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in High Current Storage Rings**

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# Control of Coupled-Bunch Instabilities in High-Current Storage Rings\*

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## ABSTRACT

Intense particle beams may be subject to coupled-bunch instabilities that would grow at rates greater than the bunch oscillation frequencies. The suppression of this growth requires both reduction of the driving impedances and active feedback of bunch motions. The shunt impedances of higher-order cavity resonances can be reduced by passive dampers and the beam impedance within the band of the fundamental resonance can be reduced by rf feedback around the cavity and power amplifier. The feedback of bunch motions composed of numerous coupled-bunch modes requires broad-band systems for which the amplifiers are costly. Examples proposed for electron storage rings are presented.

## I. INTRODUCTION AND GENERAL RELATIONS

In the intense stored electron beams of light sources and large  $e^+e^-$  colliders, the strongest collective instabilities are expected to be the coupled-bunch (c.b.) motions. This is largely a response to the presence of strong rf systems needed to produce the many short intense bunches. Suppression of c.b. growth calls for both reduction of the normal resonant impedances of rf cavities and the provision of strong broadband feedback of longitudinal and transverse bunch motions.

The fact that the bunch length is usually much shorter than the wave length of the highest resonances below the beam tube cutoff frequency simplifies some relations. The effective driving voltages for the rigid-body motions, which grow most rapidly, are simply the voltages excited in high-Q resonators by the bunch motions. A longitudinal mode amplitude  $\Delta\phi_0$ , measured at  $f_{rf}$ , provides a cavity exciting current of

$$\tilde{I} = j I_0 \Delta\phi_0 f_{cb} / f_{rf} \quad (1)$$

where  $f_{rf}$  is the frequency of the accelerating voltage,  $f_{cb}$  is a synchrotron-sideband frequency for the mode, and  $I_0$  is the average current. This current will excite voltage  $V_{\parallel} = \tilde{I} R_{\parallel}$  in a resonator that has shunt impedance  $R_{\parallel}$  at the frequency  $f_{cb}$ . Similarly for the transverse case we have

$$V_{\perp} = I_0 k_{cb} x R_{\perp} \quad (2)$$

where  $V_{\perp}$  is the transverse voltage impulse from a resonator with transverse shunt impedance  $R_{\perp}$  ( $R_{\perp} = R_{\parallel} / (k_{cb} a)^2$ , e.g., as given by URMEL) when excited by a c.b. mode with amplitude  $x$ .  $k_{cb}$  is the wave number  $2\pi f_{cb}/c$ .

From these driving excitations, we find the growth rate for a given c.b. mode:

$$1/\tau_s = - \frac{I_0 f_0 \eta}{2f_s \beta^2 E/c} \sum f_{cb} R_{\parallel} R_{\perp} \quad (3)$$

$$\text{or } \frac{1}{\tau_s} = - \frac{I_0 f_0}{2\beta E/c} \sum B_{\perp} k_{cb} R_{\parallel} R_{\perp}$$

where the summation is of the real impedances of all resonators at  $+$  and  $-$  frequencies of the c.b. mode.

To damp the mode, we must reduce  $1/\tau$  to below the radiation damping rate by some combination of (1) reducing the shunt impedances, (2) tuning to avoid overlap of mode frequencies and resonator frequencies, or (3) active feedback to oppose  $V_{\parallel}$  or  $V_{\perp}$ .

The strongest resonators in the storage ring are usually the higher order modes (HOM) of the accelerating cavities. Example spectra of longitudinal resonances for accelerating cavities are shown in Fig. 1. The frequencies of c.b. modes are separated by about one half the orbital frequency  $f_0$ , so that if the ring is of small radius they are spaced sufficiently apart that it may be practical to tune to avoid coincidences between c.b. modes and HOMs. For large colliders or synchrotron radiation sources this is not practical and one must reduce impedances of the HOMs or use active feedback, or both.

## II. REDUCTION OF EXCITING IMPEDANCES

Considering the cost and complexity of components of a strong active feedback system, particularly the kickers and power amplifiers, the reduction of the shunt impedances of resonators is of great advantage. Moreover, it can be a necessity as a means of reducing the growth rates to the order of the bunch frequencies ( $f_s$  or  $f_0$ ) to avoid great sophistication if not infeasibility in the feedback design.

