Measurement of Higher-Order Mode Losses in SPEAR II by Shift in Synchrotron Phase and Increase in Net Cavity Power

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It has been estimated (Matt Sands, PEP-92) that the loss to higher-order cavity modes in SPEAR II will be 135 keV per cavit ›t 100 mA for a 10-cm bunch (σ_z = 5 cm). This corresponds to a loss of 10 MeV for a 50-m PEP structure. The power lost to higher modes in each SPE/ II cavity at 100 mA would be 13.5 kW. A loss of this order can be measured by calorimetry. This loss is also large enough to cause a significant increase in the net rf power input into the cavities over the power input ·ith no higher-mode excitation. In addition, the higher-mode loss car lso produce a measurable shift in the synchronous phase angle. Numbers for these effects are computed below.

Choice of Peak Rf Voltage

We want to choose the minimum peak cavity voltage that will give a reasonable quantum lifetime in the presence of higher-mode losses at the maximum current at which we expect to make measurements. To be conservative, let us choose this current to be 50 mA. We assume that three cavities are installed in the ring. Based on 135 keV per cavity at 100 mA, the total higher-mode loss at 50 mA is S = 202.5 keV. At an energy of 1.5 GeV, the synchrotron radiation loss per turn is U_0 = 35.0 keV. The total loss is then $U_0 + S$ = 237.5 keV. Using also the following parameters:

Quantum lifetime	4.73×10^4 sec (13.2 hr)
Momentum compaction factor	0.043
Synchrotron damping time	33.5×10^{-3} sec
Energy spread (σ_ε)	0.54 MeV
Harmonic number	280

we calculate that a peak cavity voltage $\hat{V}$ of 437 kV is required.

Measurement by Shift in Synchronous Phase

The synchronous phase angle at $e\hat{V}$ = 437 keV and $U_0 + S$ = 237.5 keV is

$$\phi = \cos^{-1}\left(\frac{U_0 + S}{e\hat{V}}\right) = \cos^{-1}\left(\frac{237.5}{437}\right) = 57.1^0 \quad .$$

The synchronous phase without higher-mode losses, or, in any case, at very low current, is

$$\phi_0 = \cos^{-1}\left(\frac{U_0}{e\hat{V}}\right) = \cos^{-1}\left(\frac{35.0}{437}\right) = 85.4^0 \quad .$$

Thus the change in synchronous phase in going from 50 mA to low current is $\phi - \phi_0 = 28.3^0$ for this value of S. A phase shift of this order should be readily measurable by comparing the phase of a signal obtained from a cavity pick-up loop with the phase of a signal (at the 280^{th} harmonic of the revolution frequency) obtained from a beam pick-up electrode.

One fly in the ointment is that an increased energy spread may be associated with bunch lengthening at 50 mA. In SPEAR I, a maximum increase in energy spread (as measured by an increase in beam width and by quantum lifetime experiments) by a factor of 1.8 was seen. If we recalculate the peak voltage using an energy spread of σ_E = 1.0 MeV (≈ 1.8 × 0.54 MeV), we find that a peak voltage of 782 kV is required to give the same quantum lifetime. The synchronous phase at $U_0 + S$ = 237.5 keV is 72.3^0, a shift by 15.1^0 from the zero current synchronous phase of $\phi_0 = \cos^{-1}$ (35.0/782) = 87.4^0. Thus, even if there is a considerable increase in energy spread associated with bunch lengthening, a reasonable measurement of higher-mode losses can be made using the shift in synchronous phase, assuming that experimental techniques can be worked out to compare the phases of the beam and cavity signals to within a few degrees.

Measurement by Change in Cavity Power Balance

Let us compute the cavity power input for the two previous cases (σ_ε = 0.54 MeV and 1.0 MeV). For σ_ε = 0.54 MeV, a peak voltage of 437 kV is required for reasonable quantum lifetime at 50 mA with S = 202.5 keV. The cavity shunt impedance is 38 MΩ (based on 18 MΩ/m). The power dissipation per cavity, the power lost to synchrotron radiation per cavity and the power going into higher-mode losses per cavity are given below for two cases. In the first column, results are given for a beam which is stored using a single cavity. The second column lists results for the case in which all three cavities are equally powered.

