BEAM LOADING STUDIES AT CEBAF*

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Abstract

When the CEBAF accelerator operates at 200 μA beam current, the superconducting cavities run with high beam loading. The CEBAF RF system (including the cavities, klystrons, and control systems) has been measured to obtain the response to low frequency current fluctuations and to obtain the transient response to rapid changes in the beam current. The data were collected both through RF tests where beam pulses are simulated by RF pulses and through beam tests. Both closed loop and open loop measurements were made, and the results are compared to detailed SPICE numerical simulations. It is concluded that CEBAF will operate with high control under a wide variety of loads.

Introduction

One source of phase and amplitude noise in the field of a superconducting cavity is created by beam current noise. Since the cavity may operate when highly beam loaded, substantial voltage fluctuations could result if the cavity field was not controlled. The RF controls reduce the noise by the closed-loop gain of the control system, but since the cavities and control loops are nearly identical throughout the linacs, errors in the control system generated by beam noise are likely to be correlated throughout the linacs. Therefore, the fluctuations due to beam noise must be suppressed to $\Delta V/V < 2 \times 10^{-5}$ in amplitude and $\Delta\phi < 0.1°$ in phase in order to be consistent with the CEBAF design specifications[1]. Our measurements indicate that for the gains to be found in the controls, the beam current fluctuations are small enough that the specifications are achieved.

To begin, the voltage fluctuation induced by a given current fluctuation is calculated when the control system is unlocked. When all the reflected power is absorbed by a circulator, the differential equation for the accelerating cavity voltage V_c is

$$\frac{d^2V_c}{dt^2} + \frac{\omega_c}{Q_L}\frac{dV_c}{dt} + \omega_c^2 V_c = \frac{\omega_c}{Q_c}\frac{dV_+}{dt} - \frac{\omega_c}{Q_c}\frac{dV_B}{dt}$$

where $\omega_c = 2\pi f_c$ is the cavity angular frequency, Q_c is the unloaded quality factor of the cavity, Q_L is the loaded quality factor of the cavity

$$Q_L = \frac{Q_c}{1+\beta},$$

β is the coupling factor,

$$V_+ = 2\sqrt{\beta}\sqrt{2Z_cP(t)}\cos(\omega_c t - \phi(t))$$

is the voltage induced in the cavity by the RF generator multiplied by $1+\beta$, Z_c is the cavity shunt impedance, $P(t)$ is the power from the generator, $\phi(t)$ gives the phase of the voltage, and $V_B(t) = Z_cI(t)$ is the beam loading voltage where $I(t)$ is the beam current. It is convenient to use $R = 2Z_c$, the accelerator shunt impedance[2], in the subsequent formulas.

For $P(t)$ and $\phi(t)$ constant, consider the voltage spread induced by a beam fluctuation at a given modulation frequency. If

$$\delta I(t) = \sum_{l=-\infty}^{\infty} q\cos(\omega_m t)\delta(t - l\tau),$$

the fluctuation in the voltage, δV_c, is

$$\delta V_c(t) = -\frac{\omega_c Rq}{2Q}\frac{e^{-\omega_c(t-n'\tau)/2Q_L}}{2} \times \left\{ \frac{e^{2x}\cos[\hat\omega t - n'\hat\omega\tau + n'\omega_m\tau]}{1 - 2\cos(-\hat\omega\tau + \omega_m\tau)e^x + e^{2x}} - \frac{e^x\cos[\hat\omega t - (n'+1)\hat\omega\tau + (n'+1)\omega_m\tau]}{1 - 2\cos(-\hat\omega\tau + \omega_m\tau)e^x + e^{2x}} + \omega_m \leftrightarrow -\omega_m \right\} \quad (1)$$

where $x = \omega_c\tau/2Q_L$, $\hat\omega = \omega_c\sqrt{1 - 1/4Q_L^2}$, and n' is the greatest integer less than f_ct. If $1 \gg \omega_m\tau \gg \omega_c\tau/2Q_L$, Eqn. (1) may be expanded to yield

$$\delta V_c(t) \doteq -\frac{q}{2\tau}\frac{R}{Q}\frac{\omega_c}{\omega_m}\cos(\hat\omega t)[\omega_m\tau/2 + \sin(n'\omega_m\tau)], \quad (2)$$

a result independent of the cavity bandwidth $\omega_c/2Q_L$.

