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PARASITIC MODE LOSS PARAMETERS*

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ABSTRACT

This note discusses various ways the parasitic mode losses from a bunched beam to a vacuum chamber can be measured, calculated or estimated. A listing of the parameter, k , for the various PEP ring components is included. A number of formulas for calculating multiple and single pass losses are discussed and evaluated for several cases.

I. Introduction

The interaction between a bunched, relativistic beam and its vacuum chamber can result in significant beam energy losses, especially if the peak bunch currents are as high as in a storage ring.¹ Most vacuum chamber components with changing cross sections have a multitude of low Q_0 resonances or reactances in the several hundred MHz to several GHz range. To what extent the individual resonances or reactances within a particular vacuum chamber contribute to a loss of beam energy depends in addition upon the bunch length.

The total power loss that results from a beam traversing a chamber is generally referred to as the parasitic mode loss, P_{pm} , for that component. This loss can be calculated from a parameter called the parasitic mode loss parameter, k_{pm} , that is simply one-half the voltage

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induced by a bunch of charge q_b passing through a vacuum chamber, or $V = 2kq_b$.

The energy, U , extracted from this bunch is then just the charge in the bunch times the average of the voltage induced by the same bunch. For what is called the single pass case, the voltage V , as defined above, decays to zero before the arrival of the next bunch. Thus, the average voltage equals $\frac{1}{2}V$, and $U = \frac{1}{2}q_b V = kq_b^2$. The power loss is calculated by considering a continuous stream of bunches passing through a component with a time interval T_b between bunches, or by considering a specific number of bunches, n_b , passing through a component repetitively with a revolution frequency f_r and an interval T_b between bunches. Furthermore, an average beam current, $i_o = q_b/T_b = n_b q_b f_r$, and a parasitic mode impedance, $Z_{pm} = k_{pm} T_b$, can be defined. Thus, the loss for a single beam is given by:

$$P_{pm} = q_b^2 k_{pm} / T_b = i_o^2 k_{pm} T_b = i_o^2 k_{pm} / n_b f_r = i_o^2 Z_{pm} \quad (1)$$

If there are two equal-magnitude, counter-rotating beams (for instance, electrons and positrons) in a machine, the loss is double, or

$$P_{pm} = 2q_b^2 k_{pm} / T_b = 2i_o^2 k_{pm} T_b = 2i_o^2 k_{pm} / n_b f_r = 2i_o^2 Z_{pm} \quad (2)$$

Also, it may be interesting to note that the loss is inversely proportional to how many bunches the current is spread out into; i.e., the loss is greatest if all the current in the machine is in one bunch!

As discussed further in Sect. II, k_{pm} is not solely a property of the geometry of a particular vacuum chamber, but is dependent also on the beam bunch length, σ_z , relative to the component dimensions. If the

voltage (wake field) induced in a component does not decay to zero before the next bunch comes along, an additional factor, F_R , must be included in Eqs. (1) and (2). This is discussed in more detail as the multiple pass case in Sect. III and in Ref. 2.

There are some components, such as the RF cavities, bellows, and separating plates, that have one or a few resonances that dominate or stand out in contributing to the component's total parasitic mode loss. In the case of the RF cavities, they are intentionally designed so that the lowest resonant frequency or fundamental mode is enhanced. Thus, for the RF cavities it is convenient for accounting purposes to itemize the fundamental mode, fm, and the sum of all the higher order modes, hm, separately. That is,

$$k_{pm} = k_{fm} + k_{hm} = Bk_{fm} \quad (3)$$

where B is defined as the beam-loading enhancement factor.³ Furthermore, it should be noted that the total ring pm loss specifically excludes only the RF cavity fm loss, since to include it would involve more of the details of the machine-operating conditions; that is, the cavity tuning, the synchronous phase angle, and the amount of RF drive. See Refs. 2 and 4 for a detailed discussion. The fm loss of all other components that are discussed or listed below is included with the hm loss in their pm loss.

