PROPOSED LLRF IMPROVEMENTS FOR FERMILAB 201.25 MHZ LINAC

T. Butler, L. Allen, E. Cullerton, V. Tupikov, FNAL, Batavia, IL 60510, U.S.A

Abstract

The Fermilab Proton Plan [1], tasked to increase the intensity and reliability of the Proton Source for 10 or more years of operation, has identified the Low Level RF (LLRF) system as the critical component to be upgraded in the Linac. The current 201.25 MHz Drift Tube Linac was designed and built over 30 years ago and does not meet the higher beam quality demands required under the new Proton Plan. Measurement data, used to characterize the system, has been collected as input for a new computer model of the system. This model shows what improvements can be made by replacing the LLRF system to improve beam quality. The model includes RF driver amplifiers, a 5 MW 7835 triode power amplifier, the high voltage switch tube modulator, and the drift tube cavity. Complete system gain and bandwidth characterization data has been collected for the 7835 triode power amplifier, modulator and RF driver stages. This model will be a useful analysis tool for present and future Linac system upgrades.

LINAC RF SYSTEM

The current Linac RF system (see Fig. 1) has had only minor upgrades since it was commissioned in the late sixties. The Linac LLRF was upgraded in 1994, but still does not give the amplitude and phase control that is currently achievable in the second stage 805 MHz Linac.

Figure 1: Typical Fermilab Linac RF Station

Over the last five years, the number of beam pulses accelerated through the Linac has increased by a factor of 10, making it important to reduce the amount unused beam in the Linac enclosure. Currently, the first 10 µs of beam is sent to the Linac beam dump because it can not be used in the Booster due to excessive momentum drift in the beam. Furthermore, 2 mm of movement, both horizontally and vertically, is seen at the end of the 400 MeV Linac as a result of this 10 µs of beam. By reducing the RF phase and amplitude variation time to fewer than 2 µs, beam losses can be reduced by at least 20 % at the present Booster intensities. Reduction in losses is important in lowering the overall activation of the Linac enclosure.

As can be seen from the RF gradient amplitude and inter-tank phase plots (see Fig. 2), the cavity RF fields are unstable for the first 20 µs of beam. During beam time (see Fig. 3), the present beam loading is 2% of the nominal value [1]. The goal of the LLRF upgrade is to reduce this amplitude variation to < 0.2% and the settling time to < 2 µs. It is important to note that this data is taken from RF station 2, which was not optimally tuned at the time of the measurement. This emphasizes the worst case effect of beam loading.

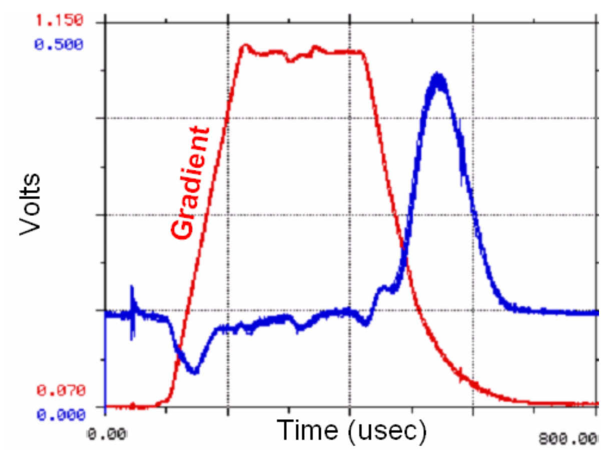

Figure 2: Detected Gradient from Cavity [200 µs/div] RF Gradient Amplitude (Red) & Phase (Blue).

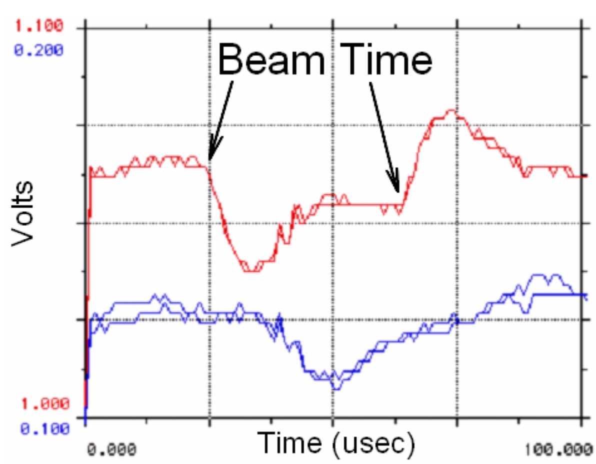

Figure 3: Detected Gradient from Cavity [25 µs/div] RF Gradient Amplitude (Red) & Phase (Blue).

PROPOSED LINAC IMPROVMENTS

In order to reduce the unstable beam time to 2 µs or less, a complete RF system model (see Fig. 4) of all amplifiers and related electronics was created and simulated using Agilent's ADS modeling software [2] and SPICE. This model has become the building block in understanding the current deficiencies in the system. Based on this model, ideas for tuning the current system and how to implement an effective upgrade are proposed. Many of these ideas have been shown to improve the beam loading effect, but still need to be tested on a running RF station to determine the actual real world improvement.

