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Results Of Adaptive Feedforward On GTA*

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Abstract

This paper presents the results of the adaptive feedforward system in use on the Ground Test Accelerator (GTA). The adaptive feedforward system was shown to correct repetitive, high–frequency errors in the amplitude and phase of the RF field of the pulsed accelerator. The adaptive feedforward system was designed as an augmentation to the RF field feedback control system and was able to extend the closed–loop bandwidth and disturbance rejection by a factor of ten. Within a second implementation, the adaptive feedforward hardware was implemented in place of the feedback control system and was shown to negate both beam transients and phase droop in the klystron amplifier.

I. Introduction

The GTA control system uses feedback to control the RF fields in the accelerating cavities. A simplified block diagram of the GTA RF control system is depicted in figure 1.

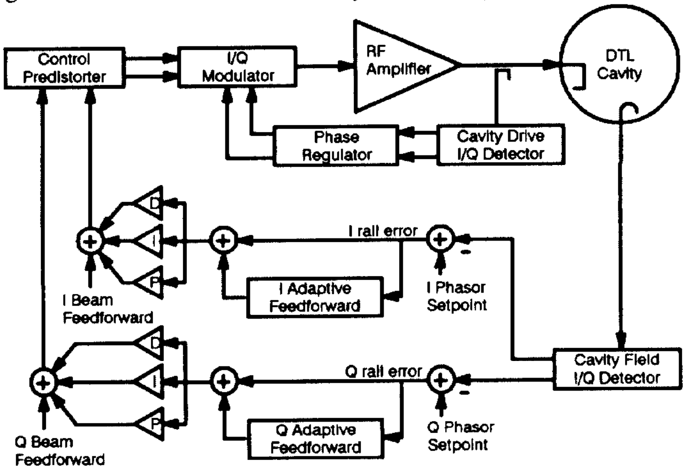

Figure 1. Simplified block diagram of GTA control system

Closed–loop bandwidths of a few hundred kHz have been demonstrated by the GTA RF control systems [1]. These bandwidths are limited by the physical properties of the high–Q cryogenic cavities, the high–power amplifier responses, and the long propagation delays due to the large physical distances between equipment. The amplitude and phase disturbances to the RF field that are beyond the closed loop bandwidth cause amplitude and phase errors in the accelerating field. A significant disturbance that occurs with every RF pulse is the beam turn–on transient. The fast rise-time of the beam causes the accelerating field to droop before the feedback system can compensate. The beam turn–on disturbance causes transient errors in the field amplitude and phase for a few microseconds as the feedback loop recovers. Due to the repetitive nature of the beam transients, a feedforward correction function can be inserted into the drive signal that will predict the beam transient affects. This correction function is adaptively updated as the accelerator operates to optimize a correction function that negates the repetitive disturbances. The detailed theory of operation is described elsewhere [2–4]. This paper will focus on the experimental results of the hardware functioning on the first drift tube linac (DTL) cavity of GTA.

II. Enhancement To Feedback

The adaptive feedforward hardware was designed to operate as a modular addition to enhance the feedback control system. Figure 1 shows the experimental setup for the adaptive feedforward tests on the first 850 MHz DTL cavity of GTA. The operating conditions for the DTL consist of a gap voltage of 2.1 MV, a beam current of 30 mA with a -30° synchronous phase, and copper losses of 33 kW. From this, the beam loading calculates to be 62%.