PEP's parasitic-mode-shield bellows are calculated to incur most of their loss via a single travelling wave mode at 6 GHz.⁷ The shield bellows are small convolution, copper, folded bellows, concentric with and inside the welded, stainless steel vacuum bellows. They are used to decrease FM losses by shielding abrupt changes in the vacuum chamber

cross section from the beam image currents. Other storage rings notably, CESR⁵ and DESY⁶, use sliding contact shields inside their welded vacuum bellows to reduce and contain pm losses. Since the loss is a strong function of the component's resonant frequencies and the beam bunch length, the shield bellows can and have been designed to have little loss. The separating plates have a number of moderately high Q_0 resonances in the 400 to 1000 MHz range and above. A de-Quing electrode has been built into the separating plates to at least allow faster dissipation of the losses and thus prevent multi-turn field build-up and bunch to bunch coupling.

II. Methods for Calculating and Measuring k_{pm}

There are several ways to arrive at the value for the total parasitic mode loss parameter k_{pm} .

1. Computer Calculated: If axial symmetry exists, programs like KN7C or SUPERFISH can be used to calculate the R_0/Q_0 and resonant frequency for each mode. Then if a Gaussian distribution of charge is assumed along the bunch length, the following frequency-dependent weighting factor can be applied to the unweighted loss parameter, k_n , for each mode before summing them up to arrive at the total weighted loss parameter, k_{pm} .⁸ That is,

$$k_{pm} = \sum_{n=0}^{\infty} k_n \exp \left[- \left(\frac{\omega_n \sigma_z}{c} \right)^2 \right] = \sum_{n=0}^{\infty} \left(\frac{\omega_n}{4} \right) \left(\frac{R_0}{Q_0} \right)_n \exp \left[- \left(\frac{\omega_n \sigma_z}{c} \right)^2 \right], \quad (4)$$

where

$$k_n \equiv \frac{\omega_n}{4} \left(\frac{R_0}{Q_0} \right)_n. \quad (5)$$

For the RF cavities the k_{fm} is obtained from Eq. (4) by setting $n=0$. The k_{hm} is obtained by summing n from 1 to ∞ .

2. Swept Frequency Technique: If the chamber being investigated is treated as the outer conductor of a coaxial line segment, with matched transitions to a generator at one end and a detector at the other, it can be swept in frequency. If the resulting transmission plot consists of a number of non-overlapping resonant curves, the individual $(R_0/Q_0)_n$'s and ω_n 's can be determined directly from the plot. The k_n 's are given by:⁹

$$k_n \approx 2\pi Z_0 \Delta f_n (1 - T_n) \quad , \quad (6)$$

where Z_0 is the line's matched termination (usually 50 Ω), Δf_n is the full 3 dB bandwidth of the n^{th} resonance and T_n is the normalized transmitted power for the n^{th} resonance. Equation (4) can then be used to determine the total k_{pm} .

3. Simulated Pulse Technique: A pulse comparison technique¹⁰ can be used in the lab on air-filled models of the component to determine k_{pm} . This method neither yields nor requires any information as to which resonance contributes what. Also, the component can be modeled fairly simply (sheet metal techniques, etc.), since the Q_0 can be very, very poor without affecting the measurement accuracy. The main limitation to this technique is that of general measurement accuracy and how small a loss can be measured. With the pulse technique equipment that was used to measure many of the PEP components, values of $k_{pm} < 0.003$ V/pC were not clearly discernable.¹¹ For PEP, with three bunches per beam and 55 mA in each beam, that corresponds to a minimum measurable loss of 45 W. The groups at CESR and PETRA have devised simulated pulse measurement schemes

that are somewhat more complicated than the one used for PEP, and they have a resolution that perhaps can be a factor of 10 better. This was done by sacrificing flexibility and ease of measurement, especially with regards to physically large components.^{12,13} See the Appendix for some of the approximate formulas used to analyze the pulse shapes obtained by the technique.

4. Frequency Perturbation Method: The $(R_o/Q_o)_o$ and ω_o , and thus k_o for the fundamental mode, can be measured for a finished component (Q_o must be fairly good) by the standard dielectric bead or rod frequency perturbation methods.¹⁴ In some cases it may even be possible, although tedious, to measure the shunt impedance of a limited number of higher order modes, too.

