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BENCH MEASUREMENTS OF THE LOSS IMPEDANCE FOR PEP BEAM LINE COMPONENTS*

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Summary

Bench measurements of the parasitic model loss parameter k, due to the interaction of a bunched beam with discontinuities in the vacuum pipe, are presented for many of the PEP beamline components. The measurements were made using the pulsed, coaxial transmission method of Sands and Rees[1]. Full-scale machined and sheet metal models containing tapers, gaps, tanks (cavities), collimators, plates, electrodes and other irregular shapes were investigated. Accuracies, errors and modeling difficulties are pointed out. Loss curves and rules of thumb are discussed that should aid in the design of similar components. Also described is a moderately successful effort to de-Q some of the resonances in a particularly complicated chamber (separating plates) with a strip line coupling loop that is externally terminated at both ends.

Introduction

With the advent of large storage rings with short bunches and high peak currents, the problems associated with significant coupling of RF power between the beam and the ring vacuum enclosure have been the subject of intensive investigation at a number of laboratories around the world. These parasitic mode losses to ring vacuum chamber components can limit the operating current and energy of a storage ring in several ways. First, significant heating due to these losses can occur at flange joints, bellows, ceramic seals and other discontinuities in the vacuum envelope. This heating can lead to chronic outgassing and, under extreme conditions, to leaks or catastrophic vacuum failures. Second, the sum total of all such losses around the ring can inflate the RF power budget, leaving less power available for stored beam current at the top operating energy. Finally, the net ring impedance determines the current thresholds for both single and multibunch beam instabilities.

Considerable experience at SPEAR has shown[2,3] that parasitic mode losses can indeed result in heating and vacuum failure. Motivated by this experience, an extensive program to estimate the parasitic mode losses for the PEP vacuum chamber components has been carried out, primarily using the bench measurement technique of Sands and Rees[1]. Computer computations of the parasitic mode loss impedance are possible for some cavities and discontinuities having simple geometries. All major PEP vacuum chamber components have been modeled for bench measurements. In many cases design modifications were made to reduce the losses. In addition, a number of standard shapes (irises gaps, collimators, and tapers) were tested for the dependence of the loss on bunch length and geometry.

Definitions and Measurement Limitations

The losses described above are often referred to as higher-order-mode (HOM) losses. In this paper these losses will be called parasitic mode (PM) losses, since the losses to both fundamental mode and all higher-order modes are normally measured. The parasitic mode loss parameter k is used to parameterize the loss for a particular beam line component. Physically, k is the energy loss in electron volts for a bunch with a charge of one coulomb passing through the component. The PM loss resistance R is obtained by multiplying k by the passage time between bunches, or $R = k/(n_b f_r)$, where n_b is the number of (equal) bunches and $f_r = 136.296$ kHz, giving $R(k\Omega) = 2446\,k(V/pC)$. If I is the average current per beam, then IR gives the energy loss per turn in electron volts, while $2I^2R$ gives the power lost to the component for two equal beams.

Most PM impedances are not broken down into their fundamental and higher-order-mode components. The major exception is the RF cavities, for which the fundamental mode impedance (shunt impedance) is of interest by itself. It should be noted also that the total PM impedance for a component is a sum of the individual mode impedances weighted by the frequency spectrum of the exciting bunch, and therefore is highly bunch-length dependent.

A diagram of the bench measurement set-up is given in Ref. 4. The measurement proceeds by first obtaining the pulse response, $i_0(t)$, for a smooth reference pipe with the same diameter as the beam ports of the component under test and having the same overall length. The reference pipe is then replaced by the component and a modified pulse, $i_m(t)$, is obtained. The PM loss parameter is then given by[1]

$$k = \frac{2Z_0 \int i_0(t)[i_0(t) - i_m(t)]\,dt}{[\int i_0(t)\,dt]^2} , \qquad (1)$$

where Z_0 is the characteristic impedance of the coaxial line formed by the reference pipe and its center conductor. For irregular shapes this can be either estimated or measured by time domain reflectometer techniques.

The pulse lengths used in the measurement must correspond to the bunch lengths, σ_z to be expected in a storage ring. Since these are very short ($\sigma_z \approx 1-3$ cm), a sampling oscilloscope is used to detect and display the output pulses. There are several ways to record and analyze the pulse data. The output of the oscilloscope can be digitized, signal-averaged and stored in memory for computer processing, or a trace can be recorded using an x - y plotter. A more complex experimental set-up, using parallel arms for the component and reference with pulse subtraction, is also possible.[5] At PEP, the simple single-arm method is used, and the analog output of the oscilloscope is displayed directly on an x - y recorder. The x - y recorder plot is useful in catching system errors and instabilities, as well as producing some averaging and smoothing of the data.

