PARASITIC MODE LOSSES VERSUS SIGNAL SENSITIVITY IN BEAM POSITION MONITORS*

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ABSTRACT

A beam position monitor (BPM) for a storage or damping ring may be subject to heating problems due to the parasitic mode (PM) losses, beam interception and synchrotron radiation interception. In addition, high PM losses can cause beam instabilities under some conditions. Recessing and/or masking the BPM may increase the PM losses in the process of solving the latter two problems. This paper presents three complementary methods for estimating the PM losses and for improving the design of a stripline directional coupler type of BPM: bench measurements, computer modeling (TBCI) and an equivalent circuit representation. These methods lead to a decrease in PM losses without significant reduction in output signal for the north SLC damping ring BPMs.

INTRODUCTION

The south (electron) damping ring was the first part of the Stanford SLC Project to be completed[1] and it has now been running for about 18 months. During this period the stripline beam position monitors (BPM) in both the ring and the two transfer lines have suffered damage by heating. In some cases the cause was certainly beam interception by the strips. In the ring, some strips may have been damaged due to parasitic mode losses. For a 6 mm bunch length, the requirements are to be able to detect a minimum of 5×10^8 particles/bunch and to locate the beam with an accuracy of $\pm100\,\mu m$ over the range of 5×10^9 to 5×10^{10} particles/bunch. The north (positron) damping ring and its transfer lines are being built with more robust monitors which should have similar sensitivity to drive the same electronics. In the ring itself their number will increase from 26 to 40, so that parasitic mode losses must be more carefully controlled to avoid producing beam instabilities.

This paper focuses on the results of theoretical calculations and bench measurements which have led to the design of two slightly different monitors: one for the transfer lines where PM losses are not a problem and one for the ring where the losses have been reduced without significantly affecting the sensitivity. The south ring BPM's and their electronics are similar to those used in the Linac[2,3]; *i.e.*, four 50 Ω striplines 120 mm long, 5 mm wide in a 1 inch diameter vacuum chamber. The monitors are rotated by 45° to avoid synchrotron radiation, but they are not protected from the injected beam for lack of space. Before installation, the electrical center of each monitor is measured. These offsets become part of the data base and are subtracted from each measured beam position. Nevertheless, the fabrication process aims at keeping this offset within $\pm100\,\mu m$.

DESIGN CONSIDERATIONS

The north ring BPM's must be protected from the injected beam. The only space available to recess the electrodes is under the quadrupole coils, which makes them shorter and thus less sensitive. As partial compensation, their width is increased to cover 80% of the circumference. The distance to the wall is set to give a characteristic impedance of 50Ω. When the electrodes cover more than half the circumference, the sensitivity to position deteriorates slightly; in this case by 7%.

The first eight monitors tested showed small electrical center offsets of typically $50\,\mu m$. The new electrodes are rigid because of their circular shape and short length and thus more reliable. These qualities led us to adopt this type of monitor for the transport lines. However, their PM losses are too high for the ring. The PM loss factor k corresponds to the potential lost by each electron of a one picocoulomb bunch at each passage. The k can be measured by injecting a Gaussian current pulse on a wire that is stretched along the axis of the monitor[4,5]. Not having a pulse as short as the beam, we used a pulse 3.3 times longer in a 3.3 scale model. We found $k = 0.24$ V/pC, after scaling to the actual beam and monitor sizes. With forty monitors and one 8 nC bunch in the ring, the beam will lose 76.8 kV each turn and each monitor will absorb 130 W ($P = k\,q_b^2\,f$, where the revolution frequency f is 8.5 MHz). This is too large; it could affect the beam stability and heat the cables, the electrodes and the vacuum feedthroughs.