5. Analytic Calculation: For special geometries, sometimes an estimate of the loss can be made from a fundamental electromagnetic field calculation. Two examples are the resistive wall losses of a smooth pipe¹⁵ and the radiation through multiple slots in the beam pipe walls to the storage ring distributed Vac-Ion pump chamber.¹⁶

6. Scaling: Estimating by scaling from components with known loss parameters can be very helpful. From Eq. (4) the following scaling relationship can be derived:

$$k'_{pm} = k_{pm} \left\{ \frac{\sum_{n=0}^{\infty} \frac{\omega_n}{4s} \left(\frac{R_o}{Q_o} \right)_n \exp \left[- \left(\frac{g \omega_n \sigma_z}{sc} \right)^2 \right]}{\sum_{n=0}^{\infty} \frac{\omega_n}{4} \left(\frac{R_o}{Q_o} \right)_n \exp \left[- \left(\frac{\omega_n \sigma_z}{c} \right)^2 \right]} \right\}, \quad (7)$$

where $1/s \hat{=} (\omega'_n/\omega_n)$, $g \hat{=} (\sigma'_z/\sigma_z)$ and the primed parameters are the desired quantities and the unprimed parameters are known or measured

quantities. Implied in the definition of s is the scaling of all dimensions by the same ratio; therefore, the $(R_o/Q_o)_n$'s do not change with scaling. As usual the dimensions scale inversely with the frequencies; i.e., $s = \ell'/\ell$. The following two cases are of special interest because they can be very useful.

(a) If $fg=1$, that is, $\omega'_n \sigma'_z = \omega_n \sigma_z$, Eq. (7) becomes:

$$k'_{pm} = k_{pm}/s \quad . \quad (8)$$

One possible application of this case is for a k_{pm} with a shorter σ'_z than is obtainable from the simulated pulse generator (method 3 above). The component would be built scaled up in size (down in frequency) in proportion to the ratio of the desired σ'_z and the shortest σ_z obtainable from the pulse generator. It should be noted from Eq. (8) that the measured value, k_{pm} , will be less than k'_{pm} , since for scaling to a shorter σ_z , $s < 1$. Thus, if the expected value of k'_{pm} is small, k_{pm} may not be accurately measurable or even measurable at all by this means.

(b) If $(R_o/Q_o)_n = 0$ for $n > 0$, that is, only a single resonance exists or predominates, Eq. (7) becomes:

$$\begin{aligned} k'_{pm} &= \frac{k_{pm}}{s} \exp \left[\left(\frac{\omega_o \sigma_z}{c} \right)^2 \right] \exp \left[- \left(\frac{g \omega_o \sigma_z}{sc} \right)^2 \right] \\ &= \frac{k_o}{s} \exp \left[- \left(\frac{g \omega_o \sigma_z}{sc} \right)^2 \right] \quad . \end{aligned} \quad (9)$$

Some periodic structures such as the CERN vacuum chamber or any corrugated pipe with the periodicity less than the σ_z can be scaled with Eq. (9).

Furthermore, if a component has a periodic nature and its length is much greater than its diameter, it probably can be considered to have

a loss that is linearly proportional to its length and thus can be specified in terms of a k/unit length. The CERN vacuum chamber and the PEP shield bellows are two such components.

Also, it should be pointed out that, if methods 1 or 2 are used to find the known k_{pm} , Eq. (7) can be used directly with the appropriate f and g to sum all the calculated or measured values, respectively, of the $(R_o/Q_o)_n$'s and ω_n 's and determine the desired k' .

