

EXPERIMENTS AND SIMULATION OF HIGH CURRENT OPERATION AT CEBAF

L. Merminga, K. Crawford, J. R. Delayen, L. Doolittle, C. Hovater,
R. Kazimi, G. Krafft, C. Reece, S. Simrock, M. Tiefenback, D. X. Wang,
Thomas Jefferson National Accelerator Facility, Newport News, Virginia, USA

Abstract

The superconducting rf, cw electron accelerator at CEBAF has achieved the design energy of 4 GeV using five-pass recirculation through a pair of 400 MeV linacs. Stable beam current of 35 μA has been delivered to the Experimental Hall C. The total beam current that has been recirculated so far is 248 μA [1]. Measurements of the performance of the rf control system have been made in both pulsed and cw mode, and a numerical model has been developed which describes the beam-cavity interaction, includes a realistic representation of low level controls, klystron characteristics and microphonic noise. Experimental data and simulation results on transient beam loading, klystron saturation, a new technique for cavity phasing, and heavy beam loading tests are described here. In conclusion, an outlook on full current operation is presented.

1 INTRODUCTION

At CEBAF's design current of 200 μA which results in a beam loading of up to 1 mA, the beam induced voltage is approximately equal to the accelerating voltage in the superconducting cavities. Even though the beam current recirculated thus far is one-fourth of the full current, beam loading is substantial. We have measured the performance of the rf control system in both pulsed and cw mode to quantify the system performance, develop procedures to improve stability of operation, and demonstrate stable operation at the design current. We have benchmarked the numerical model of CEBAF's rf control system against experimental data and have used it to predict and provide insight into upcoming operational scenarios.

We start this paper with a detailed description of the model. Next we present experimental data and simulation results on transient beam loading, on a new technique for cavity phasing which utilizes the amplified gradient and phase error signals, on klystron saturation and on heavy beam loading tests. In conclusion we present an outlook on full current operation based largely on data obtained thus far, and if not available, on conservative extrapolations.

2 THE MODEL

To simulate the performance of the CEBAF rf control system, we developed a model of the cavity and low level controls using SIMULINK, a MATLAB based program for simulating dynamic systems. The interaction of the beam

with the cavity fields can be described by the following first order differential equation,

$$\frac{d\tilde{V}_c}{dt} + \frac{\omega_0}{2Q_L}(1 - i \tan \Psi)\tilde{V}_c = \frac{\omega_0 R_L}{2Q_L}(\tilde{I}_g - \tilde{I}_b) \quad (1)$$

where ω_0 is the cavity resonant frequency, Q_L is the loaded quality factor Q of the cavity and R_L is the loaded shunt impedance $R_L = (R/Q)Q_L$. The beam in the cavity is represented by a current generator. In arriving at (1) we assume that the cavity voltage, generator and beam current vary as $e^{i\omega t}$, where ω is the rf frequency, and \tilde{V}_c , \tilde{I}_g and \tilde{I}_b are the corresponding complex amplitudes (phasors) in the rotating frame of reference, varying slowly with time. In this equation I_b (absence of tilde denotes the magnitude of the corresponding quantity) is equal to the average beam current (in the limit of short bunches). Also Ψ is the tuning angle defined by $\tan \Psi = -2Q_L(\omega - \omega_0)/\omega_0$. The model includes microphonic noise in the form of sinusoidal modulation of the cavity's resonant frequency, $\delta\omega = \omega_M \sin(\omega_f t)$ where ω_M is the amplitude and ω_f the frequency of the noise. Lorentz-force detuning is included although it is not important in the present, cw rf, operational scenario. The current source is the sum of the generator and beam current. Outputs of the cavity model are the amplitude and phase of the cavity voltage. The amplitude signal is compared to the amplitude set-point and the normalized error signal is amplified by the loop gain. The loop gain is given by $C(s) = H(s)[1+G(s)]$ where $H(s)$, $G(s)$ are the transfer functions of the broadband and low-frequency gain respectively, $H(s) = \frac{K_1}{1+sT_1}$, $G(s) = \frac{K_2}{1+sT_2}$, $K_1=100$ and $(2\pi T_1)^{-1} = 1$ MHz, and $K_2=30$ and $(2\pi T_2)^{-1} = 150$ Hz. The broadband gain of 100 (up to 1 MHz) is boosted by an additional low-frequency gain of 30 which allows for an error reduction by a factor of 3000 for frequencies up to 150 Hz. The model includes three additional poles at 3 MHz, contributed from the klystron hardware, as well as the cavity pole which occurs at 125 Hz (on resonance).

The controller for the phase of the accelerating field employs a vector modulator. The two inputs control the in-phase (real) and quadrature (imaginary) (I/Q control) components of the incident wave. The in-phase input (PBIS) is set to a fixed bias voltage of 5V, while the quadrature input (PASK) is used to control the cavity phase error. A control voltage range of $\pm 5\text{V}$ allows therefore for a phase control range of $\pm 45^\circ$ which is sufficient for the microphonics observed at CEBAF. The vector modulator has the inverse transfer function of the cavity. The amplitude is increased

as function of phase as $A/A_0 = \sqrt{1 + \tan^2 \Psi}$ therefore exactly compensating the reduced gradient when the cavity is detuned by an angle Ψ . Phase control by itself stabilizes the amplitude if the origin of the phase noise is purely microphonics, and if the cavity is operated on resonance on average.