Single Cavity Powered	Three Cavities Powered
$P_c = \frac{\hat{V}^2}{R} = \frac{(437)^2}{38 \times 10^3} = 5.0$ kW	$P_c = \frac{\hat{V}^2}{9R} = 0.6$ kW
$P_{U_0} = U_0 i = (35.0\ \text{kV})(50\ \text{mA}) = 1.8$ kW	$P_{U_0} = U_0 i/3 = 0.6$ kW
$P_S = Si = (202.5\ \text{kV})(50\ \text{mA}) = 10.1$ kW	$P_S = Si/3 = 3.4$ kW

The net power input into a single driven cavity is seen to be 16.9 kW with higher-mode losses and 6.8 kW without higher-mode losses (a 2.5 to 1 ratio). If all three cavities are equally powered, the net power inputs with and without higher-mode losses are 4.6 kW and 1.2 kW (a 3.8 to 1 ratio). Thus the measurement is somewhat more sensitive to the presence of higher-mode losses if all three cavities are equally powered. If all three cavities are used, and if the cavities are not properly phased, the true peak voltage may be less than the sum of the individual cavity voltages. The quantum lifetime may then be less than calculated on the assumption that $\hat{V} = \hat{V}_1 + \hat{V}_2 + \hat{V}_3$. However, the total power going into higher-mode losses is still given by the total net input power into all three cavities, minus the quantity $U_0 i + (\hat{V}_1^2 + \hat{V}_2^2 + \hat{V}_3^2)/R$.

In the case of the larger energy spread (σ_E = 1.0 MeV) and higher peak voltage ($\hat{V}$ = 782 kV), we calculate that P_c = 16.1 kW for the case of a single driven cavity, while the power per cavity is 1.8 kW if all three cavities are equally powered. The synchrotron loss and higher-mode loss per cavity remain as before. In the single cavity case, therefore, the net input power is 28.0 kW with higher-mode loss and 17.9 without. For the case of three equally-powered cavities, the net input power per cavity is 5.8 kW with higher-mode loss and 2.4 kW without. Again, changes in power of this order should be readily measurable.

Experimental Procedure

The most accurate measurement of higher-mode losses, based on changes in either synchronous phase or cavity input power, will be obtained by using the lowest peak voltage consistent with reasonable beam lifetime. The experiment might proceed as follows for the case in which a beam current of, say, 50 mA is stored at 1.5 GeV using a single cavity. After injection, the cavity voltage is reduced as much as possible while still maintaining good beam lifetime. The phase bridge would then be zeroed and the direct and reverse power meters read. The stored beam current would then be reduced to a few milliamperes and the changes in phase and power measured, keeping the cavity voltage constant. A correction must be made for the fact that some power will be lost to the fundamental mode in the two idling cavities, which are tuned off resonance. This loss might be on the order of one kilowatt, but it can be calculated. It should also be noted that the limit on beam lifetime might be the Touschek lifetime rather than the quantum lifetime. If this is the case, a higher peak voltage might be necessary, and the numbers would not be as favorable as those calculated here.

Energy Loss to Vacuum Chamber Components

In addition to losing energy to higher modes in the rf cavities, the beam can also excite fields in the various vacuum chamber boxes and transitions it encounters during a circuit of the ring. The energy loss to these components is included in the loss as measured by the techniques just described. By December we expect to install a fourth rf cavity in the ring. The energy loss can then be remeasured to obtain the increment due to a single cavity. On the assumption that the higher-mode losses are the same in each of the rf cavities, the sum of the cavity losses can be subtracted from the total loss to give the loss, if any, due to the excitation of vacuum chamber components.