If a structure has a number of contributing resonances, such as the higher order modes of an RF cavity, simulated pulse measurements and computer calculations give the following approximation for the dependence of the higher order mode loss parameter on the bunch length:

$$k_{hm} = a \exp(-b\sigma_z) \quad , \quad (10)$$

where for three different RF cavities, a and b are given by:^{3,11,17}

CAVITY TYPE (ONE CELL ONLY)		a(V/pC)	b(cm ⁻¹)
TM ₀₁₀	CAV-38 cm dia x 23 cm with 7.6 cm dia drift pipes	0.70	0.32
TM ₀₁₀	CAV-38 cm dia x 23 cm with 15.3 cm dia drift pipes	0.46	0.31
SPEAR II RF CAVITY with 15.3 cm dia drift pipes and nose cones (358 MHz)		0.54	0.45

Note that the drift tube diameter has a large effect on the value of k_{hm} . Other shapes can have more complicated dependencies upon σ_z .¹¹

7. Measurements on the Operating Storage Ring: The total parasitic mode loss of an operating storage ring, with the RF cavity fm loss excluded as noted in Sect. I above, can be measured by varying the beam

current and noting the resulting change in the synchronous phase angle, which is proportional to the total beam energy loss.¹ The difference between the computed or pulse measurements of the active or driven RF cavity hm losses and the measured total ring pm loss is the ring vacuum chamber pm loss. If a RF cavity is not being driven from an RF source, its tuning and therefore its multiple pass fm losses must be subtracted out too to get the vacuum chamber pm loss. This measurement has been done for SPEAR II and PETRA^{4,18,19} as a function of σ_z . Currently, only the values for PEP's individual components have been computed, estimated or measured in the lab by simulated pulse techniques, etc. The resulting k_{pm} values for PEP are given in considerable detail in Sect. IV. The total k_{pm} for PEP has yet to be measured experimentally during stored beam operation. An equation similar to Eq. (10) gives the total machine loss parameter as follows:

$$k_{pm}(V/pC) = a[\sigma_z(cm)/2.3]^{-b} \quad , \quad (11)$$

where for SPEAR II, PETRA and PEP the following values apply:

STORAGE RING	RF* Cells	a	b	n_b	f_r (MHz)
SPEAR II (excluding RF cav)	0	15.3	1.23	1	1.2804
SPEAR II (including RF cav)	20	18.6	1.21	"	1.2804
PEP** (excluding RF cav)	0	25	1.21- 1.23	3	0.1352
PEP** (including RF cav)	120	35	"	"	"
PETRA (including RF cav)	300	50	1.30	4	0.1302

* Number of RF cavity cells included in the k_{pm} described by the a and b values.

** The values for a and b are based on the estimated, computed and simulated pulse measured values given in Sect. IV.

III. Multiple Pass Case

If a component has a relatively high Q_L for one of its resonant modes and the inverse of T_b is harmonically related to the component's resonant frequency, the multiple pass case must be considered for that mode. The multiple pass case reduces to the single pass case if (1) the time of arrival of the bunch is unknown or random relative to the phase of the initially-induced fields, or (2) the decay time is short compared to the time between bunches; i.e., the fields decay away before the next bunch arrives. It follows, therefore, that most parasitic mode losses fall into the single pass category, with the fundamental modes of the RF cavities and the feedback cavities being the notable multiple pass exceptions.

For the multiple pass case for a single beam, the loss is given by:

$$P_{pm} = P_{fm} + P_{hm} = i_o^2 k_o I_b F_R + i_o^2 k_{hm} T_b \quad , \quad (12)$$

where F_R is the fundamental mode resonance factor due to the vector summation of all of the induced fields that do not decay completely between passages of a bunch. It is given by:

$$F_R = \frac{(1 - e^{-2\tau})}{(1 - 2e^{-\tau} \cos \delta + e^{-2\tau})} \quad , \quad (13)$$

where $\tau = T_b/T_f$ and δ is the phase change of the fundamental mode frequency between the passage of successive bunches. The fundamental mode-loaded filling time, T_f , is given by:

$$T_f = \frac{2Q_o}{\omega_o(1 + \beta)} \quad , \quad (14)$$

where β is the coupling coefficient of the RF cavity to the RF drive source (external load also when the drive is off). The phase-shift δ is related to the cavity tuning angle ψ by $\delta = \tau \tan \psi$.⁴ Using Eqs. (7), (12), and (14) with $n=0$, the fundamental loss is given by:

$$P_{fm} = \frac{I_o^2 R_o}{(1+\beta_o)} \left(\frac{\tau F_R}{2} \right) \exp \left[- \left(\frac{\omega_o \sigma_z}{c} \right)^2 \right] \quad (15)$$

The power dissipation in the RF cavities in the fundamental mode depends upon the cavity tuning and whether they are driven or not. If they are driven, the calculation is even more complicated and dependent upon several optimization conditions. A PEP computer program, RIPPLES,²³ makes that calculation and the calculation is explained in Refs. 2, 4, and 20.