With the assumption that resistive damping can be provided for the HOMs, it is the values of  $R/Q$  of those modes in the basic cavity shape that is of importance. For cavities made of normal-conducting (NC) metal, such as copper, economy of rf power calls for a large value of  $R$  for the fundamental, accelerating mode; then one seeks a favorable ratio

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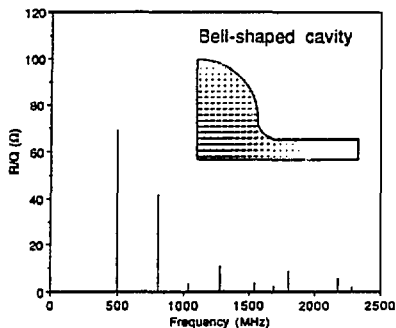


Fig. 1a.

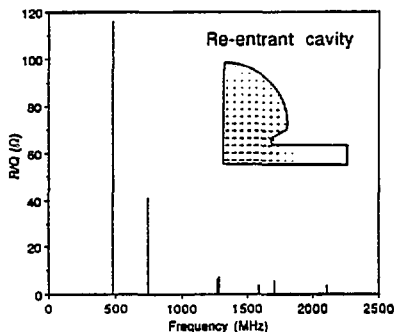


Fig. 1b.

Fig. 1 R/Q of resonances of two cavity shapes

of this to the R/Q's of HOMs. Fig. 1 compares the spectra of R/Q for cavities of closed or open configuration. We see that for the same bore diameter, as shown, the usual shape having nose cones is more favorable. This shape is chosen for the Advanced Light Source and the design of the SLAC/LBL/LLL B-Factor [1,2]. With larger bore, the number and strengths of the HOMs decrease but the power-efficiency of the cavity at the fundamental becomes uneconomically low. If the cavities are superconducting (SC), power cost is less important and the open shape is more suitable for other reasons. A large bore is the best choice for low R/Q of HOMs and best as a port for damping those modes. The value of R/Q may be as low as a few ohm. The open cavity is chosen for the design of a B-Factor at Cornell [3].

A waveguide attached to the cavity can couple to the HOMs and carry power to a terminating load. For damping of

all HOMs, the cutoff frequency of the waveguide should be between the fundamental and the lowest HOM. For calculating the performance of this method, Slater's analysis [4] has been used as adapted for c.m. field calculations by Kroll and Yu [5]. Fig. 2 shows a NC cavity with three attached waveguides. Computations for the first 4 modes yield Q-values in the range 12 to 64. This represents a reduction of  $> 1000$  over the undamped shunt impedances [1] and brings the c.b. growth rates well within the range of feasible and affordable feedback systems. The loss of impedance at the fundamental is about 10%. This arrangement of dampers has been modeled on a test pillbox and Q-values of  $< 37$  were measured [6] compared with 25 - 55 predicted. For the damping of SC cavities for a B-Factor [2], the scheme of Fig. 3 is proposed. The waveguide in this case is the enlarged bore tube with fluted walls leading to a resistive-surface load. Longitudinal Q-values of  $< 70$  are calculated. With this damping and the relatively strong radiation-damping from a 120 meter radius, the need for active damping would be greatly reduced or zero.

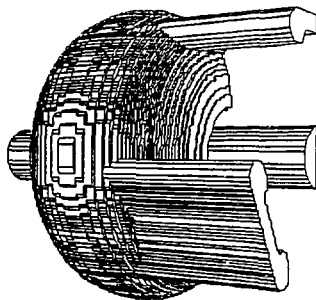


Fig. 2 One half of cavity with three damping waveguides

In a large ring with NC cavities, the low orbital frequency may bring the frequencies of longitudinal c.b. modes with low mode numbers within the response width of the fundamental cavity resonance. For the zero<sup>th</sup> (phase oscillation) mode this is always true and has commonly been stabilized by detuning the cavity so as to provide net (Robinson) damping by the shunt impedances at the mode frequencies  $f_{rf} \pm f_s$ . Other modes, at frequencies  $f_{rf} \pm mf_o \pm f_s$ , as shown in Fig. 4 are either damped or driven depending upon their positions on the rf resonance curve. Not only can this net driving impedance be greater than that from the typical HOM, but as part of the fundamental cavity resonance, it must not be resistively damped. However, the shunt impedance seen by the beam can

