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PEP II: RF and Feedback R&D*

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ABSTRACT

The key elements of the PEP II approach to dealing with the problem of coupled-bunch instabilities are presented. The approach involves using warm copper RF cavities with damping waveguides (above the cutoff of the fundamental) attached to the cavity walls. These couple out the troublesome higher-order modes (HOMs) into absorbing loads, while the fundamental mode remains in the cavity. The Q of the worst HOM is reduced to below 70. Instabilities due to residual coupling are damped using a bunch-by-bunch feedback system, which is implemented using digital signal processors. A prototype cavity has been built and the concept of HOM damping has been verified. A prototype feedback system has been built and tested at SPEAR. Results to date indicate that the combination of damped cavities and bunch-by-bunch feedback provide a very effective means of dealing with the problem.

All future high-luminosity e^+e^- colliding beam machines or high current single beam machines (light sources) will have to contend with the problem of coupled-bunch instabilities. In PEP II, the beam will be made up of 1658 bunches, each of which will execute oscillations in energy. These oscillators are coupled through the large cavity impedance, causing the beam to behave like a system of 1658 coupled harmonic oscillators with 1658 modes of oscillation. Some of these modes are unstable and cause the energy of the particles to diverge from the design energy. This causes them to follow different orbits and eventually results in beam loss. In the sections to follow, we give an elementary description of the techniques used to damp these coupled-bunch instabilities in PEP II. The problem is tackled in two stages: careful RF cavity design reduces the cavity impedance by reducing the Qs of the dangerous HOMs via damping waveguides; bunch-by-bunch feedback using digital signal processing is used to damp out any oscillations due to residual coupling.

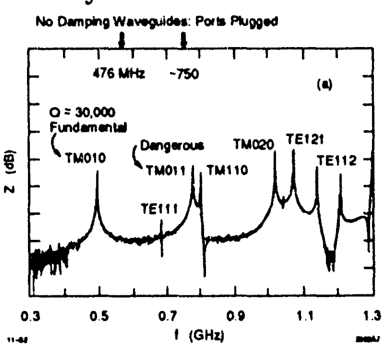

Figure 1. Undamped low power RF cavity impedance.

1. PEP II Damped-RF Cavity

In PEP II, the impedance seen by the beam is dominated by that of the RF cavities, so their design is critical from the point of view of coupled-bunch instabilities.[1] To minimize coupling, we would like to keep this impedance down to a minimum. Figure 1 shows the impedance of a low-power prototype of the copper cavities proposed for PEP II, before steps were taken to

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reduce it. It is important to keep the peak at the fundamental at the RF frequency of 476 kHz large, since we would like a large response at the RF driving frequency. However, we note that in addition to the peak due to the fundamental, there are peaks due to higher-order modes (HOMs). Roughly speaking, if some of the unstable modes of the beam happen to land on the resonances of the cavity (and at PEP II they will— the ones marked as dangerous), they will lead to instabilities. It is therefore desirable to keep the impedances due to the HOMs as small as possible.

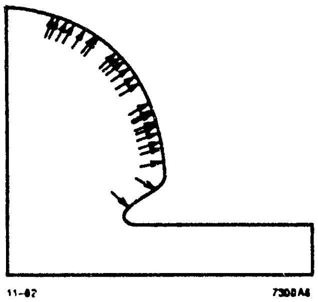

Figure 2. Undamped low power RF cavity impedance.

Figure 2 shows a cross-section of the cavity. CAD tools (MAFIA, URMEL) were used to identify the points along the wall that correspond to points of zero field for the various modes. This suggested the following strategy for lowering the impedance. Damping waveguides with cutoff above the fundamental were attached to the cavity walls in the region where none of the HOMs had zeros. The HOMs couple to these and dissipate their energy in loads at the ends of the waveguides. This technique has turned out to be very effective. Figure 3 is a plot of the modified-prototype, damped-cavity impedance.

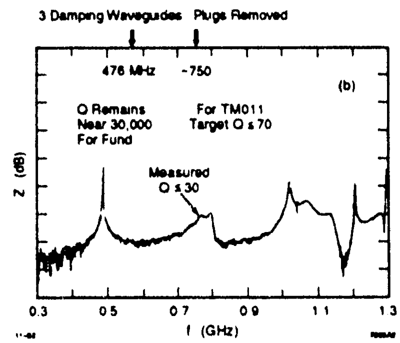

Figure 3. Damped low power RF cavity impedace.

The Qs of the dangerous HOMs have been substantially reduced, the worst by 3 orders of magnitude down to a Q of below 70. This is sufficiently low that the residual oscillations driven by the HOMs can be damped using the feedback system described below.

