ANALYSIS OF THE SUPERCONDUCTING RF CAVITY UNDER HEAVY BEAM LOADING AT TAIWAN LIGHT SOURCE

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Abstract

A super-conducting rf cavity will be installed into the Taiwan Light Source (TLS) storage ring in year 2003 for higher beam intensity and stability. Operation of this cavity under heavy beam loading condition is being studied. Basic information such as required rf power that will be forwarded to and the power that will be reflected back from the cavity at various loading angles have been calculated at equilibrium condition. Also, in terms of modified synchronous phase, the condition of beam stability has been investigated. The dynamics of beam-cavity interaction has also been studied. A customized rf system design block-set has been built in the MATLAB/SIMULINK environment to perform time-base simulation. From such simulation study, the responses of the SRF cavity with respect to excitation with and without beam loading have been analyzed.

1 INTRODUCTION

Super-conducting cavity has been widely used in high energy accelerators for particle physics research. There has been an increasing interest in using such cavities in accelerators not only for the high acceleration gradient but also for the ease of implementing HOM damper structure which is of essential importance for stable high current operation. Recently, super-conducting cavity has been employed or proposed for use in high current storage rings such as meson factories and third generation light sources. However, specific problems associated with heavy beam-loading in a SRF cavity such as large beam induced voltage, high rf power being reflected back to generator, change in cavity response during a quench and multi-pactoring at rf window at mismatched cavity operation condition should be studied in greater details.

At SRRC, a superconducting cavity will be installed into the TLS storage ring in year 2003 for improvement of stability and high current operation. Basic operation parameters for the SRF cavity in the TLS storage ring are listed in Table 1. In this study, the required rf power that will be delivered to the cavity and the rf power that will be reflected back from the cavity are calculated at equilibrium condition for nominal beam current. Those data are important for specifying the transmitter power, rf windows and many other high power rf components. The modified synchronous phase is defined as the phase of generator voltage with respect to the beam phase. It is a good measure of how close the system to the current limit imposed by Robinson instability. One may want to detune the rf cavity for Robinson damping. However, this will make the cavity forward and reverse power both increases. The parametric dependence of forward and reverse powers and modified synchronous phase on loading angle is presented in Section 2. Dynamic behaviors of the system are studied based on the Pedersen model of beam-cavity interaction [1]. For beam manipulation and measurements in longitudinal phase space, it is often required to modulate cavity voltage in amplitude or in phase. Therefore, it is of interest to know how fast a SRF cavity response to an excitation and what is the modulation bandwidth. To make use of the well developed simulation tools in the MATLAB/SIMULINK [2] environment, a customized rf system design block-set has been created for time-base analysis. Dynamic responses of the SRF cavity are discussed in section 3. Section 4 is the conclusion and discussion.

Table 1: Operation Parameters for SRF Cavity in TLS

Gap voltage, V_c	1.6 MV
Synchrotron radiation loss, U_o	168 keV
Beam current, I_b	400 mA
Cavity Ohmic quality factor, Q_o	2e9 @ 1.6 MV
Cavity external quality factor, Q_{ext}	2.5e5
Cavity R_s / Q_o	44.5
Optimized coupling coeff. β_{opt}	2921 @ 500 mA
Selected coupling coeff. β_{design}	4000
Cavity tuning angle, Ψ	-80.2°

2 BEAM LOADING AT EQUILIBRIUM

From the operation parameters listed in Table 1 and the cavity loading angle was set at minus 10 degrees, a phasor diagram can be drawn (Figure 1). As can be seen on the drawing, the cavity is heavily loaded with a 400 mA electron beam. For this nominal gap voltage setting, a large amount of the cavity voltage has been contributed by the beam instead of the rf generator. The phasor of the generator voltage has been pushed toward the reference phase. That is, the phase angle of the generator voltage with respect to beam (modified synchronous phase) is small. It is obvious that any fluctuations of beam current due to large beam motion can cause a significant change in generator voltage that may in turn cause an unstable beam or even beam loss. In our low level rf system, the angle between generator current and voltage (loading angle) is a free parameter for tuning. One can decrease loading angle to rotate V_{gr} in counter-clockwise sense so that the phasor of the generator voltage rotate also counterclockwise and therefore the beam has a larger modified synchronous phase and becomes more stable. This is called Robinson damping.

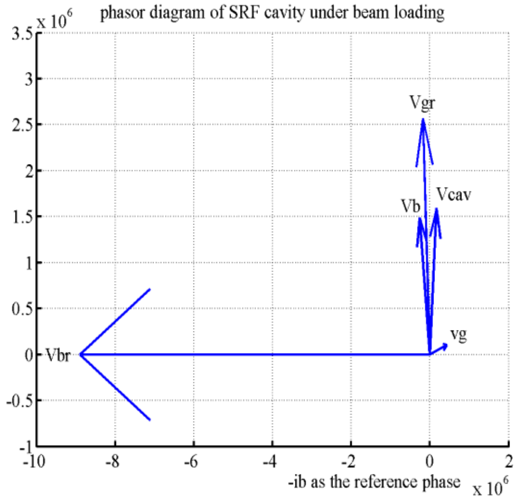

Figure 1: Phasor diagram of the SRF cavity loaded with a 400 mA electron beam at -10 degrees loading angle.

