LONGITUDINAL BEAM DYNAMICS AND LLRF REQUIREMENTS FOR THE PROJECT X PULSED LINAC*

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Abstract

Project X is a high intensity proton facility being developed to support the intensity frontier physics program over the next two decades at Fermilab. The Reference Design [1] is based on a continuous wave (CW) superconducting (SC) 3 GeV linac providing up to 1 and 3 MW of beam power at 1 and 3 GeV respectively, while a superconducting pulsed linac provides acceleration of roughly 4.3% of the beam delivered from the CW linac to the 8 GeV injection energy of the existing Recycler/Main Injector complex. In this paper we present the results of simulations of longitudinal beam dynamics and Low Level RF (LLRF) control system in the pulsed linac, operated for long pulses in presence of errors and cavity detuning for different RF configurations and settings, and set the requirements for the LLRF necessary to fulfill the specifications of the design.

INTRODUCTION

The pulsed linac is the main part of the third stage of Project X and will accelerate pulses of 4.3 ms duration and 1 mA average current of the H⁻ beam coming from the 3 GeV linac (and downstream transport beamlines) up to 8 GeV at a repetition rate of 10 Hz. The constraints on the output beam parameters come from the acceptance of the downstream 8 GeV transport line and efficient injection in the Recycler/Main Injector ring. The lattice of the pulsed linac is studied with computer codes for accelerator optics and particle tracking simulating a single bunch. Once a configuration and set of parameters that provide acceptable output are found, multi-bunch simulations are performed to study the behavior of the system (accelerator and beam) during the length of the pulse and in multi-pulse mode. The focus of this study is on the RF system and longitudinal beam dynamics, neglecting beam optics and effects from elements of the beamline except for the accelerating cavities.

SINGLE BUNCH SIMULATIONS

Single bunch simulations are performed with the computer code TraceWin [2]. The current lattice of the pulsed linac and simulation results for the bunch envelopes are showed in Fig. 1. The linac is composed of 3 cryo strings of, respectively, 10, 9 and 9 ILC Type-IV cyomodules [3]. Each cryomodule contains 8 ILC 9-cell cavities and a SC quadrupole at the center.

Each cryo string is preceded and followed by a 2.5 m service box and between service boxes of adjacent cryo strings
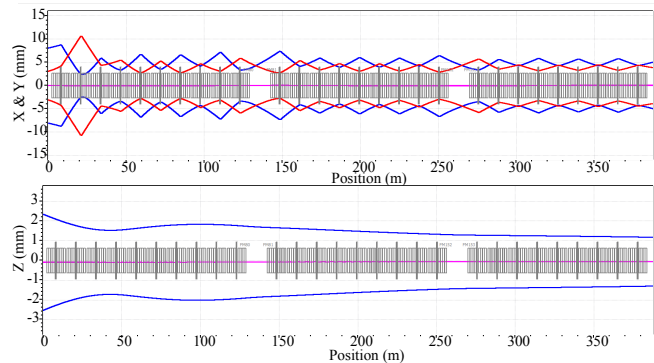

Figure 1: Beam envelopes (3 rms sigmas) in transverse (top) and longitudinal (bottom) coordinate spaces.

7.652 m room temperature areas are placed for beam collimation, diagnostics and maintenance operations. Table 1 shows relevant linac parameters and constraints to be fulfilled.

Table 1: Relevant Linac Parameters and Constraints

Beam Parameter	Initial value	Final value	Requirement
Kinetic Energy (MeV)	3000	8000	8000
Norm. hor. rms emit. (mm mrad)	0.516	0.516	≤ 0.6
Norm. vert. rms emit. (mm mrad)	0.281	0.311	≤ 0.6
Rms bunch length (ps)	2	1.3	≤ 100
Rms energy spread (MeV)	0.9	1.6	≤ 4

MULTI-BUNCH SIMULATIONS

Multi-bunch simulations are carried out employing a MATLAB based code written by the authors. The motivations for running multi-bunch simulations are various:

- To check that the configuration under study can fulfill consistently the specifications of the design during operation in presence of cavity detuning and errors in beam and RF components.
- To set the requirements for parameters of LLRF components to achieve an acceptable performance of the accelerator.

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- To study the impact of gradient spread of the cavities fed by a singe RF station.
- To evaluate the reach capabilities of different configurations of the RF power system, like the number of cryomodules fed by each RF station.

