

Low-Level RF System Design for the Next Linear Collider Damping Ring

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Abstract

The design current for the Next Linear Collider (NLC) damping rings is an order of magnitude higher than existing damping rings. As opposed to storage rings, damping rings are required to operate at a high repetition frequency. Transient beam loading is therefore particularly severe. The NLC design [1] calls for a full current fill pattern consisting of up to 4 trains of 90 bunches for a total dc current of 1.2 A. However, using conventional filling techniques, with a rapid current ramp the ring energy acceptance could decrease due to transient loading and the beam might not be captured. In this paper we describe two features of the low-level rf system design. The first avoids any reduction of duty cycle while the second ensures beam capture and regulation of the cavity voltages and beam phase.

1 INTRODUCTION

A critical requirement of the NLC damping ring rf system design is to maintain a high duty cycle (i.e. the damping ring should not limit the repetition frequency). There are three sensible schemes for injecting to full current. The usual approach uses the tuner feedback loops to compensate for detuning caused by the beam. Because conventional tuner movers are slow, however, rapid injection to full current is not possible. The second option involves minimizing the total reflected power by presetting the tuning angle ϕ_z prior to injection of each train such that the loading angle ϕ_l is zero after the train is injected. This scheme is required if the total klystron is power limited [2], but is also slow due to the tuner bandwidth. A faster technique involves one preset of the tuners to ϕ_z^* , which is the tuning angle for zero loading angle at full current, followed by consecutive injection of all bunch trains. Since the reflected power may be substantial, particularly during initial detuning without beam, the magic tee and circulator loads must be designed to absorb high power levels. In the interest of maintaining a high duty cycle the fast injection scheme has been studied for the NLC.

2 HIGH DUTY-CYCLE INJECTION

Simulations have shown that both with and without the tuner preset, the NLC damping ring could not be ramped to full current: the impulse change to the cavity voltage caused by injection of a high current pulse train caused enormous cavity voltage and beam phase oscillations. To correct this problem, direct feedback [3] was considered for correcting these beam-induced transients. However, there are a number of disadvantages introduced by the loop:

- the required gain places a tight tolerance on the total delay (less than 210 ns for an open loop gain of 2.5 for

the NLC damping ring) and hence on the delay time in the klystron,

- the required gain may introduce coupled bunch modes that could be supported by the cavity, and
- because the transient is corrected *after* it is detected, residual cavity voltage and beam phase oscillations still persist.

Alternatively, the cavity phase and amplitude may be 'preconditioned' [4] based on knowledge of the incoming charge. Preconditioning is similar to feed-forward, however the incoming charge is *anticipated* rather than measured. In either case, the total cavity current, cavity voltage, and the phase angle between them are held constant during the injection process.

The principle of the injection procedure involves presetting the external references for the cavity voltage V_{ref} and for the input rf phase ϕ_{ref} such that the cavity voltage is unchanged in phase and amplitude at injection. The required preset of the reference voltage is $\Delta V_{ref} = S\Delta I_g$ where S is the transconductance of the klystron and I_g is the generator current:

$$\Delta I_g = \frac{V_c/R + I_b^k \cos \phi_b^k}{\cos \phi_b^k} - \frac{V_c/R + I_b^{k+1} \cos \phi_b^{k+1}}{\cos \phi_b^{k+1}}, \quad (1)$$

where V_c is the total cavity voltage (which is the vector sum of the generator and beam voltages), R is the total, loaded cavity shunt impedance, I_b^k is twice the dc beam current for train k , and $\phi_b(k)$ is the synchronous phase angle (measured with respect to the crest of the cavity voltage) with k trains.