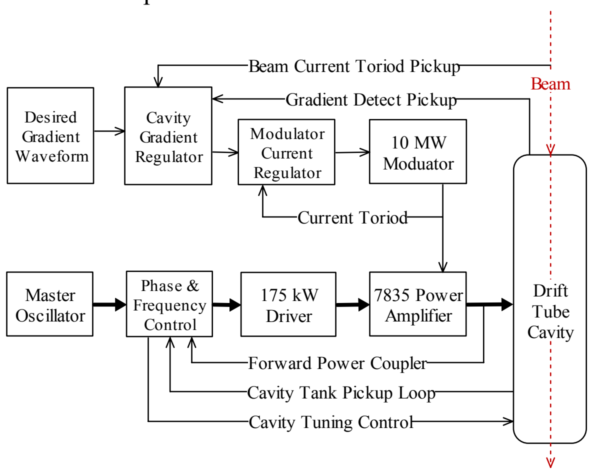

Figure 4: Linac RF System Block Diagram.

Cavity Coupling Improvement

The Drift Tube Linac (DTL) cavities are fed power through a magnetic coupling loop. This loop is not motorized and requires manual tuning to adjust the insertion depth, and therefore the coupling coefficient into the DTL. It has been over five years since any adjustments where made to this coupling loop on any RF station. In the past, changes to the input coupler insertion depth have only been done after gas barrier failures, and have not been calibrated for minimum reverse power during beam time since then.

By using the original Linac design specifications, it was found that the current cavity coupling coefficient needs to be optimized on RF stations 3 & 5 to achieve the best power match. Assuming an average beam current of 40 mA, the power absorbed by the beam can be found with Eq. 1. Since it is desired to have zero reflection when the beam is present, the coupling coefficient is set to unity (see Eq. 2) for an optimal match with beam loading. Using the beam energy gain, along with the DTL cavity excitation power for each RF station, the goal value for the no-beam coupling coefficient can be calculated with Eq. 3 [3]. By comparing the optimal goal input impedance (see Eq. 5) and the measured input impedance (see Table 1), it is clear that optimizing coupling loops on RF stations 3 & 5 will improve system beam loading response and should be implemented before any LLRF upgrade.

$$P_{beam} = P_b = \frac{E_b[\mathrm{eV}]\cdot I_b[\mathrm{A}]}{e} = E_b[\mathrm{V}]\cdot I_b[\mathrm{A}] \quad (1)$$

$$\beta_{Beam} = \frac{Q_0}{Q_e} = \frac{P_e}{P_c + P_b} = 1 \rightarrow P_e = P_c + P_b \quad (2)$$

$$\beta_{goal} = \frac{Q_0}{Q_e} = \frac{P_e}{P_c} = \frac{P_c + P_b}{P_c} = 1 + \frac{P_b}{P_c} \quad (3)$$

$$\beta_{meas} = \frac{Q_{\text{Un-loaded}}}{Q_{\text{Loaded}}} - 1 = \frac{Q_0}{Q_L} - 1 \quad (4)$$

$$Z_{goal} = Z_0 \cdot \beta_{goal} = 50 \cdot \beta_{goal} \ [\Omega] \quad (5)$$

Table 1: Input Impedance Looking into Linac Cavity

RF	P_b	β_{goal}	β_{meas}	Z_{goal}	Z_{meas}
1	0.387 MW	1.634	1.683	82 Ω	84 Ω
2	1.084 MW	1.786	1.762	89 Ω	88 Ω
3	1.145 MW	1.510	1.108	76 Ω	55 Ω
4	1.055 MW	1.426	1.505	71 Ω	75 Ω
5	0.956 MW	1.384	1.085	69 Ω	54 Ω

Beam Loading Compensation

The beam current toroid feedback (see Fig. 4) does not do an adequate job at compensating for the beam loading effect. The feedback signal comes from toroid current monitors placed upstream of each cavity. The effect of this loop is to add an additional gain to the 7835 power amplifier by boosting the current out of the modulator during beam time. Before the beam current loop is added to the cavity gradient regulator it goes through a differentiator circuit to add an extra modulator boost during the start of beam. The time constant of this differentiator circuit can be varied for each station to minimize the beam loading effect. If not properly tuned, the beam loading effect can be significant (see Fig. 3).

Using the gain and bandwidth data collected for each station, a simple RF system model was created to test the beam current toroid feedback loop and determine if a feed-forward pulse could be used instead to reduce the beam loading effect. Each RF block was modeled using the overall gain and dominant poles obtained from the measured data. When comparing the RF blocks, the modulator turns out to be the dominant pole in the system. The measured modulator has a bandwidth close to 4 kHz. By simulating the modulator with a bandwidth of 100 kHz instead of 4 kHz (see Fig. 5), it was found that, after tuning up the other stages, the beam loading effect was reduced to 2 μs, showing the effect that the dominant pole modulator has on beam loading and the RF settling time. In Figure 5, the beam pulse is 50 μs long and arrives 180 μs after the start of the RF pulse.