SIGNAL ANALYSIS

Figure 1(a) represents a simplified schematic diagram of the detection circuit. The peak value V_p detected is a measure of the low frequency part of the spectrum and is called the data signal. Imagine an equivalent beam having the shape of the Gaussian filter impulse response as shown on Fig. 1b. The four electrodes form a coaxial structure with a characteristic impedance Z_0. One electrode cannot be separated from the others and the impedance of each individual electrode is defined as four times the impedance Z_0 of the four electrodes connected together. Z_0 can be derived from a sheet of conductive paper, or measured with a reflectometer exciting all four electrodes at the same time. However, if the slots between electrodes are narrow, we can write:

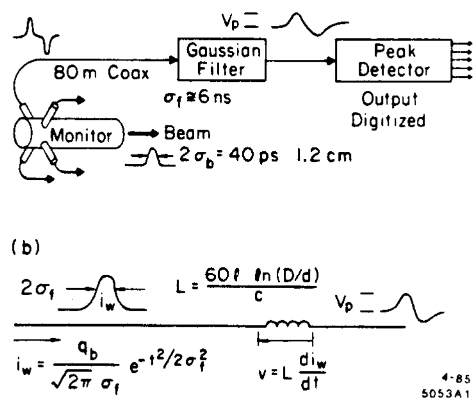

Fig. 1. Signal detection circuit: a) simplified schematic diagram and b) equivalent circuit (for definitions of the dimensions, D, d and l, see Fig. 3).

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$$Z_0 \simeq 60\, ln(D/d) \quad (1)$$

where d is the outer electrode diameter and D that of the wall. For low frequencies, a short circuited coaxial line of length l in vacuum is equivalent to a small inductor $L = Z_0 l/c$ (c is the speed of light). So, for a centered beam of charge q_b, the four signals after the filters will have the amplitude:

$$V_p \simeq \frac{e^{-1/2} q_b}{\sqrt{2\pi\sigma_f^2}} \times \frac{60\, l\, ln(D/d)}{c}\, f(\Theta) \quad (2)$$

where σ_f characterizes the filter impulse response, and f(Θ) is a function of the fraction of the circumference covered by the electrodes. The latter is approximately equal to unity with 80% coverage. This formula shows that for values of D/d close to unity or $(D-d)$ small, the electrode sensitivity is proportional to the area

$$A = l \times (D-d) \quad (3)$$

ESTIMATES OF PM LOSSES

We want to reduce the losses, but not the data signal. One of the most obvious choices is to change the gap dimension g represented in Fig. 3a. With a model it was determined that the data signal does not change for gaps between 25 μm and 5 mm. A small gap can be represented by a capacitor at the end of the electrode and it does not affect the low frequency spectrum used for data processing.

The program TBCI[6] was used to compute the losses of a model having cylindrical symmetry. These results are in good agreement with the bench measurements. Therefore, TBCI provides an efficient way to investigate the effects of the gap on the loss factor k. We can see from Figure 2 that this factor decreases to 0.013 V/pC when the gap is completely closed. This curve was checked with the test bench, using two different models: one with cylindrical symmetry (*i.e.*, no slot between electrodes) and one in which the electrodes occupy 80% of the circumference. The results were almost identical, which means that the TBCI program is valid for narrow slots.

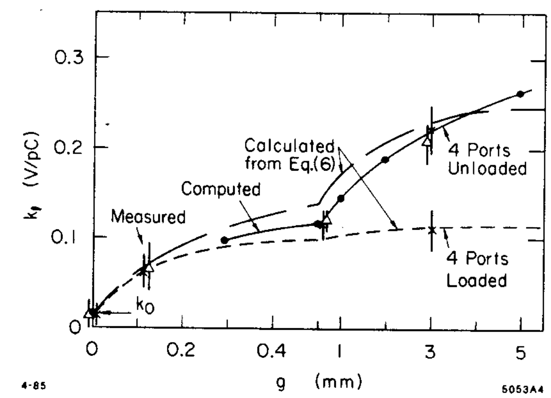


Fig. 2. PM loss parameter k versus gap g. Note the change of scale on the horizontal axis at .5 mm. Plotted are the computation data points •; bench measurement points without slots (cylindrical symmetry) Δ, and with slots (the actual geometry with the four electrodes separated by four slots) X. The error bars indicate the accuracy of the bench measurements. The other two curves result from Eq. (6) with the ports unloaded and loaded with 50 Ω cables.