The preset for the reference phase is given by

$$\begin{aligned} \Delta \phi_{ref} &= \tan^{-1} \left[\frac{\tan \phi_z^* + \frac{I_b^k R}{V_c} \sin \phi_b^k}{1 + \frac{I_b^k R}{V_c} \cos \phi_b^k} \right] \\ &- \tan^{-1} \left[\frac{\tan \phi_z^* + \frac{I_b^{k+1} R}{V_c} \sin \phi_b^{k+1}}{1 + \frac{I_b^{k+1} R}{V_c} \cos \phi_b^{k+1}} \right]. \end{aligned} \quad (2)$$

Here ϕ_z^* is the tuning angle for at maximum current I_m and desired loading angle ϕ_l at maximum current:

$$\tan \phi_z^* = \left(1 + \frac{I_m R}{V_c} \cos \phi_b \right) \tan \phi_l - \frac{I_m R}{V_c} \sin \phi_b. \quad (3)$$

Typically the loading angle is zero at maximum current so

$$\phi_z^* = \tan^{-1} \left(\frac{I_m R}{V_c} \sin \phi_b \right). \quad (4)$$

The steady-state phasor diagram for the injection process is shown in Fig. 1. Here I_c is the total cavity current, and

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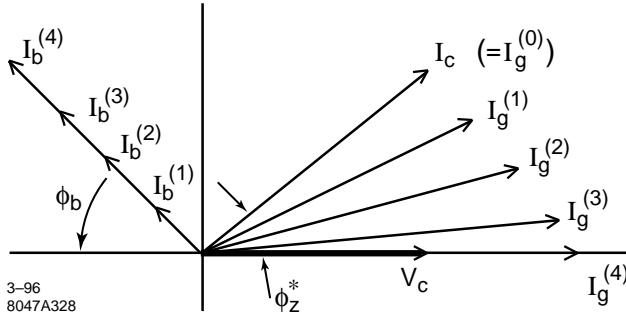


Figure 1: Phasor diagrams for injection. The superscripts (1) through (4) refers to the total number of bunches in the damping ring.

I_b^k and I_g^k are respectively the beam and generator currents for train k . The total cavity voltage V_c and total cavity current I_c have contributions from both the beam and the power generator. By presetting the rf amplitude and phase at injection of each bunch train, V_c and I_c are constant for all bunch trains. As shown in Fig. 1, the cavity tuners are preset to ϕ_z^* to allow for rapid injection of all bunch trains. The loading angle ϕ_l decreases from $\phi_l = \phi_z^*$ with no beam to $\phi_l = 0$ at full current. The time required to reach the steady-state condition depicted is minimized by presetting the rf amplitude and phase (see Eqs. (1) and (2)) at injection of each bunch train.

The procedure for ramping to full current is:

1. With beam off, deactivate the tuner loops and detune for $\phi_l = 0$ at maximum current; that is, set the tuner position to ϕ_z^* (see Eq. 4).
2. Set the external references $V_{ref} = SI_g$ for the desired cavity voltage
3. Inject train 1.
4. Increment V_{ref} by $\Delta V_{ref} = S\Delta I_g$ and ϕ_{ref} by $\Delta\phi_{ref}$ and inject train 2.
5. Repeat step 4 until all trains have been injected.
6. Reactivate tuner loops.

This procedure could be executed at maximum duty cycle so that the total time for injection of n trains is n cycles, or 22.2 ms at 180 Hz for 4 bunch trains in the NLC damping rings.

In practice, recovery from no beam to full current would require at least 12 cycles (66.7 ms at 180 Hz) due to limitations imposed by the machine protection system (MPS). The envisioned startup sequence [1] is as follows: inject 4 single bunch trains, inject 4 trains of 10 bunches, and inject 4 trains of 90 bunches. Startup procedures under these conditions are given in detail in Ref. [1] for initial commissioning and MPS-compatible injection to full current.