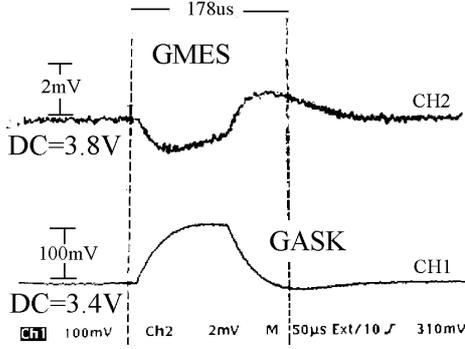


Figure 1: Measured cavity gradient (GMES) and signal used to control the amplitude error (GASK) in pulsed operation.

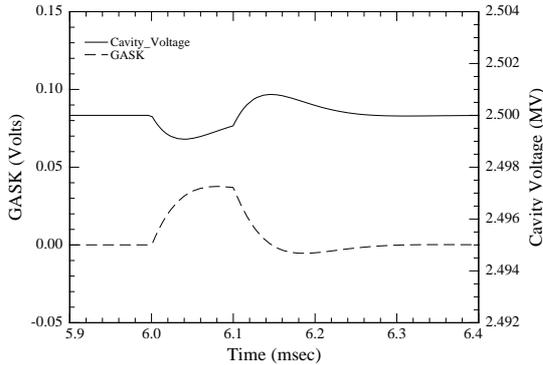


Figure 2: Simulated cavity voltage and signal used to control the amplitude error (GASK) in pulsed operation.

3 EXPERIMENTS AND SIMULATION

3.1 Transient Beam Loading

An energy shift of approximately 10^{-3} was observed last fall in the accelerator, during transitions from pulsed to cw mode of operation, with $65 \mu\text{A}$ total beam current in the cavities, due to transient beam loading. When $65 \mu\text{A}$, $100 \mu\text{sec}$ beam pulses enter the cavity, the beam-induced gradient fluctuation due to transient beam loading, reaches a maximum of 8.5×10^{-4} and recovers with a time constant of $25 \mu\text{sec}$, at the present rf system settings. As beam position monitors (BPM's) at high dispersion points were set up to read $60 \mu\text{sec}$ into the pulse, the relative energy error (compared to cw mode) was approximately 8×10^{-4} . Figures 1 and 2 display the cavity gradient, and GASK, the

signal used to control the amplitude error, as predicted by the model and as measured in the machine (In the model the beam enters the cavity at 6 msec). Both the quantitative and qualitative agreement is exceptionally good. The energy shift problem was solved by making the beam pulses longer ($250 \mu\text{sec}$) and setting up the BPMs to read at $200 \mu\text{sec}$ into the pulse, thereby setting up the machine closer to cw mode.

3.2 Cavity Phasing with Beam Induced Voltage

Equation (1) rewritten for the steady-state yields the following expressions for the generator phase Ψ_g , and generator amplitude $V_{gr} = R_L I_g$,

$$\tan \Psi_g = \frac{-\tan \Psi + K \sin \Psi_b}{1 + K \cos \Psi_b} \quad (2)$$

$$\left(\frac{V_{gr} \cos \Psi}{V_c} \right)^2 = 1 + (K \cos \Psi)^2 + 2K \cos \Psi \cos(\Psi + \Psi_b)$$

where Ψ_b is the phase of \tilde{I}_b and $K = R_L I_b / V_c$. All phases are measured with respect to the phase of the steady-state cavity voltage. In CEBAF's rf control system, $\tan \Psi_b$ is simply proportional to the amplified phase error signal PASK, directly available from the control module; $\text{PASK} = \text{PBIS} \times \tan \Psi_g$, $\text{PBIS} = 5 \text{ V}$. Similarly, V_{gr} is relatively simply related to GASK, the signal used to control the amplitude error, which is also directly available from the control module; $\text{GASK} = V_{gr} \cos \Psi_g$. The last equation reflects the effect of the vector modulator, where the phase controller also provides amplitude corrections. Since CEBAF cavities must be operated on resonance ($\Psi = 0$) and on crest ($\Psi_b = 0$), zeroing PASK without beam and zeroing it with beam should in principle ensure proper operation. However, it might be operationally more straightforward to fit the experimental data to the two curves (eqs (2)) and determine the off-crest and off-resonance phases from the fit. To test this method, we varied the beam phase (PSET) and recorded the PASK (averaged over microphonics) and GASK signals. Figure 3 shows a comparison between experimental data and the curves given by eqs (2) above. From these fits we were able to determine that the particular cavity was on resonance, but 10° off in phase. We plan to pursue these experiments in order to develop automated procedures for cavity phasing and tuning.