Initially the data was analyzed by computer after manually digitizing it with a sonic digitizer. This method is extremely time consuming and does not seem to add significantly to the accuracy achieved compared with a simple analysis technique in which the pulses are treated as if they are Gaussian. Then only the peak values and standard deviations (σ) need be measured. Using the approximations $i_0(t) = I_0 \exp[-t^2/2\sigma_0^2]$ and $i_m(t) = i_m \exp[-t^2/2\sigma_m^2]$ in Eq. 1, and replacing the first $i_0(t)$ in the numerator and the $i_0(t)$ in the denominator with $\bar{i}(t) \equiv [i_0(t) + i_m(t)]/2$,

$$k = \frac{R_0}{2\sqrt{\pi}\,\sigma_0} \; \frac{[1 - (\sigma_m/\sigma_0)(I_m/I_0)^2]}{[1/2 + 1/2(\sigma_m/\sigma_0)(I_m/I_0)]} \qquad (2)$$

The later approximation takes into account the fact that, unlike a relativistic bunch, the current pulse which excites the fields in the component is not necessarily constant as the pulse traverses the component.

It is necessary to provide a stable thermal environment ($20 \pm 0.1^{\circ}$C) for the oscilloscope mainframe, the oscilloscope sampling head and the tunnel diode pulser,

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since the sequential measurements of the reference and the component can be separated in time by as much as 30 minutes. The thermal stability was achieved by attaching heat sinks to the above three items and surrounding them by well-insulated enclosures. A fluid circulator with an internal heater and refrigeration unit pumps constant temperature ethylene glycol through the heat sinks. The above method, although not as precise as one using a signal averager, was chosen because it was found to be adequate for examining and optimizing most of the PEP design models. In addition, the equipment is relatively simple, inexpensive and easy to operate. A precision of ±0.5 ps in σ_t and ±0.1% in pulse amplitude is obtained. For a bunch length of σ_z = 2.4 cm this gives a resolution in Δk of about ±0.003, which for PEP with 55 mA in each beam is an uncertainty in loss of ±50 W.

There seems to be no obvious way to scale components for testing; therefore, the models have to be made full size, at least in the radial dimensions. Models up to one meter in diameter and four meters long can be measured relatively easily. Many of the test shapes, particularly tapers, were made from sheet aluminum or copper for simplicity. Whenever possible tests were made with the coaxial components vertical to minimize problems of a sagging center conductor. A very low density, rigid polystyrene foam was used where necessary to support the center conductor. To facilitate assembly, a short length of brass telescoping tubing is used to make a sliding joint at one end of the center conductor pipes and chambers.

Components to be checked by this measurement technique need to have beam ports of the same diameter at each end. Whenever this is not true of a particular component, two samples of the component are measured back-to-back, and 50% of the measured value is taken as the result for a single component. The separation between components must be made large compared to the outer conductor diameter.

The PM impedance is not always purely resistive. However, the k and R as measured and calculated represent the actual beam power loss, since any energy returned to the same bunch by wake fields is accounted for. Measurements using the single-arm method without a precursor pulse[5] do not allow quantitative extraction of a reactive impedance component. Another important limitation is that, while the measurement gives the total power extracted from the beam, it does not give any indication as to where the power will be dissipated. This can only be obtained by estimates of the general microwave propagation and dissipation characteristics of the component, including radiation through the beam ports and other coupling ports.

Measured Values of k and De-Q'ing

Many different components have been measured, usually at several bunch lengths. Figure 1 shows results for several gaps and irises. Note that there can be significant loss even for relatively small gaps, particularly for short bunch lengths. Conflat flange gaps were not measureable unless the pipe was quite a bit smaller than the gasket size, as in the case for the SPEAR beam-pipe extrusion (k = 0.014 at σ_z = 3.3 cm). Figures 2 and 3 show how shallow-angle tapers can drastically reduce the losses, and that reentrant chambers (3d) are particularly lossy. Other measurements show that stepped tapers are an improvement over a single-step discontinuity. Figure 4 is the summary of many measurements of a separating plates model with 0.15 cm thick, 19 cm wide plates. The ends were rounded to fit into the conical ends for $\theta = 13^\circ$ and 25°, but squared off for $\theta = 90^\circ$. The single point for $\theta = 25^\circ$ and d = 11 cm is for a measured value of k on a more elaborate model that included thicker plates, four support posts and ceramic feedthrus. The latter model is more lossy, as one might expect, but is closer to the actual separating plates design. It is clear from Figure 4 that a chamber with tapered ends, with the plates rounded and protruding into the tapers, is to be preferred. Voltage breakdown (the plate voltages are ±60 KV dc to ground) sets the minimum spacing. Figure 5 gives the k for some experimental region vacuum chambers. Some parts of the profiles shown are PM shields and not vacuum envelopes. Again, gentle tapers have kept the PM losses low. The design of these shields is not trivial since they are large in size and thin (required for low attenuation of particles). Because there is vacuum on both sides, they are hard to cool and there may be considerable heating even if the PM loss is low. Thermal radiation is then the only mechanism for heat loss.

