Operation of the CEBAF Linac With High Beam Loading*

L. Merminga, J. J. Bisognano, C. Hovater, G. A. Krafft, S. N. Simrock,
Continuous Electron Beam Accelerator Facility
12000 Jefferson Avenue, Newport News, VA 23606-1909 USA
and K. Kubo,
National Laboratory for High Energy Physics (KEK)
Oho, Tsukuba-shi, Ibaraki-ken, 305, Japan

Abstract

The superconducting RF, CW CEBAF accelerator will use a pair of antiparallel 400 MeV linacs connected by recirculation arcs for nominal 4 GeV in five passes. Single-pass, high power testing of the first linac has been conducted during the months preceding the conference. The RF control system [1] has been designed to control cavity gradient and phase under a wide range of gradients and significant beam loading. At full beam current, accelerating gradient is approximately equal to accelerating voltage in the superconducting RF cavities. Even though the beam current during the high power testing is one-fifth of the full current, beam loading is substantial. Operational experience of the response of the RF system is presented. A tuning algorithm which compensates for beam loading effects has been developed and tested. Heavy beam loading, corresponding to five-pass operation, was studied by increasing the loaded Q of the cavities. A current modulation experiment addressed the issue of energy spread increase due to current fluctuations, and the effect of by-passed cavities on beam properties was investigated.

I. INTRODUCTION

The superconducting RF, CW CEBAF accelerator consists of two antiparallel 400 MeV linacs connected by recirculation arcs for nominal 4 GeV in five passes. At full beam current of 1 mA the beam loading is significant, resulting in a beam induced voltage approximately equal to the accelerating voltage in the RF cavities, $V_{br} = I_b(R/Q)Q_{ext}$. For the CEBAF cavities $(R/Q) = 960\ \Omega/\mathrm{m}$, nominal Q_{ext} $= 6.6\times10^6$, thus $V_{br} = 6.3$ MV/m.

To achieve the low specification on the beam energy spread of $\sigma_E/E = 2.5\times10^{-5}$, strict amplitude and phase control of the RF field in the 338 cavities is required. The RF control system has been designed to control the cavity gradient and phase under a wide range of gradients and significant beam loading.

During the months preceding the conference, single-pass, high power testing of the first linac was conducted. Even though the beam current during the high power testing is one-fifth of the full current, beam loading is substantial. A number of tests aiming towards gaining operational experience of the response of the RF system were carried out and are presented here: the beam loading algorithm, RF performance with heavy beam loading, current modulation and cavity by-passing experiments. More tests were carried out during the high power testing which are described elsewhere [2], [3], [4], [5].

*Supported by U.S. DOE contract DE-AC05-84ER40150

II. BEAM LOADING ALGORITHM

To demonstrate the necessity of beam loading compensation of the tuning algorithm, we start with Fig. 1, which is a vector representation of the generator V_g, beam loading V_b, and total cavity V_c voltages in an RF cavity [6]. The generator and beam induced voltages for an on-resonance cavity are represented by V_{gr} and V_{br} respectively. The three angles noted on the figure are: the phase angle ϕ between beam current and the crest of the RF voltage wave, the detuning angle ψ between generator (beam loading) voltage on and off resonance, and the angle α between cavity voltage and generator voltage on resonance. In reality the detuning angle is modulated by microphonic noise in the frequency range of 1 to 200 Hz with a typical amplitude of $\pm5^0$. In the CEBAF accelerator the tuning mechanism allows only for slow corrections; therefore the detuning angle is controlled on average. The average detuning angle has to be maintained to better than $\pm3^0$ in order to meet the specifications for amplitude and phase regulation and minimise power requirements.

The phase detector in the RF control system can not measure directly the detuning angle, but the phase difference between incident and transmitted (probe) signals, which is the angle α in Fig. 1. For zero beam current, the detuning angle is equal to angle α. However, for finite beam current the two angles are different. For example, for $I_b = 1$ mA, $\phi = 30^0$ and $\psi = 10^0$, $\alpha = 20.07^0$. Thus the purpose of the algorithm is to find the true detuning angle in terms of α, ϕ, V_c and V_{br} and use this as the signal to which the tuners respond. From Fig. 1,

$$\tan\psi = \frac{\tan\alpha[V_c + V_{br}\cos\phi] - V_{br}\sin\phi}{V_c} \qquad (1)$$

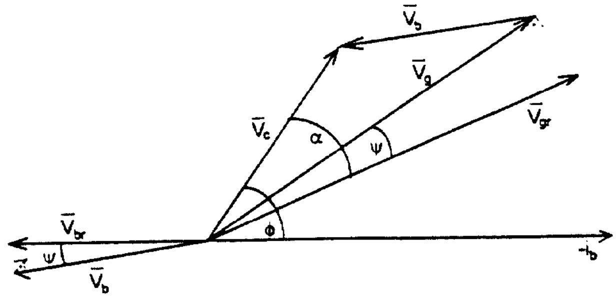

Figure 1: Vector representation of the generator, beam induced and total cavity voltages in an RF cavity.

