# INSTABILITY OF THE RF CONTROL LOOP IN THE PRESENCE OF A HIGH-Q PASSIVE SUPERCONDUCTING CAVITY *

S. Belomestnykh#, R. Kaplan, J. Reilly, V. Veshcherevich
Laboratory for Elementary-Particle Physics, Cornell University, Ithaca, NY 14853, U.S.A.

*Abstract*

Instability of the active RF cavity field control loop was observed during experiments with beam-driven (passive) superconducting cavities in CESR when the cavity external $Q$ factor was raised to a value above $1x10^7$. A computer model was developed to study this instability and find a way to cure it. The results of simulations are presented alongside the experimental results.

## INTRODUCTION

Operating CESR in a charm/tau factory mode (CESR-c) presents new challenges to superconducting RF system [1]. While the high RF voltage is required to produce short bunch length and high synchrotron tune in CESR-c, the beam power demand is very moderate [2]. It was proposed operating some of the cavities in a passive bunch-shortening mode.

A proof-of-principle experiment was performed in February 2001 to check feasibility of this mode of operation [3]. The experiment was done at high beam energy (5.3 GeV) with one of four CESR cavities being beam-driven. The cavity was detuned far from resonance until beam current reached 100 mA. Then the tuner feedback loop was activated to keep the cavity voltage at 0.9 MV. It was possible to store beam current of 400 mA. The measured dependence of the synchrotron frequency on the beam current was in good agreement with calculations.

More experiments followed at low beam energy with the cavity external $Q$ factor adjusted to $10^6$ from the nominal value of $2\times10^5$ using waveguide transformer [4]. Trial HEP run showed that it is possible to reach luminosity comparable with that reached during normal operating conditions. However, an energy kick due to beam interaction with this relatively low-$Q$ cavity can produce rather large beam-current dependent differential orbit perturbation between electrons and positrons at the interaction point and, as a result, can reduce the luminosity of the collider [5]. To avoid this undesirable effect, it is necessary to increase external $Q$ even more, to $10^7$ or higher, which is possible with the insertion of a short in the waveguide in an appropriate place. In this paper we present results of experimental studies and computer simulations of instability of the RF feedback loop in the presence of a passive cavity with $Q_{ext} > 1\times10^7$.

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#sab@lepp.cornell.edu

## EXPERIMENTAL RESULTS

Three superconducting cavities were used in the experiment. Cavities W1 and W2 were active, connected to one klystron via a magic T RF power splitter. A short plate was inserted in the waveguide feed of the third cavity (E1) in a position corresponding to a $\lambda/4$ resonance. The quality factor for this configuration was $Q_{ext} \approx Q_L \approx 2\times10^7$.

During the experiment the cavity was initially parked in an off-resonance "home" position. As soon as the beam current exceeded the threshold value of 30 mA, the tuner feedback loop was activated to tune the cavity frequency according to the cavity field error signal. The passive cavity voltage set point was set to 1.2 MV. The description of the passive cavity tuner control loop can be found elsewhere [4]. Cavities W1 and W2 operated at 1.6 MV and 1.8 MV correspondingly. At the time of experiment analog feedback loops were used for amplitude and phase control of these cavities (average values of the cavity amplitudes and phases were regulated). The amplitude loop had only integral gain with the unity gain at about 1.25 kHz; the phase loop had integral and proportional gains and was set to have the unity gain of about 1.5 kHz and to compensate the cavity pole.

Upon activation of the tuner control loop a modulation was observed on all cavity field signals. The modulation frequency was about 780 Hz at the total beam current of 38 mA (Figure 1). This frequency is close to the detuning frequency of the passive cavity required to reach 1.2 MV. Amplitude modulation of E1 cavity field was 100%, magnitude of phase error signal modulation was very large (>40º). Similar modulation was observed on a "tuning angle error" signal, which for the passive cavity is a phase difference between the forward wave power signal in the resonating waveguide and the cavity field signal. The amplitude modulation of W1 and W2 cavity fields was less than 5%.

## STABILITY OF THE RF FIELD FEEDBACK IN THE PRESENCE OF HIGH-*Q* PASSIVE CAVITY

We used the Pedersen model to analyze the system stability [6]. For our case we added a passive cavity to the RF system signal-flow graph as shown in Figure 2. The transfer functions for transmission of phase modulation from the beam to amplitude (pa) and phase (pp) modulations of the passive cavity are given by:

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$$^{Bp}G_{pa} = \frac{Y_p\left[\sigma_p^2\left(\tan\psi_p \cdot \cos\varphi_{bp} - \sin\varphi_{bp}\right) - i\omega\cdot\sigma_p\cdot\sin\varphi_{bp}\right]}{-\omega^2 + 2i\omega\cdot\sigma_p + \sigma_p^2\cdot\left(1+\tan^2\psi_p\right)},$$

$$^{Bp}G_{pp} = \frac{Y_p\left[\sigma_p^2\left(\cos\varphi_{bp} + \tan\psi_p \cdot \sin\varphi_{bp}\right) + i\omega\cdot\sigma_p\cdot\cos\varphi_{bp}\right]}{-\omega^2 + 2i\omega\cdot\sigma_p + \sigma_p^2\cdot\left(1+\tan^2\psi_p\right)},$$