The separating plates tank has quite a few resonances (from a few hundred MHz to the GHz range) with Q's on the order of 10^3. A 2.5 cm wide strip line, spaced 3 cm off the tank wall at 35° to the vertical and extending 3 m longitudinally, will be connected to broad-band external RF loads to dampen most of these resonances by a factor of 3 to 10. Also, by making the plates out of a good electrical conductor (copper) and the tank walls out of a poor conductor (stainless steel), the power loss should be greater where it can be removed more easily.

Table I summarizes the k values measured for a number of PEP components at a bunch length of 2.4 cm.

TABLE I – k of PEP Components* (σ_z = 2.4 cm)

ITEM	k (V/pC)
Distributed Ion Pump	~0
Pipe Tee (15.4 cm diam) - without screen	0.010
Pipe Tee (15.4 cm diam) - with screen	<0.003
Dog Leg Synchrotron Radiation Shield	<0.003
Gate Valve, Shielded	<0.006
Shield Bellows	<0.006
Transition (15.4 cm diam to extruded beampipe)	0.012
Personnel Protection Stopper (PPS)	0.015
Mask for Q3	0.015
High Z Masks	0.020
CERN Corrugated Pipe (1 m length)	0.028
Mark II - interaction region pipes	0.040+
Optical Monitor	0.060
MAC - interaction region pipes	0.084+
Excitation Electrodes	0.060+
Separating Plates	>0.140
RF Cavity, one cell only	0.300

*For PEP with two 55 mA beams: P(kW) = 14.8 k(V/pC).

Several other components were investigated for their dependence upon bunch length in the range $\sigma_z = 1-4$ cm. A corrugated round pipe (CERN vacuum chamber) with a 16.9 cm maximum and a 15.0 cm minimum diameter and 38 convolutions/m made of 0.25 mm thick stainless steel has a k value as a function of bunch length given by $k(\mathrm{V/pC\cdot m}) = 1.03\,[\sigma_z(\mathrm{cm})]^{-4.1}$. Two standard TM cavities (38 cm diam by 23 cm long) with 7.6 cm diam and 15.2 cm diam beam pipes have k values respectively of $k(\mathrm{V/pC}) = 0.70\exp[-0.32\sigma_z(\mathrm{cm})]$ and $k(\mathrm{V/pC}) = 0.46\exp[-0.31\sigma_z(\mathrm{cm})]$. A 10 cm long transition from 15.2 cm diam round pipe to the standard PEP extruded beam pipe (nominally a 5.4 cm by 9.2 cm oval) has k = 0.068, 0.012 and 0.006 V/pC for σ_z = 1.2, 2.3 and 3.9 cm, respectively. Finally, a measurement at σ_z = 2.2 cm for a radial gap of length ℓ between flanges on a 15.2 cm diam pipe gave $k(\mathrm{V/pC}) = 0.0114\,\ell(\mathrm{cm})$ up to ℓ = 15 cm. Then k increased more slowly than linearly up to k = 0.23 V/pC for ℓ = 23.5 cm. The flanges were 50 cm diameter, with an open circuit at the outer diameter.

The above profusion of data shows that PM losses for components having a variety of sizes and shapes can be determined relatively easily to moderate precision and accuracy, especially if several pulse lengths are used. Greater precision, and an attempt to untangle reactive effects, would require a much greater errort, as the measurement programs at CESR[5] and DESY[6] have shown.

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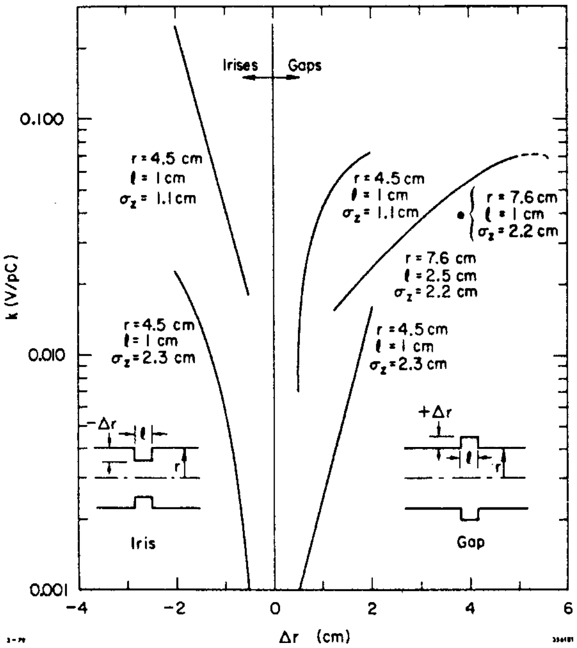

Fig. 1 Radial gaps and irises.

