Measured Performance of the GTA RF Systems*

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Abstract

This paper describes the performance of the RF systems on the Ground Test Accelerator (GTA). The RF system architecture is briefly described. Among the RF performance results presented are RF field flatness and stability, amplitude and phase control resolution, and control system bandwidth and stability. The rejection by the RF systems of beam-induced disturbances, such as transients and noise, are analyzed. The observed responses are also compared to computer-based simulations of the RF systems for validation.

I. INTRODUCTION

In recent months, an experiment was performed on GTA that resulted in the successful commissioning of the 3.2-MeV accelerator [1]. The 3.2-MeV stage included four RF accelerating cavities along the beam line: a radio frequency quadrupole (RFQ), two intermediate matching sections (IMSA and IMSB), and a drift tube LINAC (DTL1). The measured performance of the RF control systems with and without beam disturbances is presented.

II. RF SYSTEM DESCRIPTION

Much has been written in the literature regarding the design of the RF control system for GTA [2-5]. For ease of understanding the measurements, however, a brief explanation of important concepts is in order.

Figure 1 shows a block diagram of the essential RF system operating in closed-loop control. Additional modules can be incorporated for improved performance [6-10]. However, that is beyond the scope of this paper.

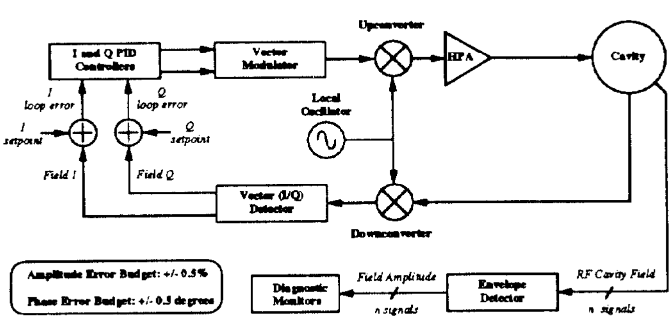

Figure 1. Block Diagram of the RF Control System

The implementation used to achieve the ± 0.5% and ± 0.5° error specification relies on the control of the in-phase (I) and quadrature (Q) components of the cavity field. These orthogonal components, Field I and Field Q, are baseband signals that are controlled independently via the I Controller and Q Controller, respectively. Regulating the Field I and Field Q vectors implies that the RF cavity field vector is regulated to the same degree. This assumes, however, that the transfer function of the sense loop (cable between the cavity and Downconverter, the Downconverter, and the Vector Detector) remains constant. Since long-term phase stability has not been implemented as yet [6], all the measurements presented in this paper will address short-term stability. The Field Amplitude and Field Phase stability can be derived using the following simple equations.

$$Field\_Amplitude = \sqrt{Field\_I^2 + Field\_Q^2} \qquad (1)$$

$$Field\_Phase = TAN^{-1}\left(Field\_Q / Field\_I\right) \qquad (2)$$

As an independent verification of the Field Amplitude stability, cavity field signals from various pick-up loops were also measured by Envelope Detectors.

III. TEST RESULTS

A. Waveform Digitization Measurements

In order to analyze various control parameters, including noise rejection, a waveform digitizer was employed. The digitizer possessed four synchronous data channels that allowed beam data and RF control system data to be measured simultaneously. The sampling rate was 5 MSamples/s and its effective resolution was 9 bits (due to digitizer noise). This provided measurement capability of ±0.4% resolution of a full-scale signal. Because the Field I and Field Q measurements needed to be resolved to within ± 0.1% for noise analysis, this was clearly a limiting factor. Fortunately, however, the I Loop Error and Q Loop Error signals were magnified by a factor of 10 before being sent to the digitizer, so the Field I and Field Q signals could be derived to ± 0.04% using the following equations.

$$Field\_I = I\_Setpoint - I\_Loop\_Error \qquad (3)$$

$$Field\_Q = Q\_Setpoint - Q\_Loop\_Error \qquad (4)$$

Figure 2 shows synchronously taken data of the RFQ beam input current, the RFQ Field Amplitude and RFQ Field Phase Error. The RF-related data was derived from the Vector Detector signals. Table 1 summarizes the Field Amplitude and Field Phase characteristics for both the RFQ and DTL1 RF systems.