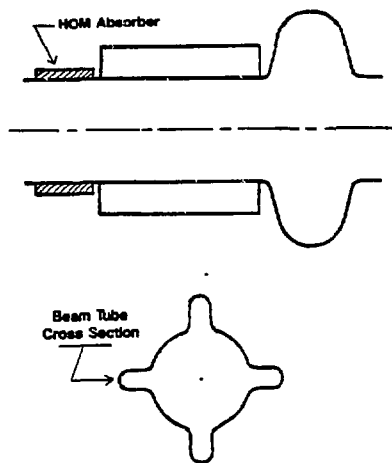


Fig. 3 Superconducting cavity with damping through beam tube

be reduced by active feedback of the rf around the cavity and power amplifier [7]. The degree of impedance reduction available from such a technique is limited by the unavoidable time delay of elements in the feedback loop, notably the power amplifier, which may amount to hundreds of nanoseconds. Feedback stability analysis of such a circuit for the B-Factor rf system has predicted a possible reduction of  $R_{||}$  of a factor 10. A comb filter added in the rf loop allows greater loop gain at the harmonics of  $f_0$ ; studies indicate that this scheme may further reduce the impedance, at least to the point where the net excitation is comparable to that of a damped HOM [8].

### III. FEEDBACK OF COUPLED-BUNCH MOTION

Cancellation of the residual c.b. excitation after reduction of the driving impedances is done by active feedback that provides voltage kicks to cancel the resonator voltages  $iR$ . This view suggests the use of narrow-band feedback at the mode frequency, i.e. mode-to-voltage kick. But we note that stable and unstable mode frequencies arise closely spaced at the sides of harmonics of  $f_0$  and therefore narrow filters are needed to avoid positive feedback. Nevertheless, this mode-by-mode feedback has been the method of choice for those cases where only a few identifiable c.b. modes are growing. The narrow-band feedback in this case permits the use of efficient narrow bandwidth electronics and kickers and hence, minimum cost.

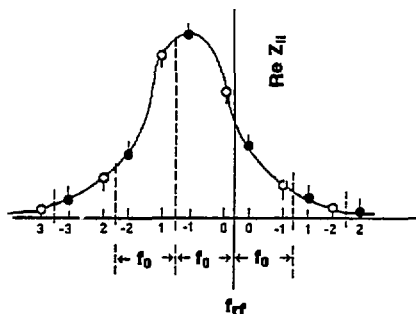


Fig. 4 Coupled-bunch modes within detuned resonance curve of fundamental

In the case of a large, high current ring, many modes may grow and the economics of a few narrow band channels is not available. A single HOM that has been broadened by damping can drive about 100 c.b. modes. The alternative to hundreds of circuits tuned to c.b. modes is the bunch-by-bunch system in which signals from individual bunch motions are kept separate in time and feed back to those same bunches after one or more turns delay. To address in this way  $M$  bunches circulating at rate  $f_0$  requires a bandwidth of at least  $1/2 M f_0$ . (Note that this same bandwidth would be required of the output stage of a mode-by-mode system that could feed back signals from a substantial fraction of the possible  $M$  modes.) It is the sensible and economic design of the single-bunch detection system, processing circuits, and output stages that is the challenge.

The gain that is required is straight forward to define for a given, expected shunt impedance  $R$ . One calculates the mode current  $I$  for a given mode amplitude and provides a kick  $V \geq iR$ . And in the absence of noise, gain is no problem to provide. In contrast, the output kicker power is costly and depends upon the initial mode amplitude one needs to overcome. The kicker power is

$$P = V^2/2 R_k = I^2 R^2/2 R_k$$

where  $R_k$  is the combined shunt impedance of the kicker or array of kickers to be powered.

For perspective, we can estimate the power and its cost for some sample parameters. A typical single longitudinal kicker has  $R_k \Delta f \approx 100$  ohm and for specific example parameters we may choose for a large ring with NC cavities:

$$\begin{aligned} R_{||} &= 20 \text{ k}\Omega \text{ for one HOM in 10 cavities at } 2 \text{ k}\Omega \text{ each.} \\ f_{c,b}/f_{rf} &= 2 \text{ at the HOM } (\sim 1000 \text{ MHz}) \\ \Delta \phi_0 &= 10 \text{ psec at } 500 \text{ MHz} = 0.03 \text{ radian c.b. amplitude} \\ I_0 &= 1 \text{ ampere average current} \\ \Delta f/f &= 1/2 \text{ at } \sim f_{rf} \end{aligned}$$

Then

$$\dot{I} = (1)(0.03)(2) = 0.06 \text{ A}$$

$$P = 1/2 (0.06)^2 (20,000)^2 / 200 = 3.6 \text{ kW}$$

At \$150 per watt the power amplifier costs 0.5 MS. These numbers point out the importance of the initial amplitude that must be suppressed and the driving shunt impedance.