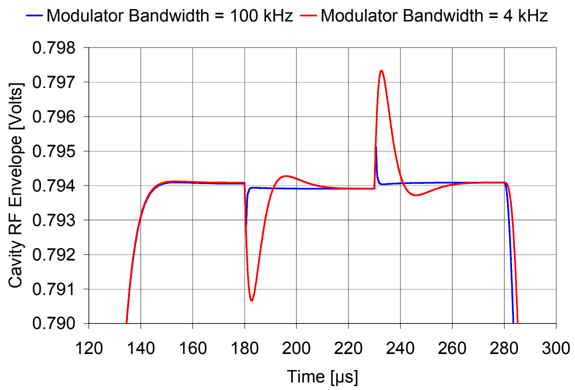

Figure 5: Cavity Gradient (RF Envelope)

We then ran the model using the actual measured bandwidth of 4 kHz and the same tuning parameters for the rest of the RF model (see Fig. 5). This time, the beam loading effect was closer to the 20 μs seen in RF station 2 (see Fig. 3), which was not optimally tuned. As mentioned previously, the settling time can be reduced by tuning the differentiating circuit time constant in the beam feedback loop, but this still will not achieve the desired beam loading time of < 2 μs. Based on our analysis, it has become apparent that the current system, instead of compensating for beam loading, is correcting for modulator bandwidth deficiency.

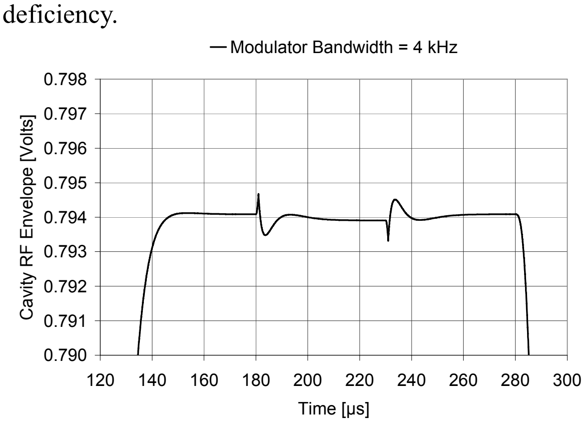

Figure 6: Feed-forward Cavity Gradient (RF Envelope).

Because of the response time of the cavity and the time delay of the beam current toroid to give feedback to the system, the idea of using a feed-forward pulse is being considered instead. Using the RF computer model, the feedback pulse was removed and replaced with a feed-forward pulse, leading the beam loading by 1 μs. The simulation results show a decrease in amplitude variation (see Fig. 6), which can be tuned by adjusting the lead time of the feed-forward pulse. Although there is substantial improvement during beam time, the effects of the modulator can still be seen during the beam pulse.

Direct RF Feedback

Using a cavity RF pickup loop (see Fig. 7) to give direct RF feedback between the current LLRF system and the driver was first considered as a way of improve the cavity gradient regulation during beam time by making up the final 1-2% of amplitude regulation. The major advantage of this method is that it can overcome the low bandwidth of the modulator control loop by directly changing the amplitude of RF during beam loading. The disadvantages are that many RF stations operate near saturation, and this loop may not have enough gain to compensate for beam loading.

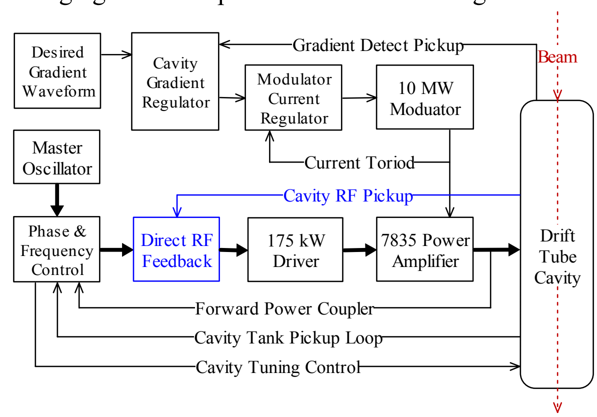

Figure 7: Linac RF System with Direct RF Feedback.

Adaptive Feed-Forward Compensation

Although no simulations have been done yet on testing adaptive feed-forward algorithms to compensate for beam loading, the idea will be considered after more research on how this could be implemented in our current system.

CONCLUSION

Creating a computer model of the entire RF system has been critical in determining all of the bandwidth and gain restrictions of the current system. This model has become an effective aid in designing the upgrade for the entire LLRF. It was determined that the major limitation of the RF system was the 4 kHz bandwidth of the modulator. We believe that implementing a new feed-forward LLRF system, either through the modulator, the RF driver, or some combination of both will reduce the beam loading effect from 10 μs to 2 μs and be able to compensate for modulator bandwidth deficiencies.

REFERENCES

[1] L. Allen, 2005 Proton Plan Review, Available: www-accel-proj.fnal.gov/Proton_Plan/index.html
[2] Agilent ADS Software: http://eesof.tm.agilent.com
[3] H. Padamsee, J. Knobloch, T. Hays, RF Superconductivity for Accelerators. New York, NY: John Wiley, 1998, pp. 388–389.