IMPEDANCE CALCULATIONS FOR THE IMPROVED SLC DAMPING RINGS*

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INTRODUCTION

A longitudinal, single bunch instability is observed in the damping rings of the Stanford Linear Collider (SLC).[1] Beyond a threshold bunch population of 3×10^{10} particles the bunch energy spread increases and a "saw-tooth" variation in bunch length and synchronous phase as functions of time is observed. Although the relative amplitude of the saw-tooth variation is small–only on the order of 10%–the resulting unpredictability of the beam properties in the rest of the SLC accelerator makes it difficult, if not impossible, to operate the machine above the threshold current. An additional problem at higher currents is that the bunch length is greatly increased: according to earlier measurements the rms length is increased by 60% at 3×10^{10}.[2] When the bunch is very long in the ring it becomes difficult or impossible to properly compress it after extraction. We want to solve both of these problems so that the SLC can run at higher currents to increase the luminosity. In order to solve these problems the vacuum chambers of both damping rings are being rebuilt with the aim of reducing their impedance.[3]

According to previous calculations the impedance of the SLC damping rings is dominated by the many small discontinuities that are located in the so-called QD and QF vacuum chamber segments—elements such as transitions, masks, bellows—that are inductive to the beam.[4] Since these earlier calculations were performed the bellows of the QD segments have been sleeved, yielding a factor of 2 increase in the instability threshold.[1] In this paper we begin by discussing the gains that might be achieved if we can reduce the impedance of the rings even further. Then we estimate the effect on the total impedance of the actual design changes that are being proposed. Three important elements—the bend-to-quad transitions, the distributed ion pump slots, and the beam position monitor (BPM) electrodes are fully 3-dimensional and will be studied using T3 of the MAFIA computer programs.[5]

EXPECTED GAINS

Since the QD and QF vacuum chamber segments are the dominant contributors to the impedance of the damping rings the main effort of the redesign project is being applied to reducing their contributions to a negligible quantity. The vertical profile of the QD and QF segments are shown in Fig. 1. In the QD segments, for example, we find a bend-to-quad transition (2), a BPM (3), a bellows [now sleeved] (4), a serf gasket (5), a synchrotron radiation mask (6), and a transition to the next bend (7). Both types are cylindrically symmetric except for the transitions and the BPM electrodes. Both segment types are repeated 20 times in the ring. Also being redesigned are the distributed ion pump slots in the bend chambers, and the kicker bellows will be sleeved.

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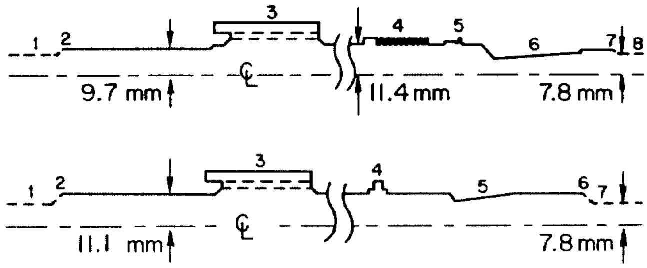

Fig. 1. The vertical profile of a QD segment (top) and a QF segment (bottom). Non-cylindrically symmetric objects are given by dashes.

Tracking simulations have been performed before to obtain the bunch shapes and instability threshold for the current damping rings.[6] The Green function wake needed for these calculations was obtained in the following manner: The wakefield for a short bunch passing through a cylindrically symmetric approximation to the QD and QF segments was carefully calculated numerically.[4] Combining these results with the wakefields for other ring objects—such as the rf cavities, kicker bellows, straight section BPM's, etc.—a wakefield representing the entire ring was obtained. To see what might be gained from the rebuilt vacuum chamber we have repeated the tracking simulations, at the nominal peak voltage of 0.8 MV, but with a wakefield that does not include the contributions of the QD/QF segments nor of the kicker bellows.