3 SIMULATIONS OF THE HIGH CURRENT RAMP

Numerical simulations were performed using a model containing two (linear) klystrons, two rf cavities, and various feedback loops including realistic nonlinear elements such as time delays and filters. At present the cavity is modeled as a narrow-band resonator so that only beam interactions

with the fundamental cavity mode are analyzed. The simulated response of the cavity voltage and beam phase to the injection of the first train is shown in Fig. 2 for three cases: no transient loading compensation (solid), correction with direct feedback using a loop gain of 2.5 (dot-dashed), and correction with presets (dashed, almost flat). The results are summarized in Fig. 3 in which the peak-to-peak cavity voltage and phase oscillations are plotted as a function of train number using direct feedback or using presets. As can be seen, the correction of the beam-transients is substantially improved (by more than a factor of 10) with the rf amplitude and phase presets.

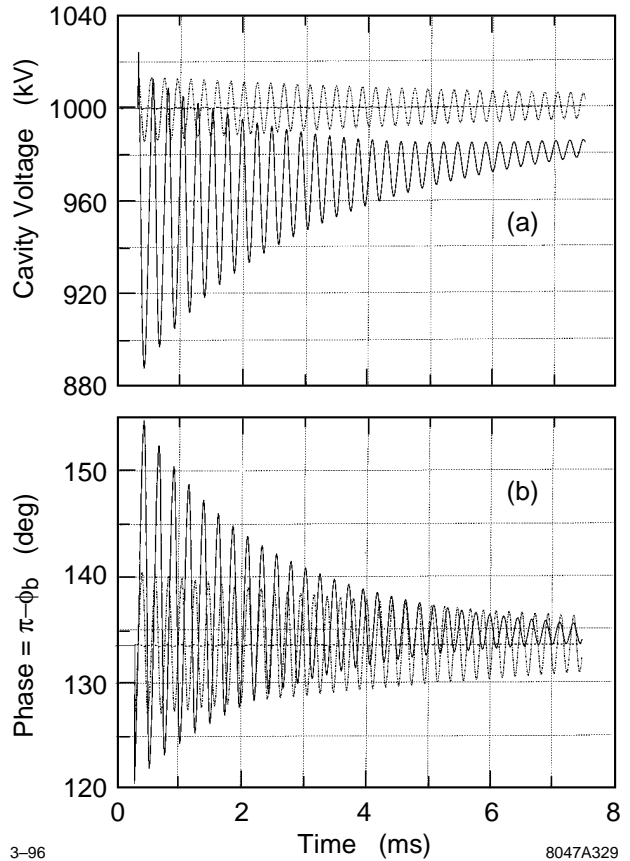


Figure 2: Simulations of injection transients in the cavity voltage (a) and beam phase (b) at injection of the first 0.6A train. There are three curves: uncorrected (largest oscillations), correction with direct feedback (intermediate oscillations), and correction with presetting the rf amplitude and phase (essentially flat).

In Fig. 4 is shown simulation results for the injection procedure outlined above for a zero to full current ramp. The cavity voltage and beam phase preset references as calculated from Eq. (1) and (2) are also shown along with the required generator and reflected powers. Notice that the Robinson damping time is shorter the higher the current. This is because of the fixed tuning angle. Also worth noting is the decrease in the coherent synchrotron oscillation frequency with current; as the beam current is increased the phase of the beam with respect to the generator crest

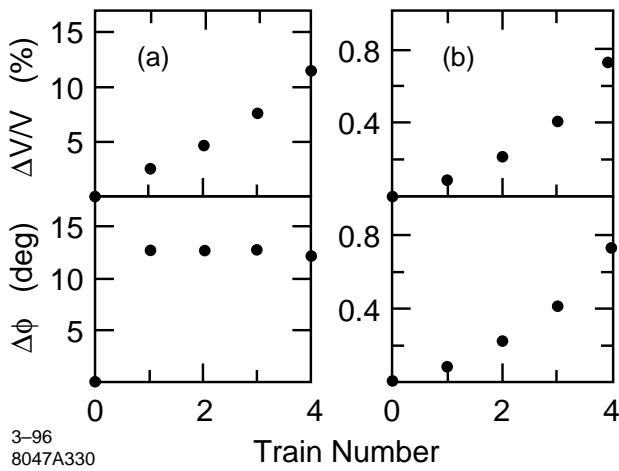


Figure 3: Simulated peak-to-peak variations in the cavity voltage and beam phase as a function of train number. The transients are corrected either with direct feedback (a) or with presets (b). Note the change in vertical scales.

becomes smaller resulting in a reduced restoring force for coherent phase perturbations.