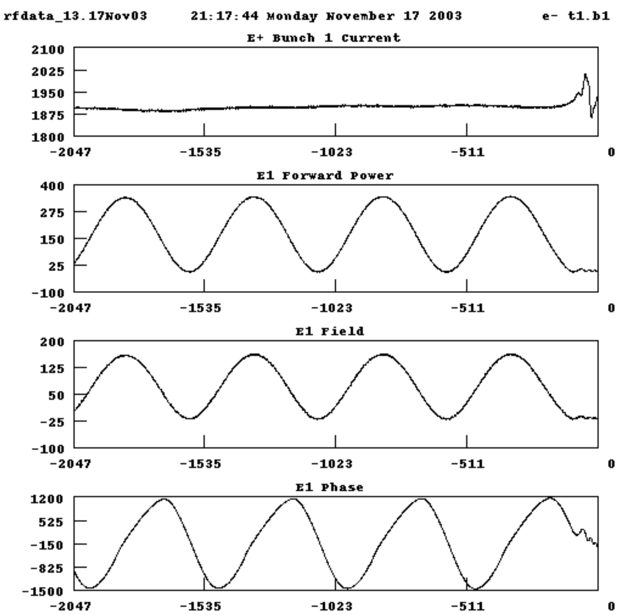


Figure 1: Beam loss plots of the passive cavity signals. Vertical axes are in arbitrary units, horizontal axis is the number of revolution periods (1 period = 2.56 µs). The "E1 forward power" signal represents the forward wave power in the resonant waveguide.

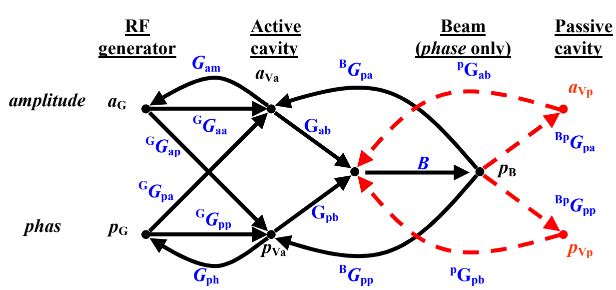


Figure 2: Signal-flow graph of the RF system.

here the index $p$ refers to the passive cavity, $Y$ is the beam loading parameter, $\sigma$ is the cavity damping rate, $\psi$ is the cavity tuning angle, and $\phi_b$ is the synchronous phase. Also, if for a case without passive cavity the transfer functions from the active cavity to the beam are simply $G_{ab} = \tan(\phi_b)$ for amplitude modulation, and $G_{pb} = 1$ for phase modulation, now they have to be modified to take into account the fact that the total voltage affecting the beam is a vector sum of the active cavity and the passive cavity voltages. For the active cavity we get

$$G_{ab} = \left(\cos(\phi_{ba} - \phi_b)\cdot\tan(\phi_b) + \sin(\phi_{ba} - \phi_b)\right)\cdot\frac{V_a}{V_{total}},$$

$$G_{pb} = \left(\sin(\phi_{ba} - \phi_b)\cdot\tan(\phi_b) + \cos(\phi_{ba} - \phi_b)\right)\cdot\frac{V_a}{V_{total}},$$

where $V_a$ is the active cavity voltage, and $V_{total}$ is the vector sum of the active and the passive cavity voltages. Similar transfer functions can be written for the passive cavity by replacing $\phi_{ba}$ with $\phi_{bp}$ and $V_a$ with $V_p$. Figure 3 presents a phasor diagram of the system.

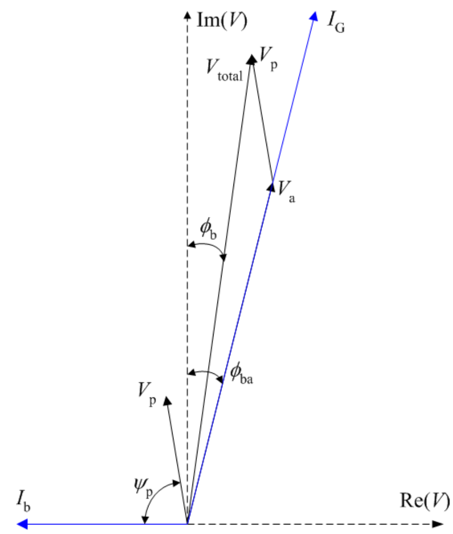


Figure 3: Phasor diagram.