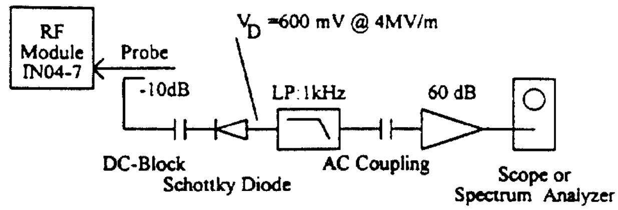

Figure 2: Experimental set-up for testing the RF performance under heavy beam loading.

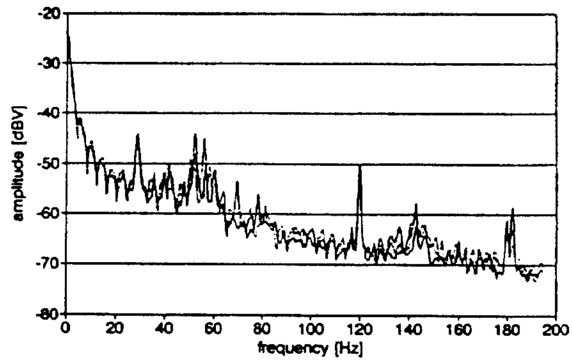

Figure 3: Spectra of gradient error for 0, 40, and 80 μA beam current.

where V_{br} is given in the Introduction.

The algorithm was tested in the Injector cavities IN04-6 and IN04-8 with $Q_{ext} = 5 \times 10^6$ and 1.6×10^7 correspondingly. CW beam was on crest and the accelerating gradient in these cavities was 2.5 MeV/m. The cavities were initially detuned by 20^0 at zero beam current. Current was then varied from 200 to 0 μA in steps of 20 μA, and the angle α was measured (at each step) with the algorithm turned off and on. For cavity IN04-6 the algorithm succeeded in returning the correct detuning angle within 0.5^0, while for IN04-8, with Q_{ext} 3 times higher, the largest error was 2^0, due to the fact that the detuning angle is 3 times more sensitive to frequency changes of the cavity.

III. Heavy Beam Loading

The purpose of this test was to measure the effect of beam loading on the quality of cavity gradient and phase regulation and to verify that RF controls are stable under heavy beam loading. The test took place in the Injector cavities IN04-7 and IN04-8 where waveguide transformers increased the external Q to 1.9×10^7 and 1.6×10^7 respectively. The above Q values provide matching at 300 μA. CW beam current of 30 MeV run in the Injector and residual gradient and phase fluctuations in the two cavities mentioned above were measured as functions of beam current. The set-up for the measurements is shown in Fig. 2. An external Schottky diode with DC-block was used to measure gradient fluctuations independently of noise generated in the electronics of the controls module. The similarity of the spectra of the gradient fluctuations at different beam currents (0, 40, 80, 160 μA), shown in Fig. 3, demonstrates that residual amplitude noise does not depend on beam current. Furthermore, a more quantitative measurement was conducted: the integral of the rms gradient error signal in the frequency range of 10 to 100 Hz was calculated (using a LeCroy type scope) for 0, 40 and 80 μA. These values were found to be -33.92 dBV, -34.22 dBV and -33.78 dBV. Taking into account the 60 dB preamplifier (see Fig. 2), the relative rms gradient error is

$$\frac{\Delta V}{V} \approx \frac{2 \times 10^{-5}\ \mathrm{V}}{600\ \mathrm{mV}} \approx 3.3 \times 10^{-5} \qquad (2)$$

in the 10 to 100 Hz frequency range. The specification for uncorrelated amplitude fluctuations is 2×10^{-4} up to 1 MHz; however, it has been observed before that the contribution from the higher frequencies is negligible.

IV. Current Modulation

In order to determine whether beam current fluctuations cause energy spread in the beam, a current modulation experiment was completed. The experiment consisted of fully modulating a high current beam, and correlating with the voltage fluctuations in the IN04-6 superconducting cavity. Two hundred microamp CW beam was square-wave modulated at 150 Hz by amplitude modulating the chopper power (the average current after modulation was 100 μA). The response of the RF control system was measured in two locations.

Firstly, the gradient modulator drive in the gradient controls was observed. The gradient mod drive controls the klystron power; it exhibited the same square wave modulation. Comparing the spectra of the beam current and the mod drive revealed that the spectra were identical at harmonics of the modulation frequency up to more than 10 kHz. They also exhibited the $1/f$ frequency dependence at odd harmonics, a characteristic of square wave modulation. The scales of the modulation peaks were consistent with the known properties of the RF controls.

