# FEEDBACK CONTROL OF THE UPGRADED LINAC AT FERMILAB

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## Summary

The last sixty-four meters of the Fermilab Linear Accelerator will be replaced with seven new higher-frequency, higher field accelerator sections.[1] Each section will be powered by a single 12 MW, 805 MHz klystron. A feedback system will be described which controls the amplitude and phase of the rf fields within the individual accelerator sections. To understand the control loops and to optimize their design, ACSL (Advanced Computer Simulation Language) has been utilized. In the analysis, the rf cavities and the klystrons are modeled as single-pole devices. Cavity fields are calculated as the convolution integral of the input phasor and the cavity impulse response. Phase and amplitude loops are coupled and exhibit non-linearities. Due to the distances between the klystrons and the accelerator sections, delays are considerable. The Smith principle will be examined as a means of improving stability in this situation.

## Description of the Loops

Figure 1 is a simplified diagram of the components in the phase and amplitude loops showing the various interconnections. The diagram represents the most basic form for the feedback system. It will provide a performance standard to compare against compensated feedback loops described later. Difficulties associated with the analysis of the feedback system stem from non-linearities in the transfer functions of the klystron and electronic attenuator, and the presence of delays and poles in a number of components.

ACSL has been used to analyze this system numerically. To use ACSL a transfer function must be assigned to each component. The conversion from physical components to transfer function equivalents is reflected in the model shown in Fig. 2. In Fig. 2, the rf cavities have been modeled as a pair of low-pass filters which process separately the real and imaginary parts of the drive signal to the cavities. This equivalent model for the cavities comes about from a consideration of a fundamental network theorem which states that the response of a network to an arbitrary input is equal to the convolution integral of the input and the impulse response. The input in this case is a phasor and the impulse response is a decaying exponential if the drive frequency is close to the resonant frequency of the cavities.

In Fig. 2, fluctuations in cavity phase and amplitude are simulated by adding signals to the phase and amplitude inputs to the rf cavities. This is equivalent to a vector addition to the vector (phasor) drive signal, as would occur when the ion beam passes through the cavities and excites rf fields.

The beam monitor predictor shown in Fig. 2 is derived from a beam intensity monitor placed upstream of the cavity being regulated. Since the beam is traveling less than the speed of light, an upstream signal traveling with the speed of light can provide an advance correction to the cavity drive to compensate for the fluctuation produced by the beam. The closed loop portion of the feedback system then regulates only the variations between the predicted correction and the exact correction required.