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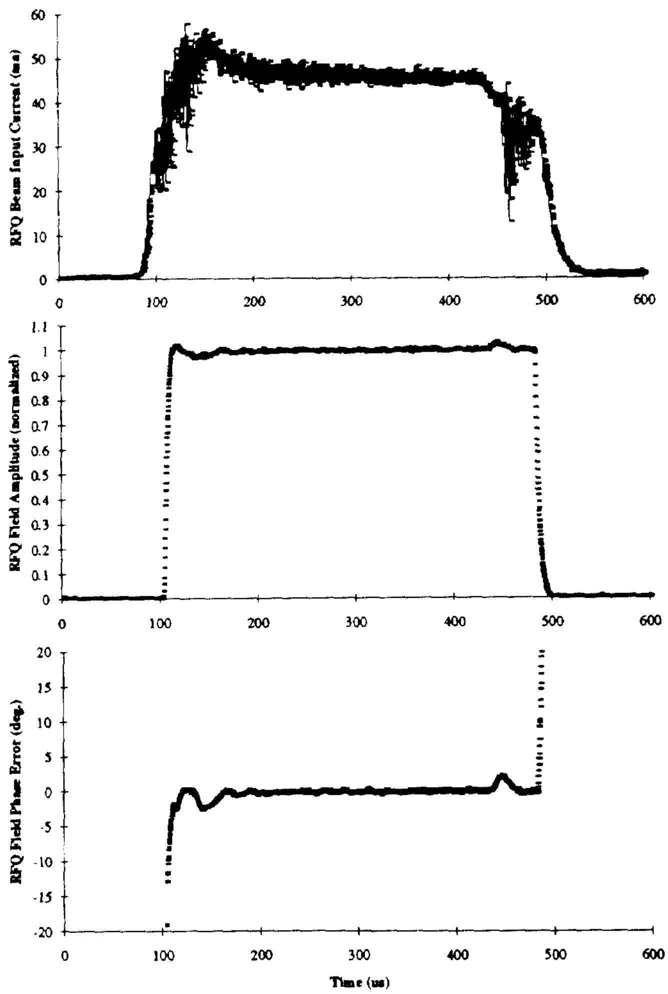

Figure 2. Synchronous Waveforms of the RFQ Beam Input Current, Field Amplitude and Field Phase.

Table 1. Characteristics of RFQ and DTL1 RF systems

Measurement	RFQ	DTL1
Cavity Fill Time (us)	6	5.2
Cavity Fill Overshoot (%)	2	6
Beam Induced Amplitude Overshoot (%	4	2
Beam Induced Phase Overshoot (deg)	3	1

Figure 3 expands the waveforms of Figure 2 from 200-400μs. Clearly, the field signals contain noise at frequencies of 50 kHz - 100 kHz. The beam signal clearly contains high-frequency noise. Figure 4 shows Field Amplitude and Field Phase Error waveforms without the beam. The noise is reduced considerably. However, the same frequency components are present. Open-loop tests did not reveal any noise at these frequencies, but the sensitivity of the measurement was only ±1%. Further testing using higher resolution digitizers is required to quantify correlations. Table 2 shows relative disturbance rejection of the RFQ and DTL1 closed-loop systems. A constant voltage signal was applied at the output of the I Controller while the Field I was measured. The data was normalized to the 10-kHz value and shows higher sensitivity to noise at 25 kHz - 100 kHz.