However, it is interesting to note that, if the RF is off and the RF cavities are tuned to one or the other of three states (resonances, a random frequency relative to a harmonic of the bunch going around frequency, or anti-resonance), the power dissipated in them can be quite different, as seen in the following equation for the power lost to the fundamental mode. Note that from Eq. (12) the hm power is the same for all three cases and that it must be added to the fundamental mode loss to get the total parasitic mode loss for an idling cavity.

1. Resonant tuning ($\cos \delta = 1$) and no RF drive,

$$P_{fm@res} = I_o^2 \left(\frac{R_o}{1+\beta} \right) \left(\frac{\tau}{2} \right) \left(\frac{1+e^{-\tau}}{1-e^{-\tau}} \right) \quad \text{or} \quad (16)$$

$$= \frac{I_o^2 R_o}{(1+\beta)} \quad \text{for } \tau \ll 1 \quad (17)$$

2. Random or unknown tuning (F_R averages out to 1)¹⁰ and no RF drive,

$$P_{fm@random} = \frac{i_o^2 R_o}{(1+\beta)} \left(\frac{\tau}{2} \right) \quad (18)$$

3. Anti-resonant tuning ($\cos\delta = 1$) and no RF drive,

$$P_{fm@anti-res} = \frac{i_o^2 R_o}{(1+\beta)} \left(\frac{\tau}{2} \right) \frac{1-e^{-\tau}}{1+e^{-\tau}} \quad \text{or} \quad (19)$$

$$= \frac{i_o^2 R_o}{(1+\beta)} \left(\frac{\tau}{2} \right)^2 \quad \text{for } \tau \ll 1 \quad (20)$$

If the cavity is idling (no RF drive), it is clear from Eqs. (17), (18), and (20) that it should not be left tuned to resonance. Preferably, it will be tuned midway between the two resonances; that is, it will be tuned to anti-resonance with a resulting power dissipation that is $(\tau/2)^2$ as much as for resonance tuning. For PEP,¹⁴

$$\left(\frac{\tau}{2} \right) = \frac{2\pi \times 353.21 \times 10^6 \times (1+1.5)}{3 \times 136.28 \times 10^3 \times 2 \times 2 \times 26300} = \frac{1}{7.756} = 0.129 \quad (21)$$

where $Q_o = 26,300$, $\beta = 1.5$, $n_b = 3$, $f_r = 136.28$ KHz, and $f_o = 353.21$ MHz.

Also, $R_o/\text{cell} = 7.6 \times 10^6 \Omega$, $F_R@res = 7.8$, $F_R@random = 1$, and $F_R@anti-res = (1/7.8)$. For $i_o = 55$ mA in each beam, the power lost in each of the five individual cells (or cavities) of the PEP RF cavities for tuning on resonance, randomly tuned or for anti-resonant tuning, is:

$$P_{fm@res/RF \text{ cell}} = \frac{2i_o^2 R_o}{(1+\beta)} = 18.4 \text{ kW} \quad (22)$$

$$P_{fm@random/RF \text{ cell}} = \left(\frac{2i_o^2 R_o}{(1+\beta)} \right) \left(\frac{\tau}{2} \right) = 2.4 \text{ kW} \quad (23)$$

$$P_{fm@anti-res/RF \text{ cell}} = \left(\frac{2i_o^2 R_o}{(1+\beta)} \right) \left(\frac{\tau}{2} \right)^2 = 0.3 \text{ kW} \quad (24)$$