The necessity to run the linac with different gradients for cavities fed by the same RF station comes from the fact that not all the cavities may be able to reach their design gradient. In this case, if the difference in voltage between the cavities is not too big, it is possible to adjust the ratios of the power couplers to set the loaded Q_L of each cavity such that they all have the same filling time. If the spectrum of the Q_Ls employed is in the range 7×10^6–1.2×10^7 then operation is possible in presence of different detuning levels. The 2 configurations of the RF power system we want to study are with one power station feeding 8 cavities (1 cryomodule) or one station for 16 cavities (2 cryomodules).

Detuning Model

Most of the cavities in the pulsed linac are supposed to work at 25 MV voltage and around $5°$ phase. For these values for matched cavities (no reflection) the power needed to drive them is around 25 kW. To take into account power distribution losses, residual detuning after compensation and control overhead a value of 50 kW per cavity has been decided as a requirement for the linac power consumption. Lorentz Force Detuning (LFD) and microphonics cause voltage amplitude and phase of a cavity to change during the pulse and requires more power to drive the cavity at the design values. Methods to compensate them have been developed, resulting in a reduction of LFD at the level of 30 Hz or less for the cavity parameters given above, while microphonics level is around 3 Hz rms [4, 5]. In our simulations we assume LFD compensation is applied and we only use a model for the residual detuning. Analyses at Fermilab led to determine the lowest mechanical resonant frequencies of the cavities to be around 150, 250 and 390 Hz. In our model we assign to each cavity i mechanical frequencies $\omega_{1,i}, \omega_{2,i}, \omega_{3,i}$ around the above values, allowing a 5% of difference from cavity to cavity. Then we assign them three phases $\phi_{1,i}, \phi_{2,i}, \phi_{3,i}$ and 3 amplitudes $\alpha_{1,i}, \alpha_{2,i}, \alpha_{3,i}$ such that $\alpha_{1,i} + \alpha_{2,i} + \alpha_{3,i}$ equals the maximum measured LFD level. We also assign a value $\alpha_{0,i}$ for microphonics compatible with measures. We can write the detuning for each cavity as:

$$
\begin{aligned}
\Delta f_i = \alpha_{0,i} &+ \alpha_{1,i}\sin(\omega_{1,i}t + \phi_{1,i}) \\
&+ \alpha_{2,i}\sin(\omega_{2,i}t + \phi_{2,i}) \\
&+ \alpha_{3,i}\sin(\omega_{3,i}t + \phi_{3,i})
\end{aligned} \tag{1}
$$

In our simulations we used 2 types of detuning model: in the first one, uncorrelated, the phases and amplitudes of each cavity are independent. In the second type, correlated, the cavities inside a cryomodule share the same phases and amplitudes. For this second model the peak power delivered by the RF station must be bigger, since all the cavi-

ties reach the maximum detuning at the same time, requiring more power from the station at about the same instant. Results of measurements conducted, show some degree of correlation between the detuning of the cavities.

LLRF Control

In order to keep the voltage of the cavities at the design values, continuous correction of the power delivered by the RF station is necessary. Furthermore, different cavities require different corrections, but we can only control their common power source, thus the control can only be applied to the vector sum of the voltages of the cavities. This operation is executed automatically by the LLRF system. A schematic layout of the LLRF of the pulsed linac is showed in Fig. 2.
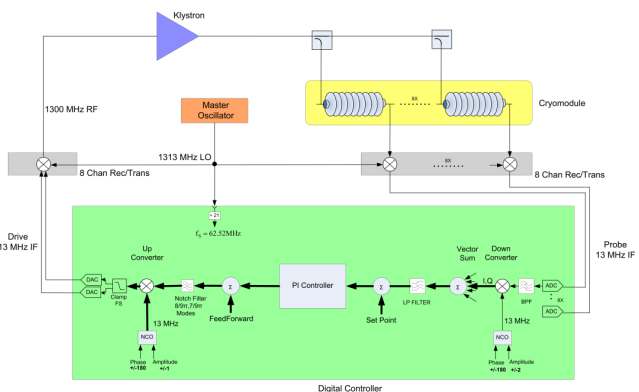

Figure 2: Schematic layout of the LLRF control of the pulsed linac.

More details of the system are available [6]. In our simulations it would be too time consuming to simulate the behavior of each element of the LLRF system, thus we simplify a little the scheme. Our simulated feedback works at a frequency of 1 MHz instead of 62.52 MHz. At each time step, the static and dynamic receiver errors are added to the voltages of the cavities (complex vector variables) and their vector sum is compared to the set point value. For the moment our system only has a proportional gain (no integral gain), so the difference just calculated is multiplied by the proportional gain and the result is summed to the feedforward value. We only simulate the fundamental mode of the cavity. The calculated power and phase are directly sent to the station (Klystron) with a delay of 1 time step (1 μs). The RF station delivers the power and phase requested with RF station errors added to them. Table 2 shows the LLRF parameters used in the simulations.