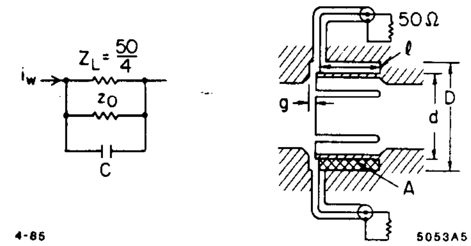


Fig. 3. Equivalent circuit seen by the beam and actual monitor geometry.

At the other limit, the effect of very large slots can be estimated by computing with no electrodes. Then TBCI yields $k = 0.29$ V/pC.

A helpful estimate of k can be made using the equivalent circuit of Fig. 3. The total image current of the beam goes through three elements in parallel: the gap capacitor C, the characteristic impedance Z_0 of the coaxial structure and the equivalent load Z_L of the four electrode output circuits. For a large gap ($C \simeq 0$) this circuit allows us to calculate the energy lost in Z_0 and Z_L during a single passage of the beam: $E = (R_e q_b^2)/(2\sqrt{\pi}\,\sigma_b)$, where σ_b is the bunch length and $R_e = Z_0 \| Z_L$. Dividing E by q_b^2 gives:

$$k = R_e / 2\sqrt{\pi}\,\sigma_b \quad (4)$$

This relation yields $k = 0.233$ V/pC for unloaded electrodes ($Z_L = \infty$), and $K = 0.100$ (we measured 0.114) when the four 50 Ω cables are connected ($Z_L \approx 12.5\,\Omega$).

For a very small gap the capacitor C is large enough so that the energy left by a short bunch is $E \simeq q_b^2/2C$. The corresponding k factor becomes:

$$k \simeq 1/2C + k_0 \quad (5)$$

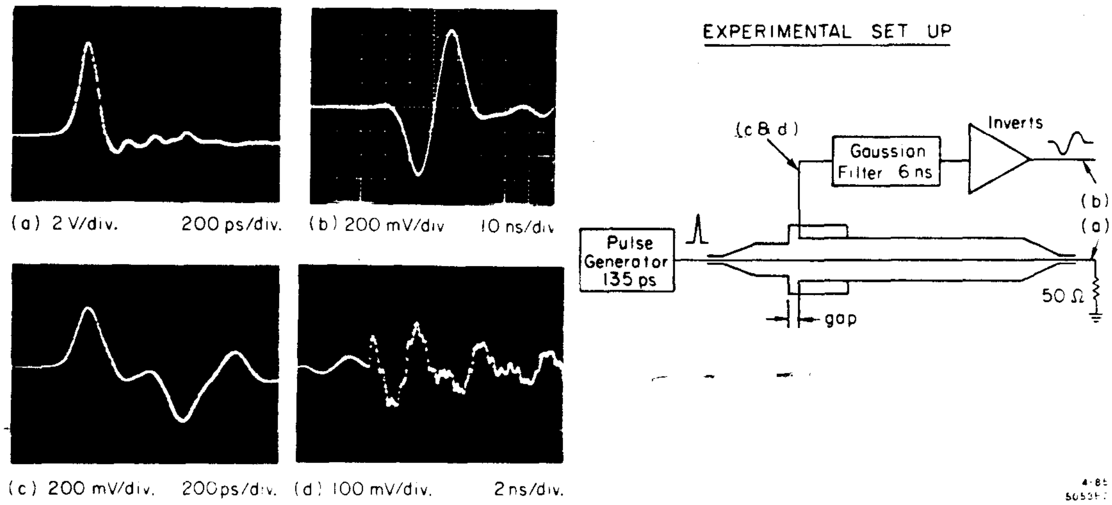
where C is in pF and k_0 is the k previously computed for a closed gap. The gap capacitance can be approximated by that of a microstripline at a distance g from an infinite ground plane. The microstrip width is the electrode thickness and its length is the part of circumference covered by the electrodes. Over most of the gap range, C is neither large enough to use Eq.(5) nor small enough to use Eq.(4). A rough interpolation between these two asymptotes is given by:

$$k \simeq k_0 + \frac{R_e}{2\sqrt{\pi}\sigma_b}\left[1 + \left(\frac{R_e C}{\sqrt{\pi}\,\sigma_b}\right)^2\right]^{-1/2} \quad (6)$$

This equation supposes that the beam has a pure spectrum with $\omega_c = 1/\sqrt{\pi}\sigma_b$. The power associated with k_0 is dissipated in the nearby vacuum chamber. The second term corresponds to the power extracted by the coaxial cables, except for some small fraction that is lost on the electrodes. Figure 2 represents two curves from Eq. (6), calculated respectively with $Z_L = 12.5\,\Omega$ and $Z_L = \infty$. The feedthroughs and their connections to the electrodes are not perfect, so the actual value probably lies between these two limits.