Secondly, the gradient fluctuations in the cavity were also observed using the Schottky diode described previously. The spectrum of the diode output had peaks at harmonics of the modulation frequency. A one parameter theoretical calculation was done using the formula

$$\delta V(\omega) = \frac{R(\omega)I(\omega)}{1+G(\omega)}$$

to calculate the peak locations based on the current spectrum and the Bode plot of the RF controls. The Bode plot shows that the loop gain $G(\omega)$ falls as $1/f^2$ in the region between 1 and 10 kHz, accounting for the flat peak values observed in this frequency range.

The smallness of the voltage fluctuations induced by the ambient current fluctuations in the CW beam combined with the relatively large noise in the RF controls (at the $\delta V/V \approx 10^{-4}$ level) made it difficult to directly measure the ambient voltage fluctuations due to beam loading effects. However, these modulation measurements, along with measurements that show that the ambient current fluctuations are less than 1.5%, demonstrate that the beam induced relative voltage fluctuations are under 10^{-6}. Because the correlated relative amplitude error specification is 10^{-5}, beam loading should be a negligible contributor to the energy spread in the final beam.

V. Cavity By-Passing

Hardware failures such as defective klystrons or high voltage power supplies may require the shutdown of individual cavities or cryomodules. In this case the failing system needs to be by-passed until the defective subsystem is repaired. Non-operational cavities need to be detuned to reduce the beam induced voltage. An experiment [7] was carried out during the high power testing of the north linac in order to a) verify the validity of calculation of the beam induced voltage V_b, and its fluctuations δV_b, due to microphonic noise in a by-passed cavity, b) determine the effect of by-passing a cavity on the beam energy and energy spread and c) specify an optimum off resonance frequency for by-passing. Injector cavity IN04-6 was by-passed while the Injector was operated with 30 MeV, CW beam and up to 80 μA beam current. Cavity 6 was detuned by approximately 100, 200 and 1500 Hz, and V_b and δV_b were measured from the cavity probe. Data was recorded from both the spectrum analyser and the oscilloscope and is plotted in Fig. 4 together with the theoretically expected values of V_b (straight lines) and δV_b (dotted lines). The bars represent the experimental fluctuations of V_b. The theoretical values are derived from the LCR circuit model of a resonant cavity. There is a good agreement between measured data and predicted values for V_b. However, the fluctuations of V_b are bigger, experimentally, than one would expect simply due to microphonics. A beam position monitor (BPM) in a high dispersion region was also used to measure energy changes at different detuning angles and beam currents. The energy changes observed are consistent with the values of V_b; however, it was not possible to estimate the effect of microphonic noise on the energy spread due to insufficient accuracy of our measurements. Finally at 200 μA CW beam, a detuning frequency of 1 kHz appears to provide the required energy stability of the beam.

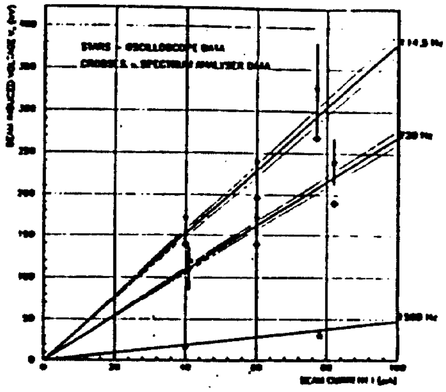

Figure 4: Measured data and predicted values of beam induced voltage and its fluctuations in a by-passed cavity.

VI. Conclusions

Results of the single-pass, high power tests during the CEBAF north linac commissioning have been reported. A tuning algorithm which provides compensation for beam loading effects has been developed and successfully verified in the machine. Heavy beam loading was simulated by increasing the loaded Q of a cavity, and the performance of the RF control system was measured. The RF control system can regulate within specifications independently of beam current. A current modulation experiment showed unambiguously that beam current fluctuations at the expected 1.5% level will have a negligible effect on the energy spread of the beam. Good agreement between predicted values and measured data of the beam induced voltage were obtained from a by-passed cavity. The optimum detuning frequency for by-passing was determined to be at least 1 kHz at 200 μA.

Acknowledgments

The authors would like to sincerely thank the machine operations crew and the RF maintenance group for their enthusiastic support during the high power tests, and Ken Crawford for help with the current modulation experiment.

References

[1] S. Simrock, *Conference Record of the 1991 IEEE PAC.*

[2] Y. Chao *et al.*, these proceedings.

[3] S. Simrock *et al.*, these proceedings.

[4] G. A. Krafft *et al.*, these proceedings.

[5] A. Hutton, these proceedings.

[6] P. Wilson, AIP Conf. Proc. No. 87, 450 (1981).

[7] O. Bazhenov *et al.*, CEBAF-TN-93-032.