

TRANSIENT BEAM LOADING IN THE SLC DAMPING RINGS*

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Abstract

Effects arising from heavy beam loading in the Stanford Linear Collider (SLC) Damping Rings are described. The stability of the rf system and particle beam is studied using a numerical model of the beam cavity interaction with multiple feedback loops. Nonlinearities of the power source are also considered. The effects of beam-induced transients and intensity jitter on the rf system are analyzed and used to determine stability tolerances for both high current and low current pulses.

I. INTRODUCTION

When a particle beam is injected into or extracted from a circular accelerator, beam-induced electromagnetic fields cause the accelerating cavity voltage to oscillate at the synchrotron frequency. For fast cycling storage rings like the SLC damping rings, the magnitude of these oscillations depends on the time between extraction and injection of beam pulses, the cavity fill time, and on the beam current. At the SLC where the single bunch beam current was increased by 20% for the recent run, transient loading occasionally caused rf system and beam instabilities. To better understand the sources of these instabilities, simulations^{1,2} were performed using Matrix_x³, a program developed for the analysis of dynamic stability. The simulations included a detailed model² of the rf system for which a block diagram is shown in Fig. 1.

II. TRANSIENT BEAM LOADING

Large oscillations in the cavity voltages induced by injection of a high current beam in the SLC damping rings resulted in substantial beam losses⁴, which were reduced using direct rf feedback⁵. Figure 2 shows simulation results with direct rf feedback (open loop gain $H = 6$) and without. With feedback, the cavity fill time is reduced by $1 + H$. The cavity therefore responds quickly to the voltage and phase errors resulting from the absence of beam. Residual oscillations still persist however because the klystron is saturated when the beam is injected.

A second problem during operation was poor regulation of the cavity voltage. Loss of regulation can result from beam-induced transients: if the klystron input power is not properly limited, there exist two solutions for the feedback loops. One solution, on the rising edge of the klystron power curve is stable. The other, beyond saturation, is unstable. Simulation results are shown in Fig. 3 (compare

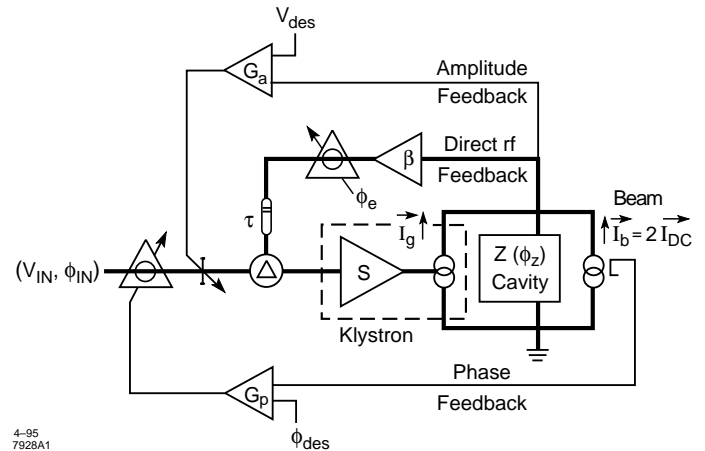


Figure 1. Circuit model of a beam loaded rf system including amplitude, phase, and direct rf feedback. The thick solid lines indicate paths for phasors which have both an amplitude and phase.

with experimental data in Ref. 4). At each beam current, the tuning angle was adjusted to maintain a zero loading angle, $\phi_l = 0$, in the steady state with beam. At high beam current more power is required in the steady state and the small signal gain approaches zero; just below saturation, any change in the klystron input power produces little effect on the output power. At high beam current the klystron is unable to return to a condition of positive small signal gain and the cavity voltage is not maintained as a result.

Intensity fluctuations of the incoming beam are considered tolerable provided the rf cavity voltage can regulate. For a fast cycling storage ring with a store time much smaller than the bandwidth of the tuner feedback loops, the effect of injecting a pulse of different current is a change in the steady state loading angle ϕ_l . This in turn requires more klystron power. As discussed previously, the rf system is stable provided that the combined effects of the transients induced by extraction and injection of the beam are such that the klystron returns to a state of positive small signal gain.