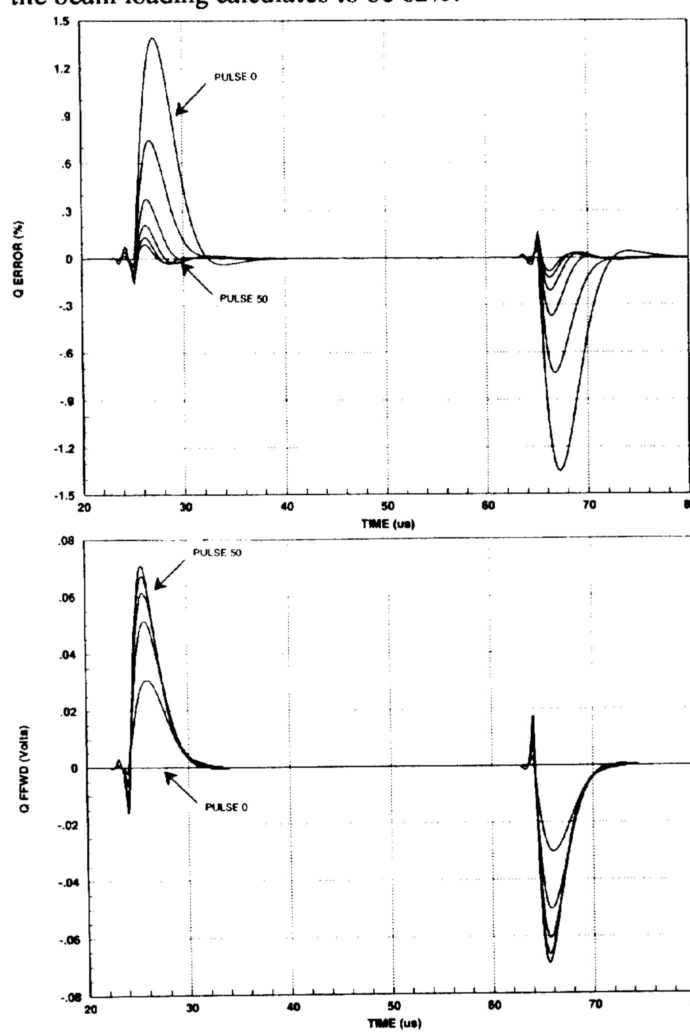

Figure 2. Modelled results of feedforward as enhancement

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Figure 2 shows the predicted RF system performance determined with a sophisticated software model of the GTA RF system. The figure shows a sequence of five traces that depict the expected feedforward and error signals as the adaptation occurs over the course of 50 pulses. The feedforward correction function adapts to the transient errors in the RF field caused by the beam pulse turning on and off. Notice that the feedforward signal grows and the error signal is reduced as the hardware adapts. These traces depict the quadrature signals only, but the in-phase errors are simultaneously reduced as well.