We have programmed all transfer functions in MathCAD and then, using Mason's rules [7], absorbed loops and nodes until only one loop remained (namely, the amplitude loop). Then this remaining loop was analyzed to determine its stability for different beam and passive cavity parameters.

Figure 4 shows open-loop Bode plots for different values of the passive cavity $Q_{ext}$. Figure 5 illustrates how feedback loop gain and phase changes with the beam current. One can see that for the beam current of 50 mA the feedback loop becomes unstable at $Q_{ext} > 10^7$ (all other parameters were assumed to be close to those in the experiment). Also, increasing beam current worsens the loop stability. This is expected, as the beam provides coupling between the passive cavity and the active cavity RF loops.

Simulations using MATLAB Simulink model of the RF system confirmed that there is an instability similar to that observed experimentally. The frequency of amplitude and phase oscillations was also very close to measured (around 800 Hz).

## SUMMARY

We have experimentally observed instability of RF feedback loops in the presence of a high-$Q$ superconducting passive cavity operating in a bunch-shortening mode. Numerical studies of the RF system confirmed that RF control loops become unstable under curtain conditions if a high-impedance resonance is located within the loop bandwidth. To avoid such instability one needs to operate the beam-driven cavity either at lower voltage or at lower $Q$ or both. More studies are needed to determine the region of stable operation in the passive cavity parameter space.

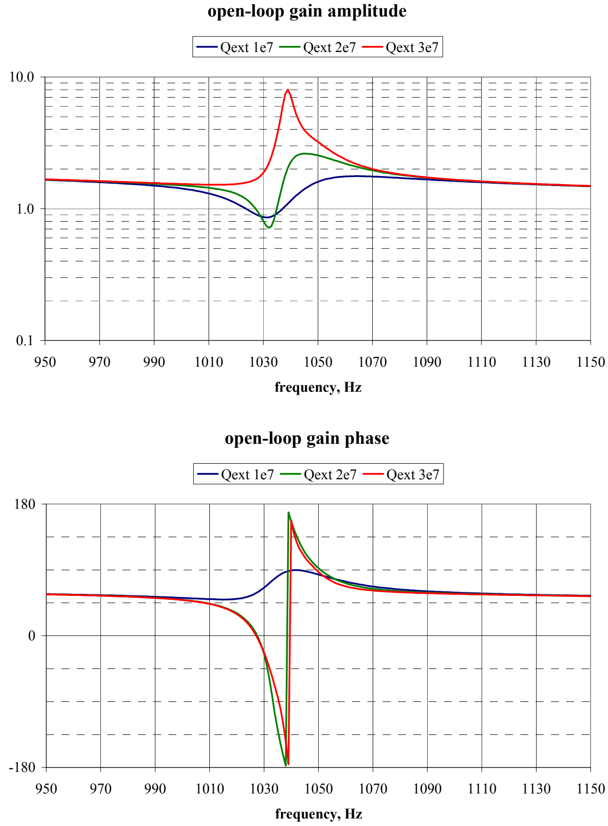


Figure 4: Open-loop Bode plot for different values of passive cavity quality factor (50 mA beam current).

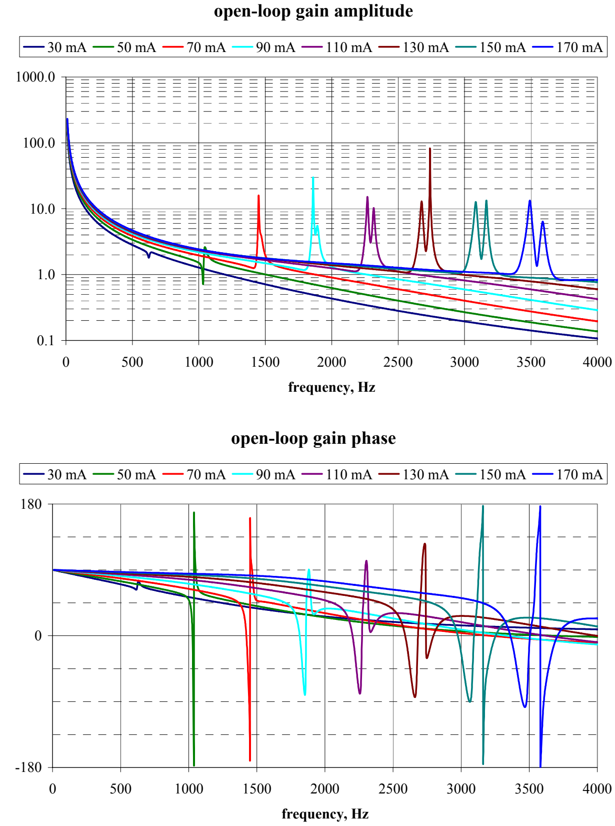


Figure 5: Open-loop Bode plot for different beam currents and the passive cavity parameters $Q_{ext} = 2\times10^7$, $V = 1.2$ MV.

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