III. STABILITY TOLERANCES

The percentage tolerable current jitter $|\frac{\delta I_b}{I_b}|$ as a function of I_b when $\phi_l = 0$ is plotted in Fig. 4. In these simulations the steady state current I_b is extracted, and a new pulse of current $\delta I_b + I_b$ is injected. The rf system is easily able to regulate for large fluctuations in the beam current except at the highest currents. With $I_b = 0.20$ A for example, the rf system would remain stable if a subsequent pulse of

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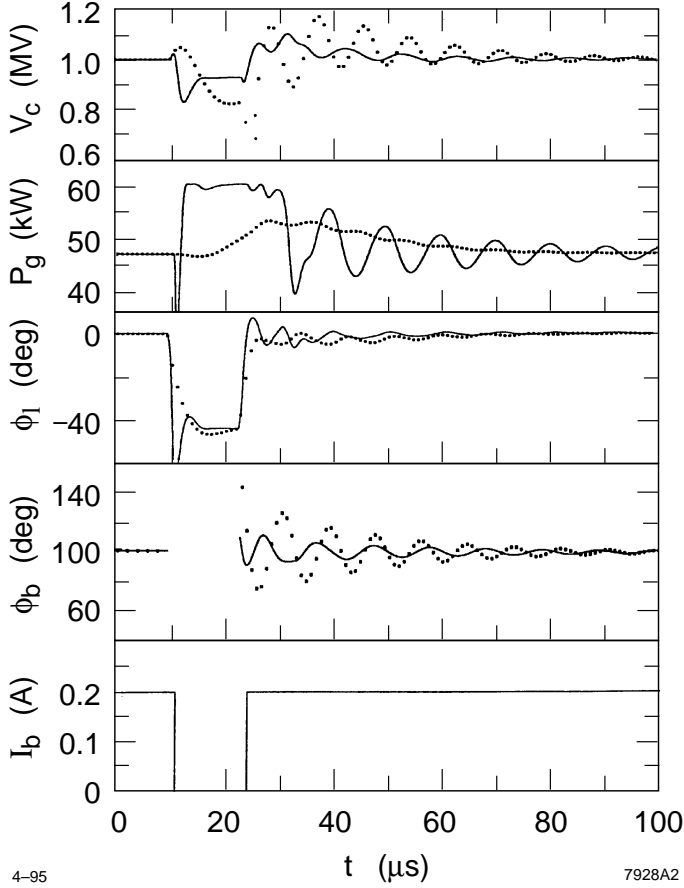


Figure 2. Simulations of transient beam loading. The cavity voltage V_c , the klystron output power P_g , the loading angle ϕ_l , the beam phase ϕ_b , and current I_b are plotted as a function of time for a direct rf feedback open loop gain of $H = 0$ (dotted curves) and $H = 6$ (solid curves).

40% above nominal, or 0.28 A, were injected into the ring. The vertical line at $I_b = I_m$, however, indicates a hard limit due to a missing pulse. With $I_b > I_m$ the klystron is driven towards saturation when the beam is absent. A subsequent pulse may then experience an arbitrary cavity voltage. The time required for the system to become stable depends on the response time of the slow tuner feedback loops and on the output of low level amplifiers which may limit the maximum klystron input power. This hard limit presents a strict limit on the maximum current. At the SLC with a cavity voltage of 1 MV, a 60 kW maximum klystron output power, and the cavities tuned to $\phi_l = 0$, stability against missing pulses is ensured for $I_b < 0.16$ A. To accommodate 0.22 A rf currents for the 1994 run, the available operating region was expanded by lowering the rf gap voltage from 1 MV to 800 kV.

The parameter space for voltage regulation in the steady state is shown in Fig. 5 for the rf operating conditions of the past 3 years. The solid curve is an analytic result⁶ for the contour of constant klystron power at the indicated power and cavity voltage. The small circles are simulation² results using a nonlinear klystron and a power limiter. The large dots indicate the operating current and tuning angle.