The instability threshold obtained from the simulations is compared with other calculations and measurements in Table 1 (Note: by "old ring" we mean the ring before the QD bellows were sleeved). We see that the calculated threshold is a factor of 2.5 higher for the improved ring than for the present one. In Fig. 2 we plot the rms bunch length σ_z obtained by the simulations for the improved ring (the solid line) and for the current ring (the dashes). We see that at 3×10^{10} the bunch length increase for the improved ring is only 10%, instead of the 60% for the current ring.

Version	Calculated	Measured
Old ring	1.1×10^{10}[6]	1.5×10^{10}[2]
Present ring	2.0×10^{10}[6]	3.0×10^{10}[1]
Improved ring	4.8×10^{10}	

Table 1. The calculated and measured thresholds currents for different ring versions.

What evidence do we have that we can believe in the simulation results? From Table 1 we see that although the absolute threshold values as calculated are 30% lower than the measured ones, the relative improvement in the present and old ring results of the calculations matches that of the measurements. In addition, the bunch shape calculations for the old ring were found to be in very good agreement with the measurements.[7]

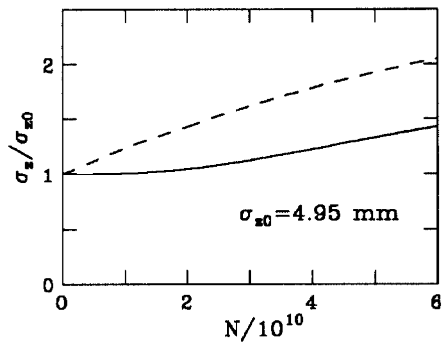

Fig. 2. Calculated rms bunch length if the QD/QF segment impedance is made negligible and the kicker bellows are sleeved.

IMPEDANCE REDUCTION

The SLC damping ring impedance is very inductive at the typical rms bunch length $\sigma_z \gtrsim 0.5$ cm. In Table 2, we reproduce a list from Ref. 4 of the approximate contributions at low frequency of the important inductive elements to the impedance of the old ring. (The "Factor" in the table represents an azimuthal filling factor, used in the calculation of of non-cylindrically symmetric objects; N gives the number of objects.) The only difference in the current ring is that the QD bellows contribution has been eliminated by their sleeving; therefore, the total now is about 38 nH. Since the ring circumference is 35 m the quantity $|Z/n|$ is 2.0 Ω. This should be compared with the impedance of the rf cavities, which is resistive/capacitive to the bunch and contributes approximately $|Z/n| = 0.44\ \Omega$. One must be aware that Table 2 is an approximation to be used only as a rough guide. Note, for example, that the QD bellows contribute only 25% of the Table 2 total, whereas the calculated threshold increased by 80% when they were eliminated from the simulations.

Ring element	L(nH) single	Factor	N	L(nH) total
QD bellows	0.62	1.0	20	12.5
QD & QF masks	0.47	1.0	20	9.5
Transitions	0.26	0.9	40	9.3
Ion pump slots	1.32	0.1	40	5.3
Kicker bellows	2.03	1.0	2	4.1
Flex joints	0.18	1.0	20	3.6
1"BPM transitions	0.10	0.8	40	3.3
Other				2.4
			Total	50.0

Table 2. The contribution to the impedance of the old ring of the major inductive elements.

From Table 2 it is clear that there are many objects that contribute to the impedance, and completely new versions of the QD and QF vacuum chamber segments will be required for their contribution to become negligible. Unfortunately, there are many practical reasons why these segments cannot just be replaced by simple smooth tubes. For example, bellows are needed in a ring so that the whole vacuum chamber can be assembled. The impedance of the bellows can be reduced by sleeving, but then masks are needed to protect the sleeves from synchrotron radiation. More specific to SLAC, the bend vacuum chambers have a rather rectangular cross-section whereas the quad chambers are circular; therefore transitions are required. This situation cannot be changed without heroic efforts, such as rebuilding the bend magnets. Finally, replacing our electrode and cavity type of BPM's by the buttons type would also require a major effort that will not be done now.