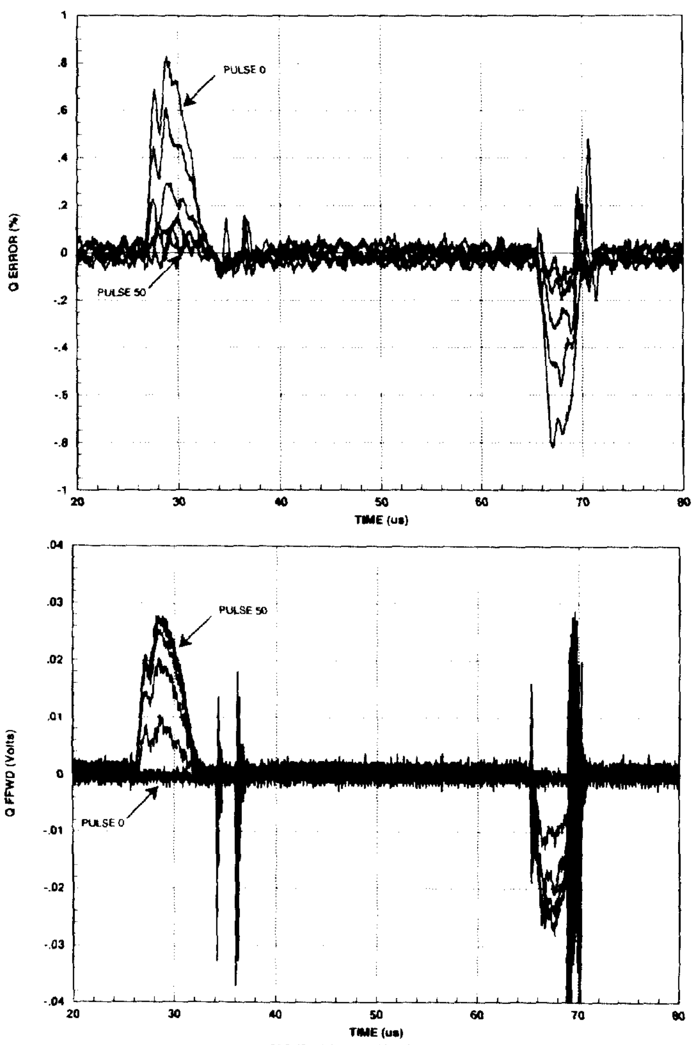

Figure 3. Measured results of feedforward on GTA

Figure 3 shows the measured data from an experiment on the first DTL cavity of GTA. Again, five feedforward and five error signals in a sequence of 50 pulses are shown. The errors are caused by the beam turn-on and turn-off transients. As the system operation progresses, the correction function improves and the error signal is reduced. Before adaptation begins (pulse 0), the magnitude of error in the quadrature component of the RF field is $\pm 0.8\%$. After 50 pulses of adaptation, the quadrature error is reduced to less than $\pm 0.1\%$. Notice that the measured DTL performance closely matches the expected performance derived from the model.

III. Replacing Feedback

In addition to the intended implementation of the adaptive feedforward module, a second functional configuration was evaluated. Instead of using the device as a feedforward enhancement to the feedback control system, the module can be used as an adaptive controller, replacing the feedback control system entirely. Figure 4 shows the topology of this configuration, where the control output is provided

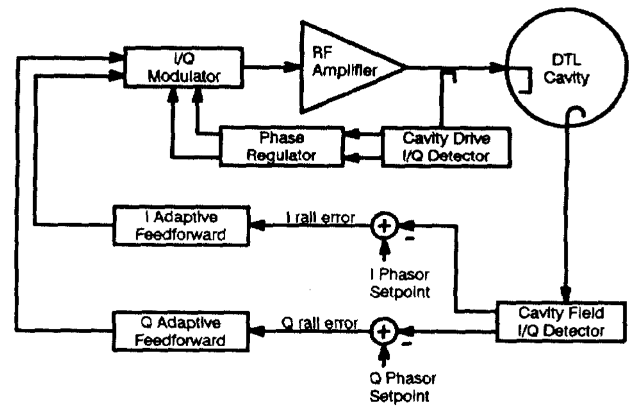

Figure 4. Diagram of adaptive control system (no feedback)

by the adaptive controllers. The measured parameters of past RF pulses are used to derive the control output for the current pulse. As system parameters vary over time, the adaptive controllers modify the control output. Any instantaneous changes in the system require a number of pulses for the control function to adapt, but the system does track slow changes very closely. As long as the time constants for the changes are significantly longer than the repetition rate for the pulsed accelerator, the field amplitude and phase can be accurately maintained. For the GTA DTL, the accelerator repetition period is hundreds of milliseconds, whereas the changes in the RF hardware performance occurs at very slow rates (many seconds or minutes). A drawback of this device is that the controller needs past data measurements in order to adaptively determine the control output. Consequently, when the system is turned on or the setpoint changes, a number of pulses occur before the field parameters settle to the operating point.

Figure 5 shows the measured results of using the device as an adaptive controller to maintain the amplitude and phase of the RF field in the accelerating cavity. These plots show 5 traces of the in-phase and quadrature errors for the entire RF pulse as the controller adapts for 50 pulses. Notice that before the adaptation begins (pulse 0), the field falls during the beam loading and there is a ramp in the quadrature error is due to the phase droop of the klystron amplifier. After 50 pulses of adaptation, the in-phase error is reduced from 0.8% to 0.1%, and the quadrature error is reduced from 2.8% to 0.1%. During this experiment, the adaptive controller was able to hold the RF field parameters within 0.2% of the operating point for many minutes of operation.