In operation, once the feedback has suppressed the c. b. motions, power demands should be very low. It is the oscillations of the injected beam and possible transients that are the most demanding. If the full ring current were injected in a time short compared to the c. b. damping rate with feedback, very large power could be demanded. Therefore it is worthwhile to damp beam as it is injected over many damping periods. Even then, a few bunches that have large excursions can readily call for large power from a broadband system. Here we note that perhaps only one tenth of the c. b. modes are unstable and hence not every frequency component in a few-bunch disturbance must be strongly damped. In the bunch-by-bunch scheme, tolerance for large local oscillations is provided by a design for controlled limiting of the output beyond a specified maximum. This non-linear behavior is most convincingly studied by numerical simulation; this has been carried out in the case of the B-Factor.

The components and parameters for longitudinal damping in the B-Factor at SLAC illustrate a bunch-by-bunch system. Transverse feedback is similar and usually less difficult and less costly.

Table 1 Parameters of B-Factor at SLAC

E	=	9.0 GeV electron energy
I <sub>0</sub>	=	1.48 ampere average current
M	=	1746 (less 5% gap = 1658 bunches)
f <sub>rf</sub>	=	476 MHz = 2x bunch rate
f <sub>0</sub>	=	136 KHz orbital frequency
f <sub>s</sub>	=	7 KHz synchrotron frequency
f <sub>cb</sub>	=	750 MHz for strongest HOM (TM011)
R <sub>  </sub>	=	27 MΩ without dampers
	=	57 KΩ after damping to Q = 70
τ	=	18.5 msec from radiation damping
	=	0.04 msec growth time with full R <sub>  </sub>
	=	5.1 msec growth time with reduced R <sub>  </sub>
Δφ	=	0.44 radian error in 1/5 bunch injected at 60 Hz rate
Δφ <sub>0</sub>	=	0.03 radian maximum amplitude of controllable c. b. osc.

The pickup electrode produces an 8-cycle burst at 2856 MHz from each passing bunch. This signal is the combined pulses from an array of 8 short pickups. A phase detector has been built that at this frequency can measure the phase of each bunch with ≤ 0.5 degree resolution at 476 MHz.[9] These signals are processed, delayed, and amplified by the power amplifier to drive the kicker structures.

Four kickers are used, each consisting of four drift tubes connected in series by half-wave delay lines. This provides a combined shunt impedance of  $R_k = 4 \times 1600 = 6400 \text{ ohm}$  and a bandwidth of 200 MHz at 1.07 GHz. Installed kicker power is 2KW, 1.25 of which is nominally needed to provide kicks that are limited at 4 KV/turn. Although each injected charge is small, its error would, if response were linear, call for 12 KV per turn. The performance of the amplitude-limited feedback at injection as calculated by a simulation program [10] is shown in Fig. 5.

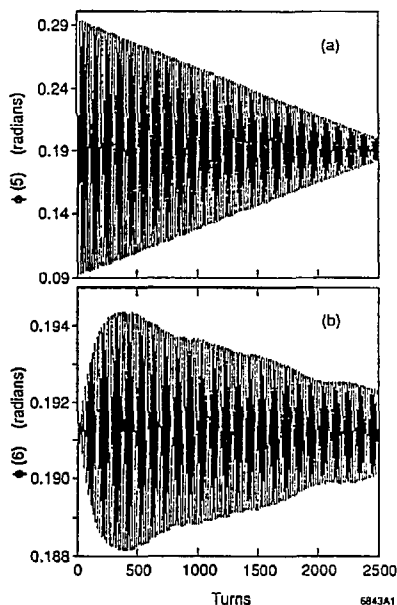


Fig. 5. Calculated phases of (a) a bunch injected with 0.1 radian effect and (b) the next following bunch (expanded scale) with damping by an amplitude-limited feedback

#### IV. SUMMARY

The damping of HOMS of accelerating cavities is necessary as part of systems to stabilize c. b. oscillations in new electron storage rings. Methods for this damping have been demonstrated in low-power cavities. Fast bunch-by-bunch feedback is possible and well suited for rings with many unstable c. b. modes. In that application it can damp disturbances from injection, noises, and beam-beam interactions as well as suppressing c. b. motion.

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