The major changes to the damping rings will be:[3] the number of QD bellows will be reduced to 12, and their sleeves will include a 1.5 mm step (for protection against synchrotron radiation); the QD/QF masks will be removed, the bend-to-quad transitions will be tapered more gently, the distributed ion pumping slots will be narrowed, the 1"BPM transitions will be removed, and the flex joints, the serf gaskets, and the kicker bellows will all be sleeved.

IMPEDANCE CALCULATIONS

To estimate the impedance of an inductive element we first find the wakefield for a gaussian bunch of typical length numerically using a time domain MAFIA program (T2 or T3). If the element is inductive the wake will be similar to the derivative of a gaussian. Fitting to $W = -L\,dI/dt$, with W the wake and I the bunch shape, we obtain the inductance L. For some simple objects—such as a small cavity, shallow iris, shallow transitions, small hole in the beam tube—analytical formulas are known and can be used.[4,8]

For 3-dimensional objects T3 was used to obtain the impedance (Note: $\sigma_z = 1$ cm):

The Bend-to-Quad Transitions

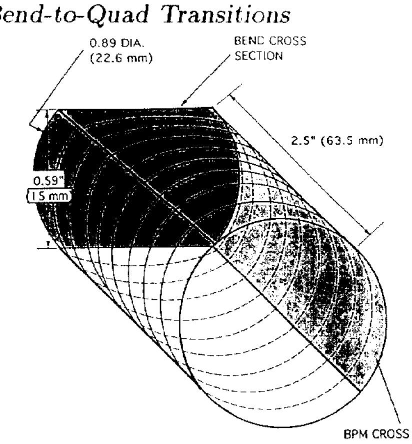

Fig. 3. The new bend-to-quad transition.

The change from the bend to the quad chamber requires a transition from a rather rectangular cross-section to a circular one. Presently the angle of transition is roughly 45°. An approximate formula that can be used for a pair of shallow, cylindrically symmetric transitions is[4]

$$L = \frac{3Z_0}{2\pi c}\frac{a\Delta^2}{b^2}\left(\frac{2\theta}{\pi}\right)^{1/2} \quad , \tag{1}$$

with $Z_0 = 377\ \Omega$, c the speed of light, a and b, respectively, the small and large radius, $\Delta = b - a$, and θ the transition angle.

A solution that has a very shallow angle in y (3.5°) and no transition in x is sketched in Fig. 3. The resulting wakefield is inductive, with $L = 0.05$ nH per transition pair, or $L = 2$ nH for all 40 transition pairs. Note that using Eq. (1) with the vertical dimensions, and then dividing the result by 2, we get the same answer.

The Distributed Ion Pumping Slots and the BPM's

For a long, narrow, longitudinal slot we expect the beam to interact only with the ends. The impedance will be inductive and we expect it to be given by the impedance of a hole with radius $r_0 = w/2$, with w the width of the slot, times a factor α on the order of 1. The inductance of a hole in a round chamber is given by[8]

$$L = \frac{Z_0 r_0^3}{6\pi^2 b^2 c} \quad , \tag{2}$$

with b the chamber radius. For a hole deeper than $r_0/2$ the above result is multiplied by 0.57.[9]

We have run T3 for deep, longitudinal slots in a round pipe, for different slot lengths ℓ. We have chosen $w = 1.5$ mm and $b = 10$ mm. Fig. 4 gives the ratio of the numerical result to the analytical solution for a deep, round hole with $r_0 = w/2$, L_0, for slots with squared ends (the diamonds) and also for slots with rounded ends (the crosses). We see that the impedance approaches a constant value when the length of the slot is 1-2 times its width, and that the assymptotic value for a slot with rounded ends is only 2/3 that of one with squared ends. Thus tapering the ends of the slots helps. Fig. 5 shows the wakefield for a long slot (squared ends). It can be seen that the impedance is very inductive (bunch center is at $s = 0.05$ m).