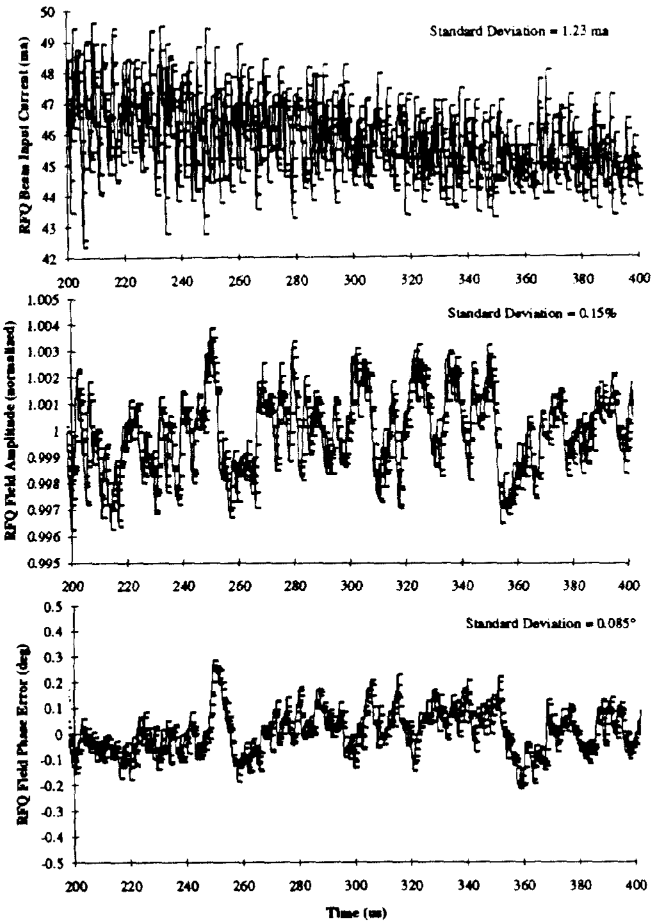

Figure 3. Data from figure 2 expanded from 200-400μs

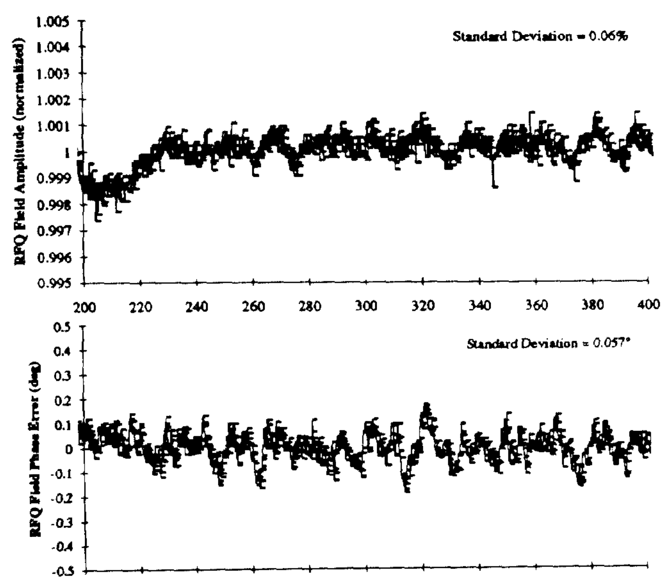

Figure 4. RFQ Field Amplitude and Field Phase without beam

Table 2. Relative Disturbance Rejection of RFQ & DTL1

RF System	10 KHz	25 KHz	50 KHz	75 KHz	100 KHz	250 KHZ
RFQ	0 dB	-7.4 dB	-13 dB	-11.7 dB	-8.5 dB	7.7 dB
DTL1	0 dB	-6 dB	-10.5 dB	-11.3 dB	-8.9 dB	-3.2 dB

B. Single Sample per Pulse Measurements

Equipped with 12-bit A/D converters, the Vector Detector and Envelope Detector synchronously sampled the Field I, Field Q, and various Field Amplitude signals at a single point during the RF pulse. A single snapshot consisted of 15 consecutive pulses. By incrementing the timing along the RF pulse, the field flatness was measured. Figure 5 shows the flatness of the DTL1 Field Amplitude without beam as measured from the Envelope Detector.