3. The Feedback System

We now describe how the oscillations due to residual coupling can be damped using the feedback system. We focus mainly on the damping of longitudinal oscillations, the more challenging problem.

The PEP II longitudinal-oscillations feedback system adopts the time domain approach to damping the energy oscillations ϵ. Each bunch is treated as an individual, damped, simple-harmonic oscillator which obeys:

$$\ddot{\epsilon} + \gamma \dot{\epsilon} + \omega_n^2 \epsilon = \frac{1}{T} \dot{u}(t) \tag{1}$$

where γ is the natural damping, ω_n^2 is the natural (synchrotron) frequency, T is the revolution time and u(t) is the unknown driving disturbance which has units of energy. Effects such as noise and driving terms from other bunches are all lumped into the unknown disturbance u(t). The idea behind the time-domain approach to feedback is to change the dynamics of each bunch individually by effectively increasing its damping term γ. An important feature of this approach is that the feedback will act to damp any disturbance to the bunch, since no assumptions have been made about the nature of the driving term.

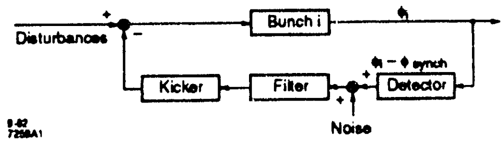

Figure 4. A schematic diagram of the bunch-by-bunch feedback scheme.

Figure 4 shows how this is done in practice. The bunch phase is detected and filtered to obtain the feedback correction signal, which is then applied as an energy kick via the kicker when the bunch passes through it. Since we are detecting phase and feeding back on energy, the required feedback signal should be proportional to the amplitude of the phase oscillations but shifted in phase by 90 degrees. This must be done for all the 1658 bunches in parallel. Thus each bunch sees a feedback loop around it of the type shown in Fig. 4. The filtering in Fig. 4 will be carried out by digital signal processors (DSPs). The prograınmmable nature of these DSPs makes the feedback system versatile and will allow its use on other machines as well.

The 4.2-ns bunch spacing at PEP II places very high bandwidth requirements on the feedback system. Wideband pickups for detection of phase and a prototype wideband kicker required to deliver the feedback signals have been built and tested [1, 2]. In addition to this, the technique of downsampling [3] has been used to reduce the amount of processing required for the DSPs to compute the feedback signals. In the following section we describe a recent experiment in which some of these feedback concepts and techniques were tested.

4. The SPEAR Experiment

The SPEAR experiment was a proof-of-principle demonstration of a one-channel, prototype feedback system. The performance of the wideband detector, the digital filter algorithm used in the DSPs, and the technique of downsampling were also evaluated, but we will concentrate on the main results here. The objective was to test whether, and to what extent, it was possible to damp the energy oscillations of a single-bunch beam with a single-channel feedback system.

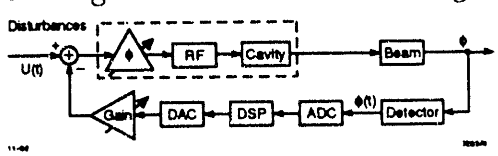

Figure 5. Experimental setup at SPEAR.

Figure 5 shows the experimental setup used at SPEAR. Since no wideband kicker was available at SPEAR, the feedback energy kicks were delivered to the beam by phase modulating the RF voltage. Figure 6 shows the transfer function from u to ϕ for various levels of gain in the feedback loop. With the 28 dB gain, the open-loop Q of 200 was reduced to a closed-loop Q of 5. Moreover, time-domain measurements have shown that the oscillations were damped down to the order of one count on the ADC, which is the input resolution of our system. These results show that the one-channel feedback system is very effective in damping the energy oscillations. They also suggest that, due to the

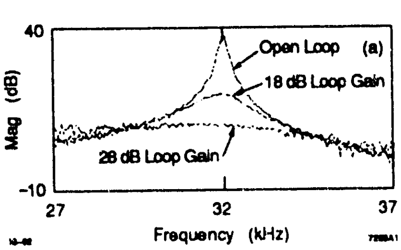

Figure 6. Magnitude response for openloop, 18 dB and 28 dB loop gains.

bunch-by-bunch nature of the feedback scheme, it should be possible to damp the oscillations of an n-bunch beam with an n-channel feedback system.

5. Summary

We have described how the problem of coupled-bunch instabilities is tackled in two stages. Careful RF cavity design reduces the cavity impedance by reducing the Qs of the dangerous HOMs via damping waveguides, and bunch-by-bunch feedback using digital signal processing is used to damp out any oscillations due to residual coupling.

R & D projects currently underway are: to build and test high-power cavities for which basic design has been developed and tools are now available; to develop a multichannel B-factory prototype feedback system for evaluation at ALS.

6. Acknowledgments

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7. References

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