2.1 Forward and Reverse Powers

Based on steady state analysis [3], generator power can be calculated with the following formula:

$$P_g = \frac{V_c^2}{R_s}\cdot\frac{(1+\beta)^2}{4\beta}\cdot\frac{1}{\cos^2\psi}\left\{\left[\cos\phi+\frac{I_b R_s}{V_c(1+\beta)}\cos^2\psi\right]^2+\left[\sin\phi+\frac{I_b R_s}{V_c(1+\beta)}\cos\psi\sin\psi\right]^2\right\}.$$

In this formula, ϕ is the synchronous phase angle. With the knowledge of the beam power, rf power dissipated on the cavity wall and the generator power, the reflected power can be deduced. Figure 2 shows the required generator and reverse power at different loading angle. Note that at 400 mA beam current and zero loading angle, the forward power to the cavity is about 72 kW and the reversed power from the cavity is about 5 kW. At loading angle equals plus or minus 20 degrees, the forward power went up to ~82 kW and reverse power at ~15 kW. Therefore, a transmitter of power larger than 100 kW is required for effective Robinson damping. For loading angle less than -30 degrees, required rf power and reverse power increase significantly and rf power usage become very ineffective.

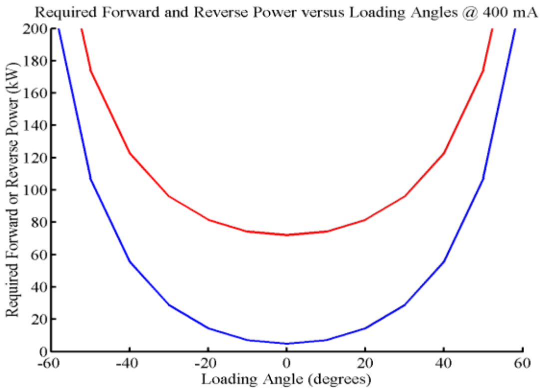

Figure 2: Required generator and reverse power versus loading angle

2.2 Modified Synchronous Phase and Beam Stability

Figure 3 shows how the modified synchronous phase [4] decreases with loading angle at 400 mA. At zero loading angle, the modified synchronous phase equals to ~4°. Further reduction of loading angle helps to improve beam stability with the expenses of generator power and a high reverse power to the generator. This suggested that means other than merely detuning the cavity for beam loading should also be considered.

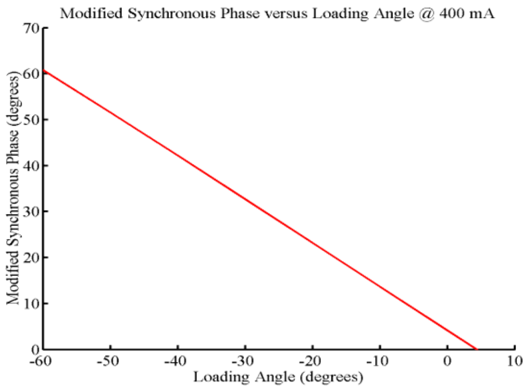

Figure 3: Coherent synchronous phase as a function of loading angle at 400 mA

3 DYNAMIC RESPONSE

For beam dynamic studies and manipulation of beam in longitudinal phase space, it is often to modulate cavity voltage in amplitude or in phase. It is of interest to know how a SRF cavity responses to an excitation.

3.1 Responses of SRF Cavity without Beam

Although the SRF cavity has a extremely high unloaded Q at ~$1\text{x}10^9$, it does not have a long filling time as expected. This is because the external or radiation Q of the cavity which coupled to external circuit is of the order of 10^5 (see Table 1). As a result, the loaded Q of the cavity is also of the order of 10^5.

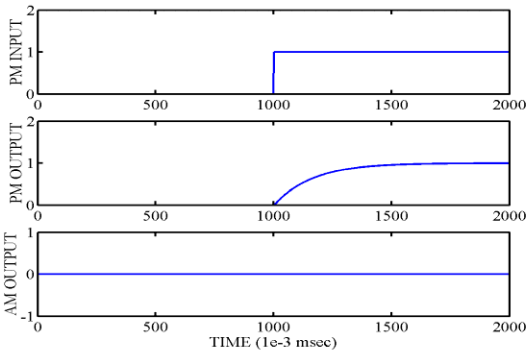

Figure 4: Change in cavity voltage phase (middle trace) and amplitude (lower trace) in response to a step change in rf current phase (upper trace) for zero loading angle without beam.