Thus, by tuning to anti-resonance, or "parking" a cavity pair (ten RF cells) when the klystron is turned off, the beam power loss to the fundamental mode can be reduced from a high value of 185 kW to 3 kW, or a decrease of approximately 180 kW per turned-off klystron as a result of parking. The RF cavity hm losses will remain constant since selective de-Qing of those modes was not attempted. With a $k_{hm} = 0.20$ V/pC per RF cell, the hm power loss is:

$$P_{hm/RF \text{ cell}} = 2i_0^2 k_{hm} T_b = 2 \times (.055)^2 \times .20 \times 10^{12} \times 2.446 \times 10^{-6} \\ = 3 \text{ kW} \quad (25)$$

Thus, the parasitic mode power loss associated with the ten RF cells (2 RF cavities) connected to one of the 500 kW cw klystrons can be in the range of 33 to 215 kW with two 55 mA beams and no RF drive, depending upon the tuning of those cavities!

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APPENDIX

A. Methods for Calculating k from the Simulated Pulse Technique Data

The simulated pulse technique requires a lab measurement of a coaxial version of the component. A wire is run through the item with suitable smooth coaxial transitions to both the pulse generator and detector. With a wire thru the component, the characteristic impedance is typically greater than 200 Ω while the detector and pulse generator impedances are 50 Ω .

The pulse width should be approximately Gaussian and be the same width in time as the bunched beam for which the measurement is to be used. The measurement consists of comparing the transmitted (or detected) pulse shape for the case of a smooth outer conductor (reference pipe) with the pulse shape for the case when the outer conductor is the particular shape of interest. The reference pipe is assumed to be lossless or have negligible loss¹⁵ and should be approximately the same length as the component. If the reactive impedance is desired, the length must be identical or some sort of precursor must be used to allow proper overlay of the reference and measured pulses.¹² For the PEP measurements the resistive loss was assumed dominant,²¹ and therefore only it was measured. Since the pulse lengths of interest are quite short (~100 ps), a sampling (TDR) oscilloscope and accessories (tunnel diode pulser and sampling detector) seems to be the best tool. In order to get any degree of accuracy for small losses the pulse jitter in amplitude and time must be kept very small (<0.1% and <1 ps, respectively). At PEP this was accomplished by thermally stabilizing the pulses, detector and oscilloscope environments to better than 1°C. First, the reference pulse was recorded with an x-y

recorder and then the component, under test, was substituted into the circuit and its pulse was recorded over the reference pulse. Initially, the graphed pulses were digitized by hand with an ultrasonic curve digitizer and fed into a computer for computation using the following formula,²²

$$k_{pm} = \left(\frac{2R_o}{q_b^2} \right) \int_{\text{pulse}} [i_o(t) - i_m(t)] i_o(t) dt \quad . \quad (26)$$

The reference and measured pulses as a function of time are given by $i_o(t)$ and $i_m(t)$, the characteristic impedance of the coaxial reference pipe is given by R_o , and q_b is the total charge in the pulse. One can argue that q_b is the charge in the reference pulse or that it is the average of the reference and the measured pulse. A slightly larger value for k results from the latter definition, which is the one used here.

$$q_b = \frac{1}{2} \int_{\text{pulse}} [i_o(t) + i_m(t)] dt \quad . \quad (27)$$

After making a number of measurements, it was found that the pulses were sufficiently Gaussian to allow the k_{pm} to be calculated to an accuracy of better than 10%, if only the pulse peak amplitudes, I_o and I_m , and the FWHM's (full-width half-maximum) were scaled off the graphs and used with the following Gaussian formulas,

$$i_o(t) = I_o \exp \left[-\left(\frac{t^2}{2\sigma_o^2} \right) \right] \quad , \quad (28)$$

and

$$i_m(t) = I_m \exp \left[-\left(\frac{(t - t_m)^2}{2\sigma_m^2} \right) \right] \quad . \quad (29)$$

If Eq. (26) is integrated, using Eqs. (27), (28), and (29), k can be

obtained very simply from plots of the measured and reference pulses.