A potential error associated with presetting the phase and amplitude is that the cavity voltage will be regulated to the specified value, V_{ref} ; if the incoming charge is of different current than anticipated, then the amplitude feedback loop would regulate to an incorrect voltage. Notice however that Eqs. (1)-(4) may be used in feed-forward, which would require a measurement of the incoming charge. Another complication arises from thermal heating in the accelerating cavities. Fortunately, the thermal time constant of the cavity is much longer than the time required for the current ramp.

4 SUMMARY

A simple technique is proposed which would allow the high duty-cycle required for the NLC damping ring. One complication is the power dissipation requirements in the circulators and magic tee loads. Fortunately, the total absorbed power is 4 times smaller that of the PEP-II [5] loads so it appears manageable. Superior cavity voltage and beam phase regulation was predicted by numerical simulations to result from using cavity voltage and rf phase presets (as opposed to using direct feedback). The preset scheme also has the advantage that no additional hardware is required to damp the coupled-bunch modes that would be introduced using direct feedback.

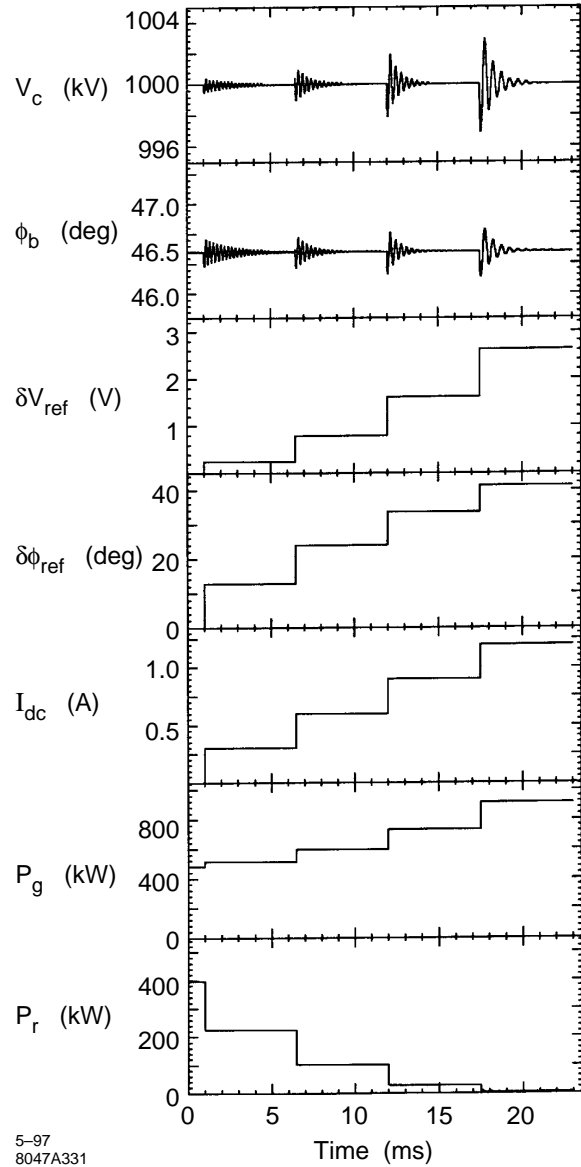
Acknowledgements

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Figure 4: Simulated current ramp from no beam to full current. Plotted are the cavity voltage V_c , the beam phase ϕ_b , the change in reference voltage δV_{ref} , the change in reference phase $\delta\phi_{ref}$, the dc beam current I_{dc} , the generator power P_g , and the reflected power P_r .