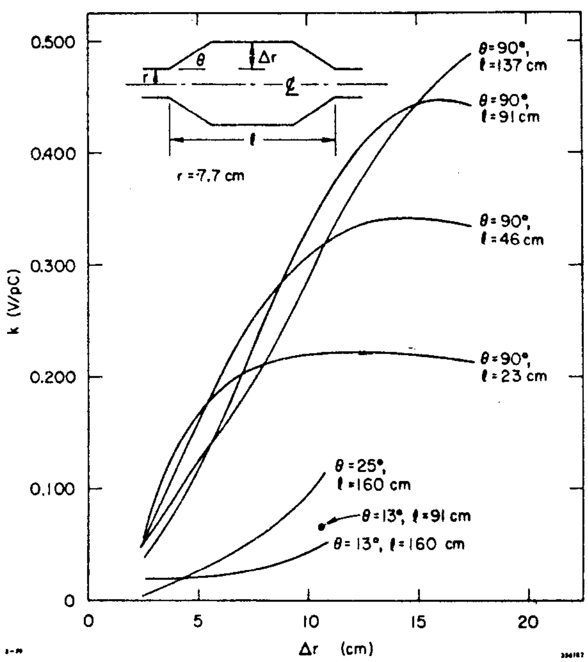

Fig. 2 Tapers with various angles and spacings between tapers (σ_z = 2.3 cm).

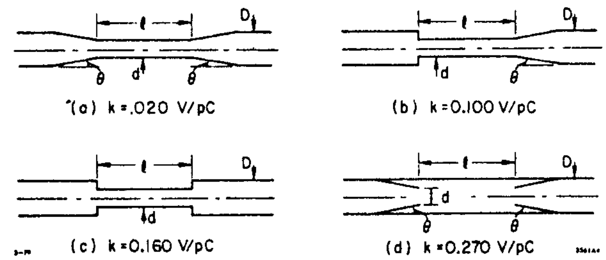

Fig. 3 Collimator chambers. D = 20 cm diam, d = 10 cm diam, $\theta = 10^o$, ℓ = 56 cm and σ_z = 2.5 cm.

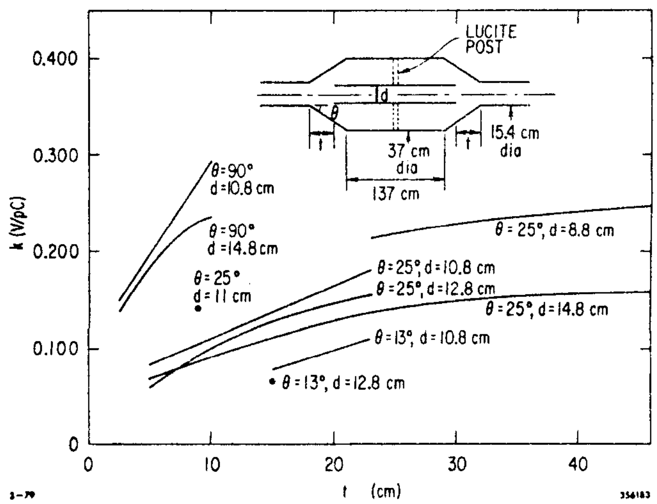

Fig. 4 Separating plates model (σ_z = 2.3 cm).

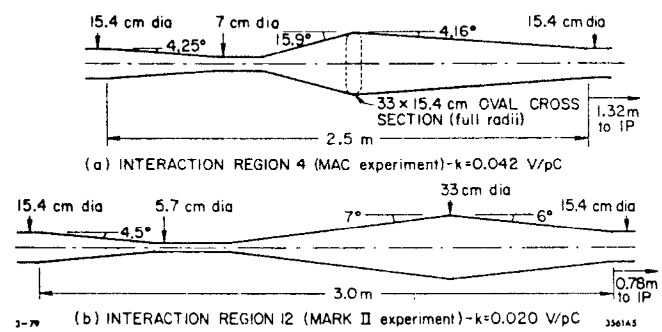

Fig. 5 Interaction region chambers (σ_z = 2.3 cm). There is symmetry about the interaction point (IP), so the total loss is twice that given above.