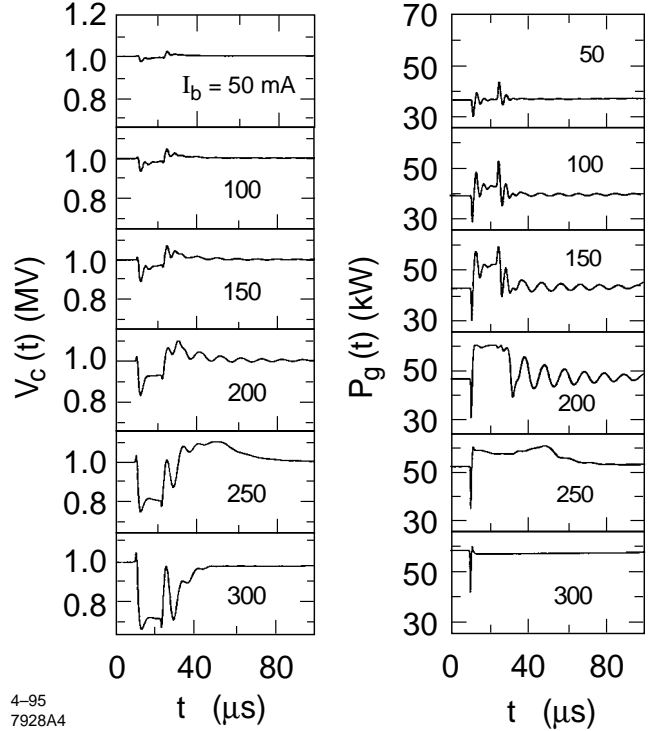


Figure 3. Transient beam loading as a function of I_b with $\phi_l = 0$ in the steady state.

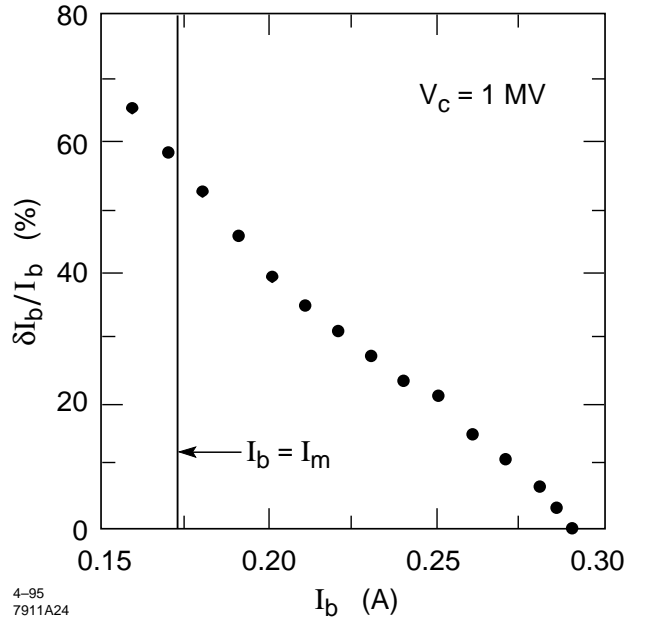


Figure 4. Tolerable current jitter $\frac{\delta I_b}{I_b}$ as a function of nominal current I_b with $\phi_l = 0$ in the steady state.

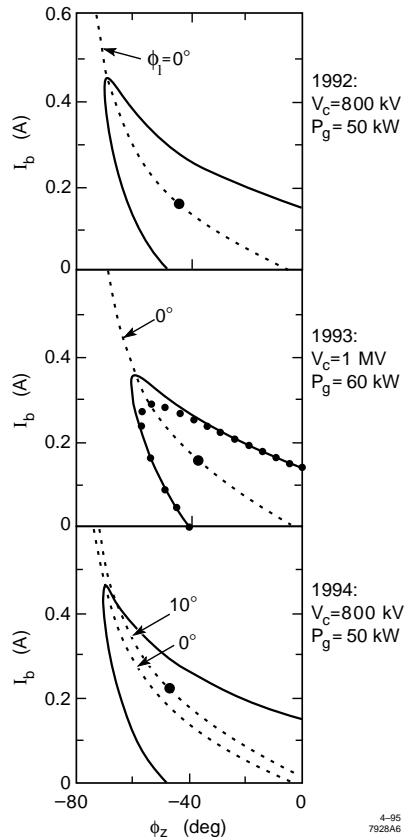


Figure 5. Parameter space for voltage regulation for SLC damping ring parameters for the past 3 years.