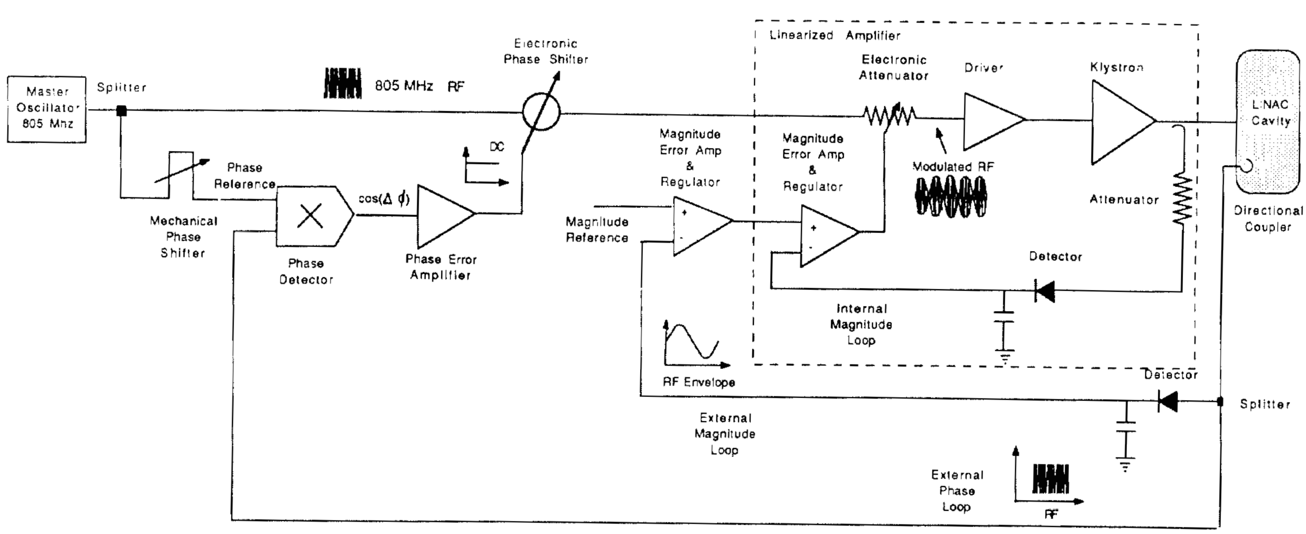
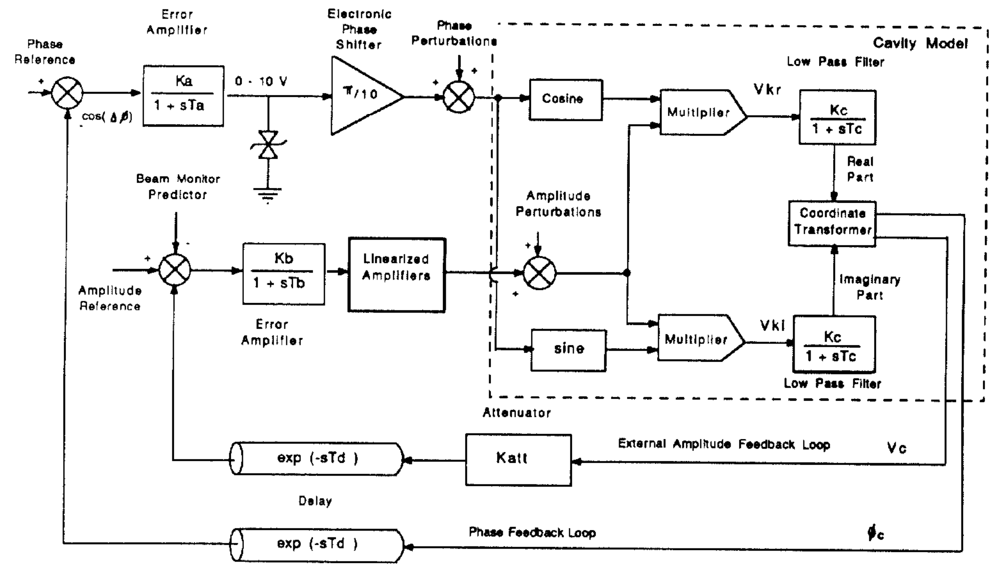



Figure 1. Physical Layout

* Operated by Universities Research association, Inc, under contract with the U.S. Department of Energy




Ka = 100

Kb = 300

Kc = 3.2E-3

Katt = 6.6E-3

Ta=Tb=.08E-6sec

Tc = 7.9E-8sec

Td = 2.0E-7sec

Figure 2. Coupled Phase and Amplitude Loop Model

The linearized amplifier block in Fig. 2 contains the klystron, broadband rf amplifiers, and the electronic attenuator. The components and model used for this block are shown in Fig. 3. The klystron output voltage saturates above a particular input voltage. Incremental gain becomes small near saturation which means that the feedback loop regulation will be poor close to saturation. The electronic attenuator has an exponential characteristic which produces largest incremental gain at higher output power levels (less attenuation), partially compensating for the reduced gain of the klystron. Overall, however, the open loop response is still highly non-linear. Stability margin and regulation therefore depend upon the operating point. The internal loop around the klystron was then created to alleviate any dependence upon operating point in the control loop containing the cavities, and to prevent klystron fluctuations from being applied to the cavities.

## Loop Performance

Figures 4-5 are examples of the response of the control loops to step inputs into the reference ports. Thirty microseconds after the step inputs a 10 % amplitude fluctuation and a 5.7 degree phase fluctuation are introduced at the input to the cavities, at the points indicated in Fig. 2. These fluctuation levels equal approximately those found when a 100 milliamp beam enters the cavity with a synchronous phase angle of -32 degrees from peak field. The magnitude of this fluctuation would presumably correspond to a worst case condition.

