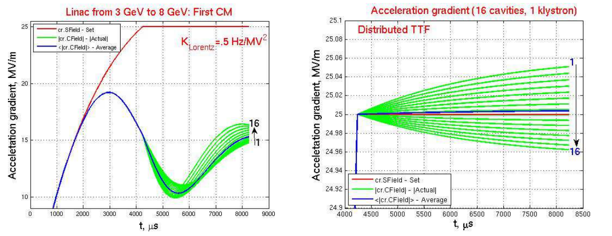


Figure 7: Accelerating gradient in the first 16 cavities, powered by one klystron in presence of Lorentz force detuning. Left: in case of feedback OFF; right: feedback ON . Note that the scales are different. LFD coefficient=0.5 Hz/ (MV/m)$^2$. Feedback gain is 100.

## CONCLUSION AND FUTURE WORK

Preliminary studies for the pulsed linac, presented in this paper, indicate that the proposed concept and the choice of parameters are sound. A vector-sum feedback system – in conjunction with mendatory active compensation of LFD and microphonics –is likely to provide the required energy stability. We are planning further studies of stability control, including errors due to fast and slow microphonics, beam energy and time jitter, calibration as well as $V_S$ errors, to further establish the viability of the concept.

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