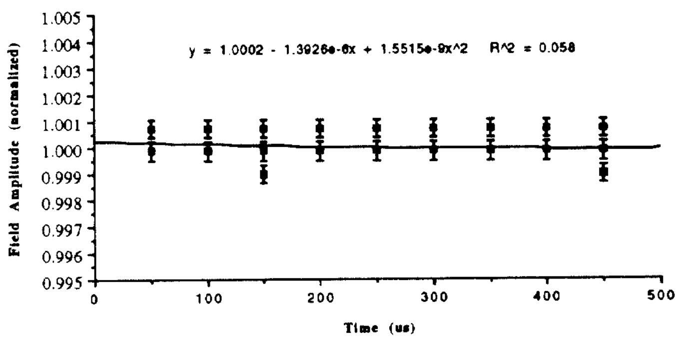

Figure 5. DTL1 Field Amplitude Flatness without beam

The statistics are summarized in Table 3 for all four RF systems. Please note that the amplitude values are normalized, and the mean values are relative to the setpoints. Because the Envelope Detector readings were normalized to the mean value, its mean is equal to unity. Also, STD represents standard deviation. Table 4 gives the statistics with beam.

Table 3. Statistics of all 4 RF systems without beam

STATISTIC	RFQ	IMSA	IMSB	DTL1
I/Q Detector				
Amplitude Mean	0.9988	0.9993	1.0023	0.9971
Amplitude STD (%)	0.041	0.081	0.12	0.074
Ampl. min,[max]	0.9980,[0.9990]	0.9972,[1.0028]	1.0014,[1.0063]	0.9964,[0.9979]
Phase Mean (deg)	0	0.04	-0.1	-0.04
Phase STD (deg)	0.068	0.064	0.161	0.051
Phs min,[max](deg)	-0.24,[0.24]	-0.06,[0.17]	-0.74,[0.20]	-0.13,[0.13]
Env. Detector				
Amplitude STD (%)	0.038	0.088	0.085	0.034
Ampl. min,[max]	0.9986,[1.0009]	0.9990,[1.0028]	0.9989,[1.0029]	0.9990,[1.0007]

Table 4. Statistics of all 4 RF systems with beam

STATISTIC	RFQ	IMSA	IMSB	DTL1
I/Q Detector				
Amplitude Mean	0.9987	0.998	1.003	0.9953
Amplitude STD (%)	0.11	0.11	0.11	0.075
Ampl. min,[max]	0.9968,[1.0003]	0.9970,[0.9999]	1.0004,[1.0052]	0.9935,[0.9970]
Phase Mean (deg)	-0.03	0.06	-0.11	-0.12
Phase STD (deg)	0.089	0.11	0.124	0.055
Phs min,[max](deg)	-0.24,[0.17]	-0.17,[0.23]	-0.42,[0.02]	-0.23,[0.00]
Env. Detector				
Amplitude STD (%)	0.089	0.032	0.065	0.054
Ampl. min,[max]	0.9981,[1.0013]	0.9970,[1.0010]	0.9989,[1.0011]	0.9992,[1.0008]

IV. SUMMARY

To summarize, all RF control systems exceed the performance specifications with and without the beam present in the cavities. As expected, the amplitude and phase errors are greater with beam present. However, further testing and analysis is required to quantify any cross correlations. The increase in forward RF power while the beam is present may also contribute to the noise. Comparisons between measured results and computer simulations will be the topic of future investigation.

Good agreement of the standard deviations was noticed between the RFQ waveform digitization measurements and the single sample per pulse tests. Also, there is excellent agreement of the standard deviations between Vector Detector and Envelope Detector Field Amplitude. This, in essence, verifies the accuracy of the measurements.

V. ACKNOWLEDGMENTS

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