In addition to the above errors we also added beam intensity errors: 1 ps bunch time jitter (rms), 0.25 MeV bunch energy jitter (rms), 3% bunch-to-bunch intensity jitter (total) and 3% pulse-to-pulse intensity jitter (rms).

RESULTS

We considered two RF configurations with 8 or 16 cavities for RF station. In both cases we studied the dependence

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Table 2: LLRF Parameters Used in the Simulations

LLRF Parameter	Value
Cavity detuning level (peak)	30 Hz
Receiver amplitude rms error (static/dynamic)	0.667% / 0.009%
Receiver phase rms error (static/dynamic)	0.667° / 0.005°
Klystron gain	1
Proportional gain	250
Loop delay	1 μs
Klystron amplitude rms error (static)	0.2%
Klystron phase rms error (static)	1°

Figure 3: Peak power per cavity dependence on detuning for the 2 configurations studied.

of the results on the cavity gradient spread. In particular we calculated the rms energy spread of the particles at the end of the linac and the peak power per cavity required during the simulation. As stated above the requirements are $\leq$ 4 MeV rms energy spread and $\leq$ 50 kW per cavity peak power. The other constraints resulted largely fulfilled by any scenario. First we compared the two models of detuning we used (correlated and uncorrelated) and found that in any case the correlated one required more power from the stations than the uncorrelated one (up to 50% more at 70 Hz detuning level) and resulted in larger energy spread (up to 50% at 45 Hz detuning level). Keeping all the other parameters at their nominal values, the difference in the results for a gradient spread varying from 0 to 10% resulted negligible for both the configurations. Since we first want to give conservative constraints we are giving results for simulations with correlated detuning, which are more pessimistic. The configuration with 8 cavities per station required 32 kW per cavity peak power at 0 detuning, resulting in final 1.86 MeV beam rms energy spread. The power needed grew up to 50 kW and more when exceeding 70 Hz of peak detuning. The energy spread grew up to 2 MeV at this detuning. At the nominal 30 Hz the power consumption was about 35 kW. For the 16 cavities configuration, the power consumption was few percent less than the other configuration, reaching the 50 kW limit at around 72 Hz. The energy spread is a more stringent constraint, since it grew from 1.87 MeV at 0 detuning up to around 3 MeV at 45 Hz and exceeding 5 MeV at 50 Hz. The power consumption dependence from the detuning is reported in Fig. 3.

A set of simulations where carried out to study the impact of the LLRF parameters (Table 2). We varied one parameter up to 10 times the nominal value, leaving the others constant, to evaluate the effect. For the moment we only applied this analysis to the receiver and generator errors. Varying the receiver amplitude error up to 0.09% produced a growth of 4% in the peak power, while the energy spread remained unchanged. Receiver phase error produced a 14%
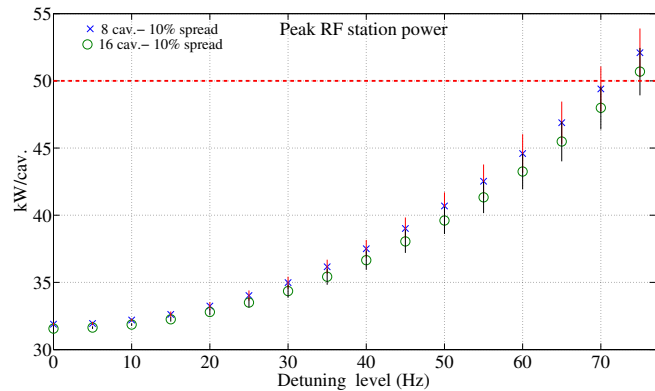
increase in power and negligible in energy spread varying up to 0.5°. Generator amplitude error showed no impact up to 2% and its phase error produced 15% increase in energy spread and 2% peak power when increased to 10°.

CONCLUSION

In this paper we presented the ongoing study on Project X pulsed linac, showing some preliminary results of the multi-bunch simulations performed. Configurations with 8 and 16 cavities per station have been compared in presence of gradient spread and different level of detuning, showing similar performance with nominal parameters but more critical dependence of the 16 cavities configuration on the detuning level, concerning the final energy spread of the beam. Impact of some LLRF parameters have been preliminary studied showing particular importance of the phase errors. A more accurate and wider study of the parameters space is needed. Improvement of the code speed is desirable, giving the opportunity of more accurate simulations of the LLRF system.

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