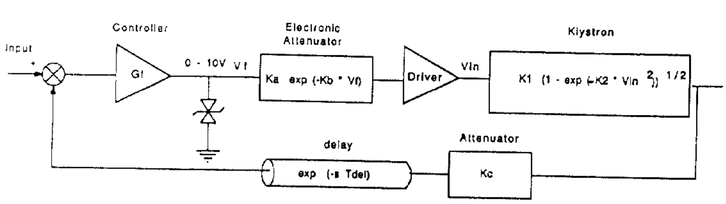



Figure 3. Linearized Amplifier

K1=1.15E4 K2=4.4E-3 Ka=Kb=.8Kc=7.8E-6

Tdel=1.0E-7sec

$$Gf = Kf \frac{(1+sTa)(1+sTb)}{(1+sTc)(1+sTd)}$$

Values for the various components in the loops are given in Figs. 2 and 3. No beam predictor signal is applied in these simulations. The loops are optimized in the sense that the error amplifier gains have been set as high as possible without driving the loops unstable. It has been found that instability results from the delays in the system. As these delays are reduced, the error amplifier gains can be increased and the regulation improved.

Figures 4-5 show that initially the klystron is driven into saturation. The cavity fields increase exponentially with a characteristic time governed by the cavity fill time. As the cavity fields reach their reference levels, the klystron comes out of saturation (Fig. 4) and settles down to a steady level after a small transient. When the beam fluctuation is applied, the klystron power increases to compensate for the drop in the cavity fields. Only a slight drop (approximately 0.5%) in the cavity fields results. Only a slight change in cavity phase (approximately 0.5 degrees) occurs when the beam is applied. Feedback loop regulation to 0.5% in amplitude and 0.5 degree would be acceptable for the linac upgrade at Fermilab.

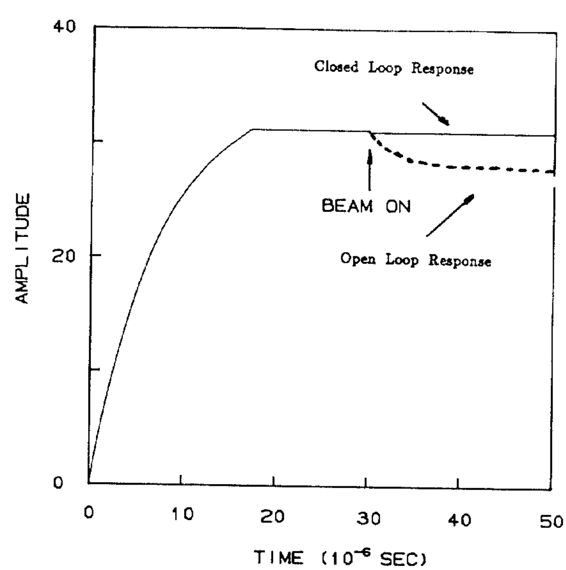



Figure 4. Calculated cavity field amplitude with and without Feedback after Klystron Power up.

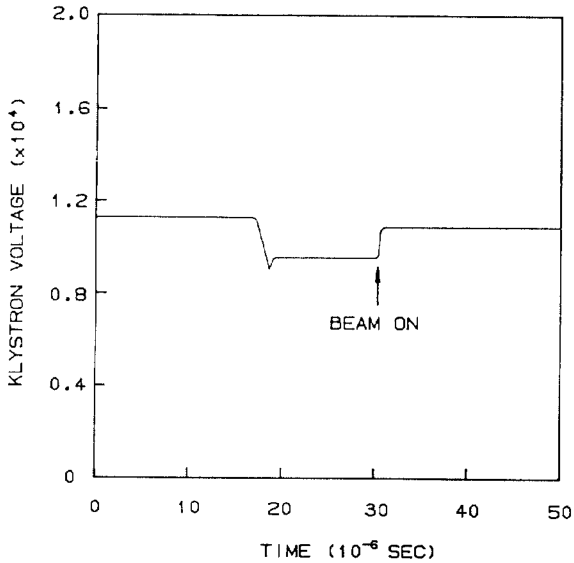



Figure 5. Calculated Klystron output (1.2 MW Klystron) with feedback and after power up

## Compensation Techniques

Improvements in the basic feedback system described above were investigated even though its performance was judged acceptable. This objective was pursued in case performance were degraded by the non-ideal nature of components and by various unknowns associated with pole locations and delays. We are currently minimizing the unknowns by measuring the characteristics of each component individually. The loop analysis will be refined as this information becomes available.