Figure 4 shows the signals measured on the 3.3 × model of the monitor. With a large gap the electrode yields two opposite

Fig. 4. BPM signals: a) simulated beam signal, b) data signal which was found to be approximately the same for a large and small gap and, c), d) electrode signals with large and small gaps. The pictures a, c, and d are taken with a scaled model and pulse width that was 3.3 times larger than their actual size.



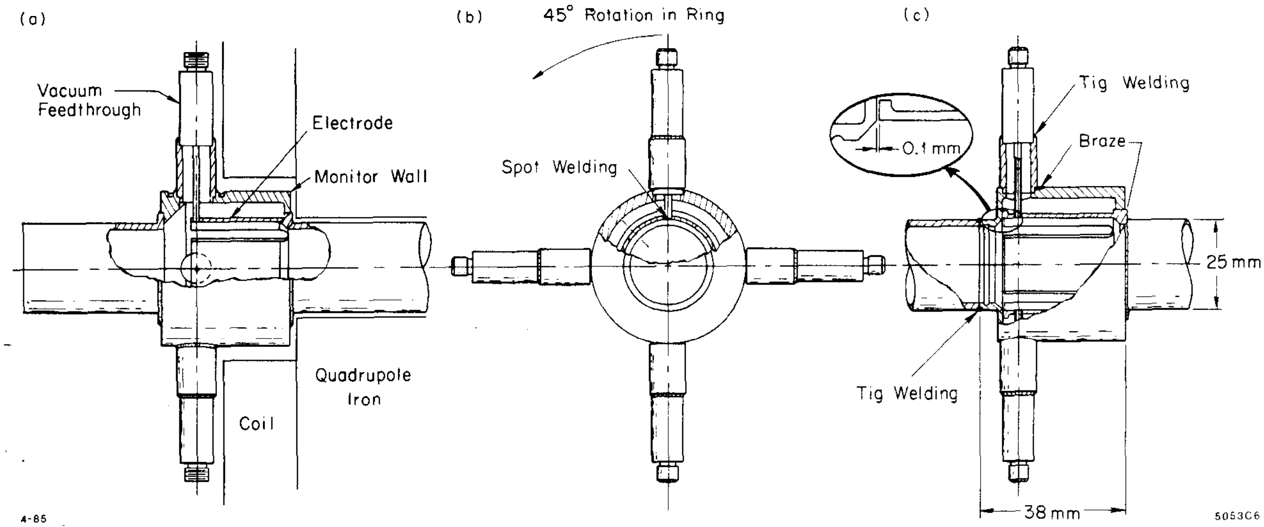


Fig. 5. Beam position monitor configurations: a) for beam transfer lines, b) general end view, and c) for the ring.

polarity pulses separated by a time $2l/c$. These pulses are wider than the beam pulse because of the output circuit connection and the losses in the electrode stripline. In Figure 4d the capacitance of a very small gap is seen to resonate with the shorted line, equivalent to an inductor. The important result is that in both cases the data pulse Fig. 4b remains the same.

A large gap capacitance is the vital feature for low losses. The technology involved in the fabrication of the monitor determines the limit we can reach. The design shown in *Fig. 5c* has a 0.1 mm gap, which is set using a removable shim during a brazing operation. The ends of the electrodes are twice as thick at the gap in order to increase C and bring the loss parameter k down to 0.040 v/pC.

CONCLUSION

The contribution of forty monitors in the north ring to its global PM losses will be less than 15 keV per revolution. This should not cause beam instabilities. For each monitor, 7 W of power dissipated in the nearby vacuum chamber will be taken away by the synchrotron radiation cooling system. About 4 W will go into each coaxial cable and almost nothing will be dissipated on the electrodes.

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