An energy argument clarifies this result. The total charge passing the cavity on the positive part of the modulation is

$$\Delta q = \sum_{n=-\pi/2\omega_m\tau}^{\pi/2\omega_m\tau} q\cos(n\omega_m\tau) \doteq \frac{2q}{\omega_m\tau}.$$

The total energy removed from the cavity by this charge is

$$\Delta U = \frac{2qV}{\omega_m\tau}.$$

Since the energy fluctuation is related to the voltage fluctuation by

$$\Delta U = 2\frac{QV}{R\omega_c}\Delta V,$$

the full width voltage fluctuation is

$$\Delta V = \frac{q}{\tau}\frac{R}{Q}\frac{\omega_c}{\omega_m} = I_{mod}\frac{R}{Q}\frac{\omega_c}{\omega_m},$$

consistent with Eqn. (2).

*This work was supported by the United States Department of Energy under contract DE-AC05-84ER40150.

For $1 \gg \omega_c\tau/2Q_L \gg \omega_m\tau$, i. e., the frequency of the fluctuation is well within the cavity bandwidth, the cavity has time to respond to the changed beam load. The voltage adjusts so that the same incident power goes into the beam

$$\delta V_c(t) \doteq -Q_L I_{mod} \frac{R}{Q} \cos(\hat{\omega} t) \cos(n'\omega_m \tau).$$

For CEBAF, $R/Q = 480\ \Omega$, $V_c = 2.5$ MV, $f_c = 1500$ MHz, $Q_L = 6.6 \times 10^6$, and $\beta = 364$. Therefore, the cavity bandwidth is 110 Hz. For frequencies of this order, the more general expression in Eqn. 1 must be used. The general case is well approximated by the single pole result

$$|\Delta V_c| \doteq \frac{2Q_L I_{mod} R/Q}{(1 + 4Q_L^2\omega_m^2/\omega_c^2)^{1/2}}.$$

Given this estimate of the voltage fluctuation in the unlocked mode, it remains to note that ideally the fluctuation is reduced by the gain of the control system at the modulation frequency in the locked mode. The control system does this by properly adjusting $P(t)$ and $\phi(t)$ to cancel most of the induced error.

SPICE Model

An analysis of the control system has been performed using the computer code SPICE. A schematic diagram of the RF controls for a superconducting cavity appears in Fig. 1[3]. The block diagram of the SPICE gradient loop is shown in Fig. 2. The calculation employs simple models for major

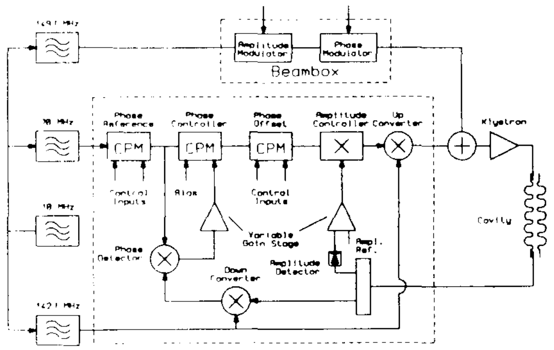

Fig. 1 RF System Schematic

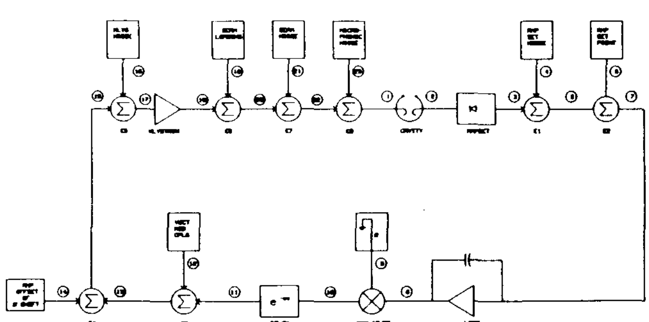

Fig. 2 SPICE Block Diagram

control loop components and error sources. Where possible, the transfer function of a model is defined numerically. Models for the loop amplifier and klystron amplifier include frequency roll off and saturation characteristics. Examples of possible error sources are beam transients, interloop coupling, and noise sources such as microphonic noise, beam noise, klystron noise, and detector noise. Of particular interest in this paper is the response of the control system to beam induced transients.