$$k_{pm} = \left(\frac{R_o}{\sqrt{\pi} \sigma_o} \right) \frac{\left[1 - \left(\frac{I_m}{I_o} \right) \frac{\exp \left[-\left(t_m^2 / 2(\sigma_o^2 + \sigma_m^2) \right) \right]}{\sqrt{\frac{1}{2} + \frac{1}{2}(\sigma_o/\sigma_m)^2}} \right]}{\left[\frac{1}{2} + \frac{1}{2} \left(\frac{\sigma_m}{\sigma_o} \right) \left(\frac{I_m}{I_o} \right) \right]^2} \quad (30)$$

The FWHM is related to the standard deviation, σ , by: $FWHM = 2.355\sigma$. See Fig. 1 for the various pulse definitions. The quantity t_m is the pulse offset and has to be quite large (on the order of 10% of σ), to produce a significant effect (like 100% for $k = 0.003$, which is nominally the minimum detectable k). This is fortunate since it is very difficult to measure t_m as accurately as σ can be measured. However, in most cases, Eq. (30) can be further simplified to:

$$k_{pm} = \left(\frac{R_o}{\sqrt{\pi} \sigma_o} \right) \frac{\left[1 - \left(\frac{I_m}{I_o} \right) \frac{1}{\sqrt{\frac{1}{2} + \frac{1}{2}(\sigma_o/\sigma_m)^2}} \right]}{\left[\frac{1}{2} + \frac{1}{2} \left(\frac{\sigma_m}{\sigma_o} \right) \left(\frac{I_m}{I_o} \right) \right]^2} \quad (31)$$

If a slightly different definition for k_{pm} than given by Eq. (26) is used, i.e.,

$$\bar{k}_{pm} = \left(\frac{2R_o}{q_b^2} \right) \int_{\text{pulse}} [i_o(t) - i_m(t)] \left(\frac{i_o + i_m}{2} \right) dt \quad (32)$$

then t_m drops out and

$$\bar{k}_{pm} = \left(\frac{R_o}{2\sqrt{\pi} \sigma_o} \right) \frac{\left[1 - \left(\frac{\sigma_m}{\sigma_o} \right) \left(\frac{I_m}{I_o} \right)^2 \right]}{\left[\frac{1}{2} + \frac{1}{2} \left(\frac{\sigma_m}{\sigma_o} \right) \left(\frac{I_m}{I_o} \right) \right]^2} \quad (33)$$

Fig. 1. Gaussian pulse definitions for the simulated pulse measurement approximation formulas. Note that the σ_t and FWHM parameters should be further subscripted with o and m for the reference and measured pulses.

In the limit of $(\sigma_m/\sigma_o) \rightarrow 1$ and $(I_m/I_o) \rightarrow 1$, Eqs. (31) and (33) converge to:

$$k \approx \bar{k} \approx \left(\frac{R_o}{\sqrt{\pi} \sigma_o} \right) \frac{\left[1 - \left(\frac{\sigma_m}{\sigma_o} \right)^2 \left(\frac{I_m}{I_o} \right) \right]}{\left[\frac{1}{2} + \frac{1}{2} \left(\frac{\sigma_m}{\sigma_o} \right) \left(\frac{I_m}{I_o} \right) \right]^2} \quad (34)$$

So, take your pick!

At Cornell a coaxial difference circuit was used to give the difference directly between two parallel, exactly equal length arms, of which one consisted of the reference pipe and one consisted of the component under test. This difference signal was digitized and averaged over many pulses with a signal averager and fed to a computer for the calculation of the parasitic mode loss parameter. The resulting measurements were more accurate than the PEP measurements, but, on the other hand, the modeling of various large components was not attempted due to mechanical limitations.