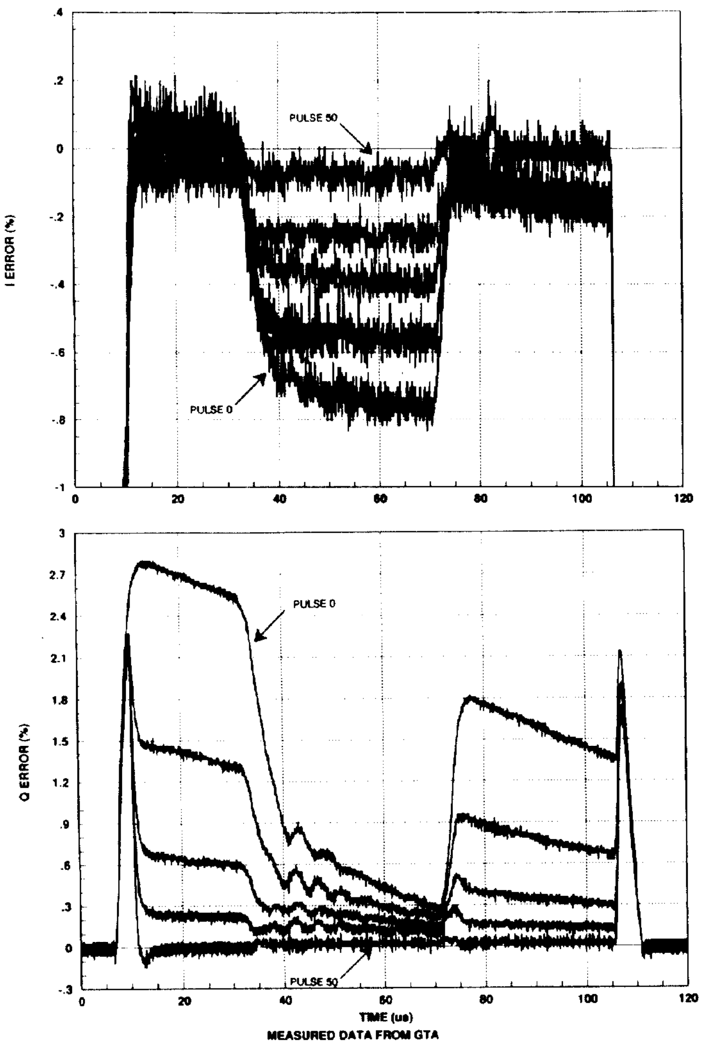

Figure 5. Measured results of adaptive control (no feedback)

IV. Future Work

These experiments proved extremely successful and verified the concept of adaptive feedforward as a viable solution to improving the field control performance for pulsed accelerators. In addition, some possibilities for additional work in the future were identified. As shown in figure 3, there are transient glitches that grow slowly as many pulses are accumulated. These glitches are a result of the adaptive algorithm used to accumulate the error functions for all past pulses with no way of eliminating some of the past data. Consequently, any circuit or computational glitches will eventually grow to become significant. A revision that incorporates a forgetting function has been designed. The algorithm governing the adaptive process remains

$$f_N(t) = \sum_{i=0}^{N-1} k_i \cdot e_i(t + \Delta T) \ . \qquad (1)$$

but whereas in the original implementation all the k_i values were equal, the revision incorporates exponential k_i values, creating a windowing or forgetting function. The forgetting function creates a sliding window that is used to weight a finite number of past data values for accumulation into the correction function. Consequently the algorithm for the revision is described by the equation

$$f_N(t) = g \cdot f_{N-1}(t) + k \cdot e_{N-1}(t + \Delta T) \ . \qquad (2)$$

In this algorithm, the gain, k, corresponds to the adaptation gain which affects the sensitivity and adaptation time for the device. The gain, g, provides the forgetting function that is used to discard old data with an exponential decay. The preliminary tests with the new design show that by including the forgetting function, g, the adaptation gain, k, can be increased significantly. Thus, the new design allows more input sensitivity (more dynamic range) and provides a faster settling and tracking time.

The success of the adaptive controller configuration suggests additional applications for this type of device. An adaptive, stand–alone controller could be useful for many accelerator RF systems where conventional feedback control is impractical. For example, short–pulse–length accelerators typically do not have time for feedback corrections. The adaptive controller could adaptively predict the correct control output.

Currently, there is significant interest in evaluating the usefulness of the current design for other accelerator applications. Adaptive feedforward tests are scheduled for LANSCE II, University of Twente FEL, AFEL, and APLE. Each of these accelerators requires control bandwidths greater than a feedback system can provide. The adaptive feedforward is a viable solution to this common accelerator RF control requirement.

VI. References

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