Beam Box Measurements

Transfer function data were obtained using a so-called beam box, which injects low-level RF power into the control loop before the klystron as in Fig. 1. If an amplitude modulated signal is fed into the control loop, by comparing the cavity voltage fluctuation levels with and without phase and amplitude lock, the overall gain of the control system is determined. For example, a square wave modulation at 10 Hz yielded the data in Fig. 3. The two curves are spectra of the amplitude error signal. For the top spectrum the amplitude lock was off and for the bottom spectrum the amplitude lock was on. Such measurements have verified the high gain ($\sim$ 80 dB) of the controls at low modulation frequencies. Given the measured gains, one can expect the CEBAF beam to be within specifications provided the current fluctuations at low frequency are less than 25 μA. By independent measurement of the beam current on apertures, it is known that the current fluctuations are in fact under 1 μA.

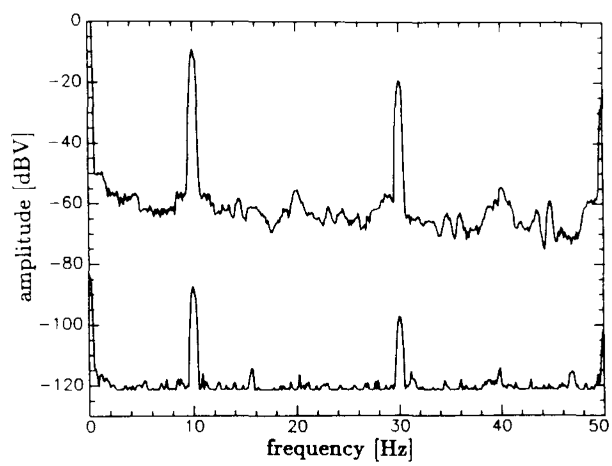

Fig. 3 Spectrum of Amplitude Error Signal in Open and Closed Loop Cases

The transient response of the control system is obtained by pulsing the RF power from the beam box on and off. A transient obtained by this technique is shown in Fig. 4, which gives the relative amplitude error vs. time after the beam box is first turned on. Overshoot oscillations were observed that were traced to the occurence of a 100 kHz pole in the control system, something eliminated in tests the with beam later on. The slow falloff evident in the trace shows the effect of low frequency gain in the system. The transient power corresponds to 800 μA of beam current, and the full range of the amplitude error was $\delta V_c/V_c = 1.7 \times 10^{-3}$. Given the acceptance of the recirculation arcs at CEBAF of 2×10^{-3}, one can expect complete tranmission of the beam up to transients of 1 mA.

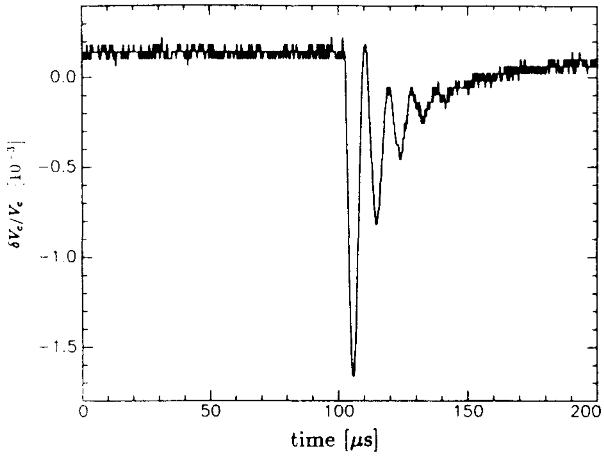

Fig. 4 Transient Amplitude Error Signal from Beam Box

Beam Measurements

An example of a beam induced amplitude transient in the superconducting cavity is shown in Fig. 5. The beam current was in 400 μA pulses of duration 1 msec. Removing the 100 kHz pole in the feedback loop has eliminated the overshoot previously observed, and the recovery time is 0.05 msec. The peak amplitude deviation is $\delta V_c/V_c = 1.9 \times 10^{-3}$.