Therefore, the filling time of the cavity is about 0.16 ms and the 3 dB bandwidth is ~2 kHz. This can be seen from a time-base simulation of the cavity response to a step change in phase of the excitation current at zero loading angle (Figure 4). Note that the cavity amplitude does not response to such phase change at this loading angle. Amplitude variation occurred at non-zero loading angle as expected (Figure 5).

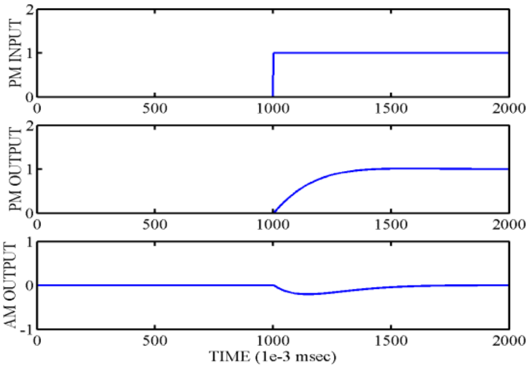

Figure 5: Change in cavity voltage phase (middle trace) and amplitude (lower trace) in response to a step change in rf current phase (upper trace) for 30° loading angle without beam.

3.2 Responses of SRF Cavity with Beam

In this simulation, the change in beam phase due to amplitude and phase changes in cavity voltage are neglected (without internal feedback by beam). With 400 mA beam, the SRF cavity response to the step change is much faster. The rise time of the phase response is ~0.04 ms. And the overshoot is as high as 60% (see Figure 6).

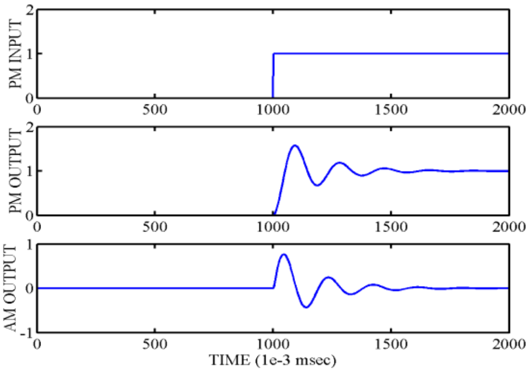

Figure 6: Change in cavity voltage phase (middle trace) and amplitude (lower trace) in response to a step change in rf current phase (upper trace) for zero loading angle with 400 mA beam.

Since there is a substantial power loss to beam, the estimated loaded Q is now ~6x10^4. Therefore, the 3 dB bandwidth is ~8 kHz. The cavity will be operating at 1.6 MV, synchrotron oscillation frequency will be at 37.8 kHz. Based on these results, beam manipulation in longitudinal phase with gap voltage modulation at synchrotron frequency or its harmonics will only be possible at very small magnitude. Figure 7 show the response of the SRF cavity with respect to 1 radian phase modulation at synchrotron oscillation frequency. It is interesting to note that the modulation in cavity amplitude is much stronger than cavity phase modulation.

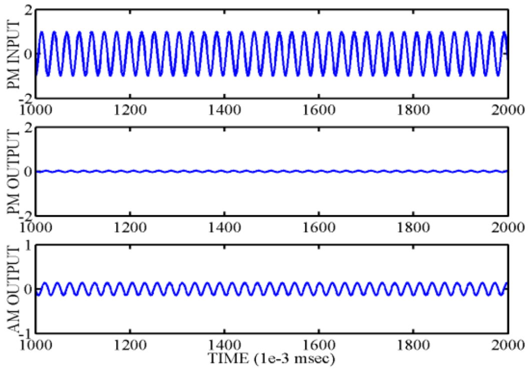

Figure 7: Change in cavity voltage phase (middle trace) and amplitude (lower trace) in response to a sinusoidal phase modulation in rf current (upper trace) for zero loading angle with 400 mA beam.

4 CONCLUSION AND DISCUSSION

Study of beam loading effects for operating SRF cavity in the 400 mA TLS storage ring has been carried out. Analysis of steady state beam loading suggests that at -0° loading angle, modified synchronous phase is ~4°. Such value is too close to the stability margin. Detune the cavity for Robinson damping is a common practice to stabilize the beam with the expense of rf power. This suggest the needs for some feedback circuit to for beam loading control. A direct rf feedback circuit which may be installed in the rf system is being tested for beam loading compensation [5].Dynamic response of the SRF cavity with and without beam loading has been simulated using SIMULINK. Simulation results show that a heavily loaded SRF cavity in our case can has a response time of a few tens of µsec but still too slow for gap voltage amplitude or phase modulation at synchrotron frequency and its harmonics. In such simulations, the beam phase feedback to the cavity model is neglected. A complete beam-cavity interaction model is being studied. More simulation works such as multi-bunch tracking have to be done for providing information of beam gap transient etc.

5 REFERENCES

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