A commonly used compensation network that was investigated for the present application is the lead-lag network[2]. This network works very well in linear systems but was found to have rather poor transient response when applied to our non-linear system with its long delays. In particular, the additional gain provided by the network could not be fully utilized for regulation of large fluctuations due to the signal limiting effect of the electronic attenuator and klystron. The networks were not effective at compensating the large phase shifts produced by delays at high frequencies.

To compensate for the signal delays, which dictate stability limits, and at the same time produce acceptable transient response, the Smith compensation principle was utilized.[3] Figure 6 is a schematic diagram illustrating the general principle. Basically, an equivalent network simulating the cavity plus delay-line is placed along a parallel path with the real cavity and delay-line. If the two branches are the same, no signal is produced when they are added.

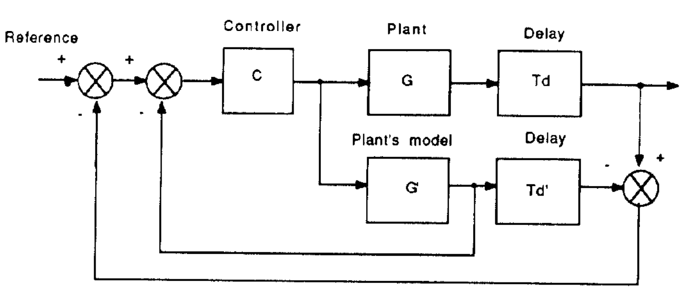



Figure 6. Smith Compensation Method

Hence, the delay produces no phase shift at the first summing junction of the loop at the left in Fig. 6. Stability is thereby maintained in spite of long circuit delays. A fast feedback path is provided from the output of the simulated rf cavity. Regulation is degraded by imprecision in the simulation of the forward path and by differences in the signals in the two paths (as occurs when cavity fluctuations are present). Figure 7 shows the response to the same 10% amplitude fluctuation that was introduced in the model used to generate Figs.4-5.

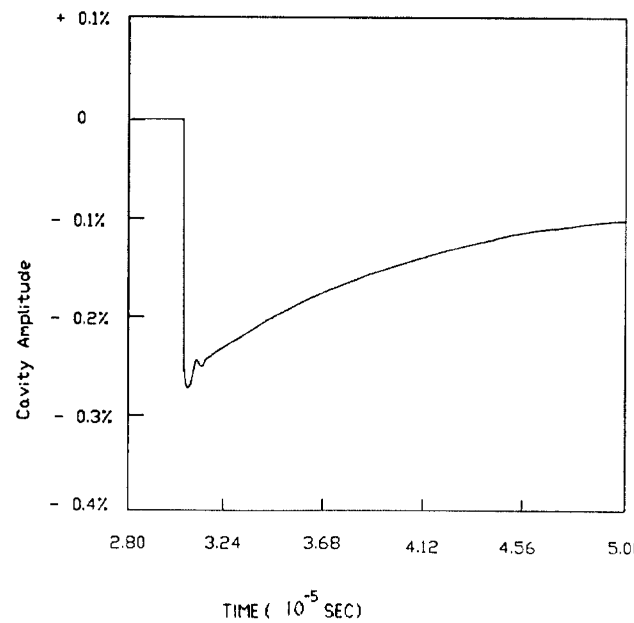



Figure 7. Cavity field amplitude with Smith Compensation under beam fluctuation.

The cavity fields are regulated to .25% initially, falling to less than 0.1% after about 20 usec. A large improvement in the basic feedback system described in the last section has been obtained in this way. A large number of ACSL simulations have shown that this result is not unreasonable sensitive to variations in the simulated network. Practical realizations should therefore be possible without extraordinary care.

## Conclusions

The analysis of control loops utilizing ACSL has shown that acceptable regulation of cavity phase and amplitude in accelerator modules for the Fermilab linac upgrade can be obtained with a basic uncompensated feedback system. Further improvements in regulation can be obtained using the Smith compensation principle and predictor signal correction.

## References

1. "Fermilab Linac Upgrade Conceptual Design Revision 2", January, 1989.

2. J. J. D'Azzo, and C. H. Houpis, Linear Control System Analysis and Design, McGraw-Hill Book Company, New York, 1988.

3. J. E. Marshall, Control of Time-Delay Systems, IEEE Control Engineering Series, 1979.