In general, the highest beam currents are obtainable for $\phi_l = 0$. The limitation due to low current or missing pulses is representable by a vertical line intersecting the contour of maximum klystron output power and $I_b = 0$. If not properly compensated, the rf system can be unstable for operation to the left of this line. Alternatively, the performance requirements of the klystron can be specified using this analysis⁶.

A. Cavity Detuning

Provided that the additional power reflected from the cavities is absorbed in an isolator between the cavities and klystron, intentional detuning ($\phi_l \neq 0$) is advantageous for two reasons. First, it provides stability against beam-induced transients as shown in Fig. 6. Notice that the peak-to-peak amplitude of the voltage oscillations is largest for $\phi_l = 0$. This is due to the large difference in the klystron output power in the steady state and in saturation. Second, cavity detuning may be used to relax the hard limit from low current or missing pulses as evidenced by the change (see Fig. 5) in operating point, from $\phi_l = 0$ to $\phi_l = 10^\circ$, for the 1994 run.

B. RF Conditioning

To achieve higher beam currents for the same maximum klystron output power and cavity voltage, the klystron

must be made to operate more efficiently; the hard limit due to missing pulses or absence of beam must be overcome. This can be accomplished by changing the voltage and phase references to the direct rf feedback loop. The required changes are calculable⁶. In practice, with a power limited klystron, the amount by which to lower the voltage reference would be to that value for which the control voltage from the amplitude feedback loop is unchanged by the change in beam current at injection. The amount by which to change the phase reference would be to minimize the change in the cavity voltage phase angle.

IV. CONCLUSION

Simulation results were used to explain performance and performance limits and to suggest changes that could be made. At the SLC, rf system and beam instabilities were shown to result from the interaction of rf feedback loops and a power limited klystron. Rf conditioning was suggested for future operations at even higher beam currents.

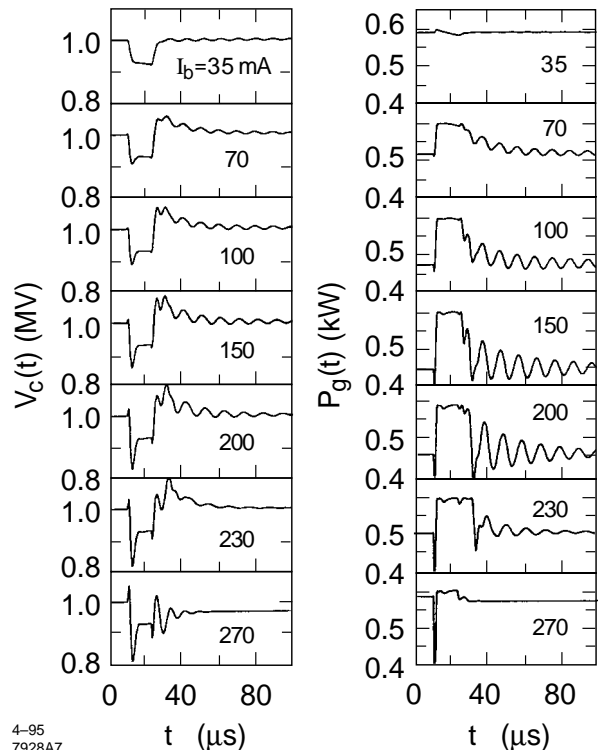


Figure 6. Transient beam loading as a function of I_b with $\phi_z = -45^\circ$ in the steady state.

References

- [1] M.G. Minty *et al*, Proc. 1993 PAC 2373.
- [2] M. G. Minty, R.H. Siemann, "Heavy Beam Loading in Storage Ring RF Systems", to be submitted to Nucl. Instr. and Methods.
- [3] Matrix_x by Integrated System, Santa Clara, CA 95054.
- [4] M. G. Minty, et al., WAB12 1995 PAC.
- [5] F. Pederson, *IEEE Tran. on Nucl. Sci.*, NS-32, No. 3 (1985) 2138.

[6] M.G. Minty, R. H. Siemann, TPA09 1995 PAC.