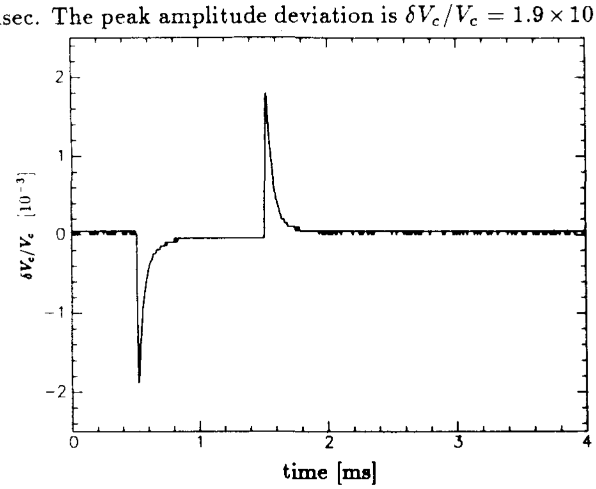

Fig. 5 Transient Amplitude Error Signal from Beam

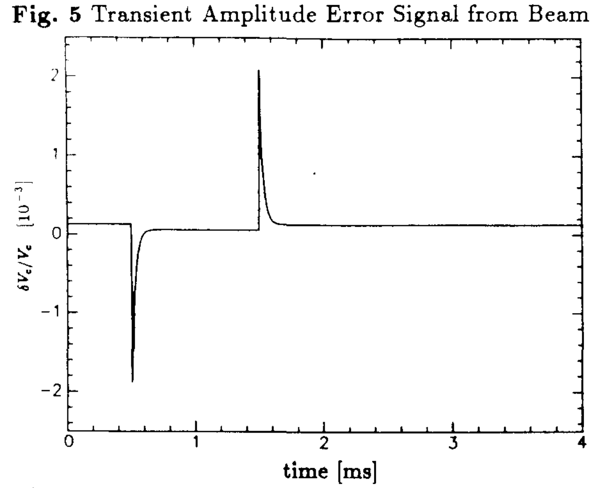

Fig. 6 Transient Amplitude Error Signal from SPICE

The level shift of 5×10^{-5} when the beam is on corresponds to a low frequency gain of 80 dB, consistent with the beam box measurements. Fig. 6 shows the results of SPICE calculations of the response of the amplitude control loop. The loop gains are the same as those for the measured response shown in Fig. 5. The agreement with the measured data is good. If transients in the system are limited to 2×10^{-3}, then rapid beam current changes must be limited to 400 μA.

The final beam measurement to be discussed was taken with a 400 μA CW beam passing through the first superconducting cavity. Very little difference was observed between the noise level when the beam was off and the noise level when the beam was on. This result is consistent with low beam induced fluctuations in the cavity, and one concludes that beam induced noise is not significant at the 2×10^{-4} level, the noise floor of the measurement. Unfortunately, the noise floor is higher than the 2×10^{-5} level that must be achieved. Thus, the beam box measurements still provide the stronger limit on the beam current fluctuations. It should be noted that at 200 μA extracted current, the current in a superconducting cavity is 1 mA.

Conclusions

In this paper, the results of studies of beam loading in the CEBAF superconducting cavities are given. Using beam box measurements, the overall gain by which the RF control system suppresses beam generated voltage fluctuations has been determined. Given the observed beam current fluctuations, the voltage fluctuations should be suppressed to acceptable levels by the controls. The measurements of noise levels in the RF controls with and without high current beam, where no appreciable difference in the noise level was observed, support this assertion. It remains to measure the transfer function directly by modulating the beam current itself, but this measurement is expected to confirm the beam box measurement. When the beam box measurements are confirmed, it can be concluded that beam loading effects will not be a significant contributor to the energy spread in the final CEBAF beam, at least in CW operation.

Data important for evaluating pulsed mode operating schemes have been obtained by our transient beam loading studies. The SPICE simulation reproduces the experimental data. It remains to use this information to evaluate individual pulsed beam schemes.

Acknowledgements

The authors wish to thank C. K. Sinclair for his help in obtaining the data with beam. J. C. Hovater and M. Crofford developed the beam box and D. Ferris set up the data aquisition software used in the experiments.

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