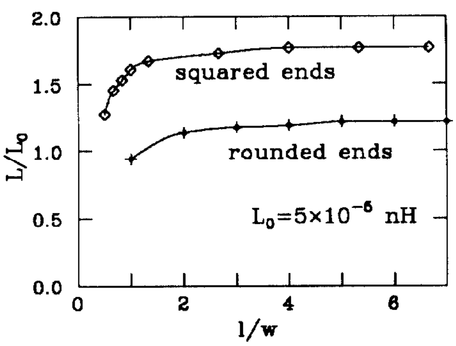

Fig. 4. The inductance of a slot; $w = 1.5$ mm.

The distributed ion pumping slots of the damping rings are located in the bend chambers. They are very long, have a width $w = 5$ mm, and are located 11 mm (in x) from the beam path; 5 mm beyond the slots are the pump electrodes. The slots have squared ends and are deep. From the foregoing (taking $\alpha = 1.75$) we estimate each slot to contribute 0.005 nH, and all 40 to contribute 0.2 nH to the ring impedance. According to this calculation the entry for ion pump slots in Table 2 is greatly overestimated. In the new vacuum chamber each of the current slots will be replaced by 3 slots: one with $w = 3$ mm and two with $w = 1.5$ mm. For the new slots, assuming they are deep and have squared ends, the total impedance contribution is 0.03 nH.

A BPM consists of four symmetrically spaced electrodes separated by gaps of 3.7 mm. At one end of the electrodes there is a 0.15 mm gap (small enough so that its impedance can be neglected). Radially reaching 4.5 mm beyond the electrodes is a cavity. Currently the BPM's are set back 2 mm by means of a pair of 45° transitions. These transitions will be removed. The new BPM's appear to the beam as 4 deep slots with squared ends in a round tube of radius 11 mm. The MAFIA mesh of 1/4 of a BPM is shown in Fig. 6. From a T3 simulation we find that to a

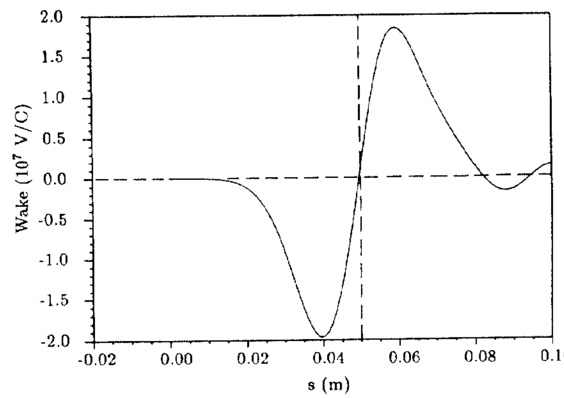

Fig. 5. The wakefield of a slot (squared ends) with width 1.5 mm and length 8 mm; $\sigma_z = 1$ cm.

1 cm bunch the BPM is inductive with $L = 0.0042$ nH for each BPM, or $L = 0.17$ nH for the entire ring. The above analytical method yields the same answer.

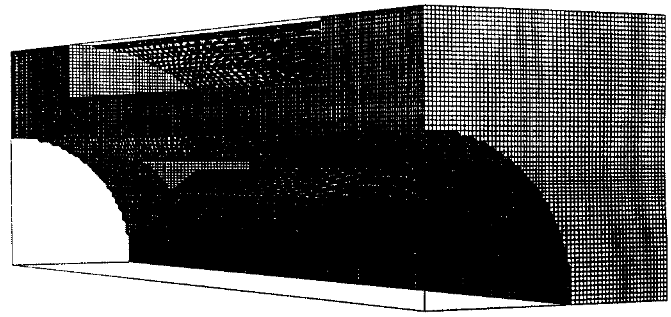

Fig. 6. MAFIA mesh for the BPM.

CONCLUSION

With the new vacuum chamber we can expect to reduce the impedance of the inductive elements from a current total of about 33 nH to about 5 nH, or $|Z/n|$ from 1.75 Ω to about 0.25 Ω. The ring should become resistive, the bunch lenthening will decrease, and the instability threshold should increase significantly.

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