3.3 Klystron Saturation

During the recent production runs, the klystron cathode voltage has been reduced to 60% of the design value (for all but 8 of CEBAF's 39 linac cryomodules), as a measure to increase the klystron lifetime and save operating cost, until the experimental program requires greater current. As a result, the maximum available klystron power dropped from 5 kW to 1.7 kW, as expected from $P \simeq V_k^{5/2}$, where V_k is the klystron cathode voltage. In some cases the limited klystron power combined with high level of microphonic noise and high beam loading resulted in degradation of rf

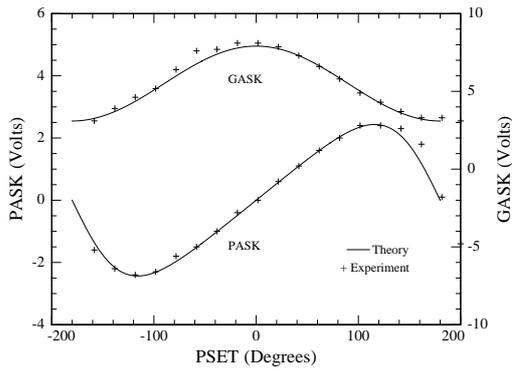


Figure 3: Measured and calculated GASK and PASK signals as function of beam phase (PSET).

control performance due to klystron saturation. Figure 4 displays output klystron power as function of input power for a cathode voltage of 11.6 kV and 7.35 kV and different modulating anode voltages. Besides the lower output power, the gain is also reduced by 10 dB for a modulating anode voltage setting of 0 Volts. In addition, the klystron's output signal shifts in phase as it saturates. This phase shift is linear in the rf drive voltage, and reaches 20° at maximum power. This effect leads to some undesired coupling between amplitude and phase loop.

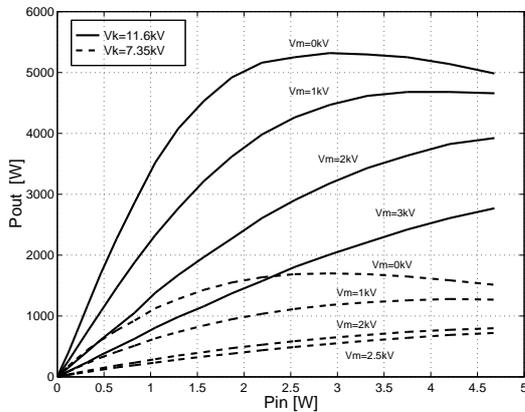


Figure 4: Measured output klystron power as function of input power for different cathode and modulating anode voltages.

3.4 Heavy Beam Loading Test

The effects of high beam loading at high gradients have been studied by scaling to low gradients of 1.5 MV/m, and available beam currents of up $150 \mu\text{A}$. The rf levels of cavity field probe signal, forward and reflected powers have been amplified or attenuated to simulate operation at 7.5 MV/m and $600 \mu\text{A}$ of beam current. No significant increase on the rms phase and amplitude errors was observed by varying the beam current from $50 \mu\text{A}$ to $150 \mu\text{A}$, with

the cavity on resonance and 45° off resonance. The module maintained its normal regulation well within the design specifications.

4 OUTLOOK AND CONCLUSIONS

We conclude with Figure 5 which shows the operational envelope limited by the klystron cathode voltage reduction. The envelope is based upon measured parameters for each cavity, including the cathode voltage. No headroom allowance for cavities used to regulate energy variations is included, nor for cavities which must be turned down or off when problems arise.

In addition to the klystron power, the maintainable gradient depends on the beam current and on static and dynamic detuning. The envelope above assumes a 10° absolute error in the measured detuning angle and a 10° regulation dead-band. The microphonic detuning allowance is taken to be 4 times the measured rms value for each cavity. The envelope calculation uses recently verified cavity limits for cavities not limited by klystron power, as well as beam-based calibration of the actual cavity gradient. No explicit allowance for off-crest operation is provided.

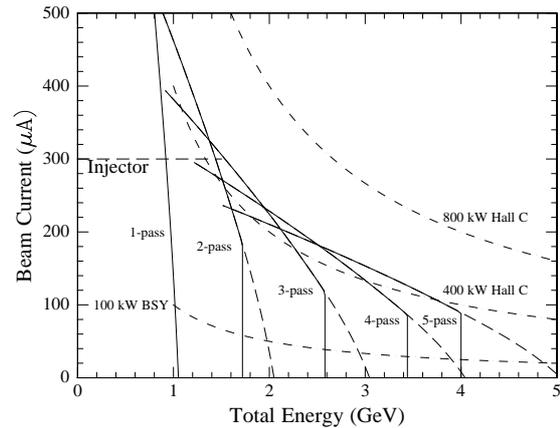


Figure 5: Operational envelope for the CEBAF accelerator at reduced klystron power.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

- [1] "Operating Experience at CEBAF," R. Legg, these proceedings (1996).