B. Corrections for the Oscilloscope Rise Time

If the oscilloscope has a 10% to 90% rise time, t_r , the actual FWHM and σ are given by:

$$(\text{FWHM})_{\text{act}} = \sqrt{(\text{FWHM})_{\text{meas}}^2 - \left(\frac{2.355 t_r}{2.568} \right)^2} \quad (35)$$

and

$$\sigma_{\text{act}} = \sqrt{\sigma_{\text{meas}}^2 - \left(\frac{t_r}{2.568} \right)^2} \quad (36)$$

For $t_r = 35$ ps and $\sigma_{\text{meas}} = 2.0$ cm = 66.7 ps or $(\text{FWHM})_{\text{meas}} = 157$ ps, $\sigma_{\text{corr}} = 65.3$ ps or a correction of 2.1%. From Eqs. (31) or (33) one can

see that this correction applies inversely to k_{pm} , also. Only when σ becomes comparable to t_r does the correction in σ approach 10%.

C. Tolerances and Limits to Accuracy

Besides the rise times discussed above, signal jitter and drift with time limit the accuracy of the measurement. For both Eqs. (31) or (33), the sensitivity of k_{pm} to σ and I is given by:

$$\frac{\partial k}{\partial I_o} = \frac{A_o}{I_o}, \quad \frac{\partial k}{\partial I_m} = -\frac{A_o}{I_m}, \quad \frac{\partial k}{\partial \sigma_o} = \frac{A_o}{\partial \sigma_o}, \quad \frac{\partial k}{\partial \sigma_m} = -\frac{A_o}{\partial \sigma_o},$$

where $A_o = (R_o / \sqrt{\pi} \sigma_o)$. Therefore,

$$dk = \sqrt{\left(\frac{\partial k}{\partial I_o} dI_o\right)^2 + \left(\frac{\partial k}{\partial I_m} dI_m\right)^2 + \left(\frac{\partial k}{\partial \sigma_o} d\sigma_o\right)^2 + \left(\frac{\partial k}{\partial \sigma_m} d\sigma_m\right)^2 + (\Delta k_{tm})^2}. \quad (37)$$

For a typical case of a 6" I.D. reference pipe with a 3/32" dia. center conductor and an $I_o = 80$ and a $\sigma_o = 66.7$ ps or $(FWHM)_o = 157$ ps, one has $R_o = 249.5\Omega$ and $A_o = 2.11$. For small losses it is reasonable to assume that $I_m \approx I_o$ and $\sigma_m \approx \sigma_o$. From repeated measurements it appears that: $dI_o \leq 0.1$, $d(FWHM) \leq 0.5$ ps, and $t_m \leq 5$ ps. Evaluating Eq. (37) with $\Delta k_{tm} \equiv k$ for $I_m = I_o$, $\sigma_o \approx \sigma_m$, and $t_m = 5$ ps:

$$dk \leq \sqrt{(.0026)^2 + (.0026)^2 + (.0034)^2 + (.0034)^2 + (.003)^2}$$

$$\leq 0.0067 \text{ V/pC},$$

or $k_{actual} = k_{meas} \pm 0.003 \text{ V/pC}$. For two 55 mA beams of three bunches each $P_{pm actual} = P_{pm meas} \pm 50 \text{ W}$.

D. PEP Vacuum Chamber (Parasitic Mode) and RF Cavity (Higher Order Mode)

Loss Factors by Significant Component Groupings Around the Ring from

Simulated Pulsed Test Measurements, Estimates, and Guesses^{24,25}

REGION	NAME ¹	COMPONENT DESCRIPTION	k(V/pC)	DETERMINED BY ²
IR 12	IP 12	MARK II - PEP 5	.100+	E/M
12B	VQ1/VO1/VQ2/RED	See note 3	.040	E/G
12B	VALV	6" Gate valve (VAT)	.006	M
12B	SEP	Separating plates	.140	M
12B	HZ36	High Z mask	.025	E/M
12B	VALV	6" gate valve (VAT)	.006	M
12B	SM1/TR1/SM2	Synch. rad. masks & transition	.042	E/M
1A	<VALV>	Future 6" gate valve (VAT)	<.006>	M
1 SYMM	TSB/WS/TSW/WIG	WIGGLER and transitions	.060	E/M
2A	SM2/TR1/SM1	Synch. rad. masks & transition	.042	E/M
2A	VALV	6" gate valve (VAT)	.006	M
2A	HZ36	High Z mask	.025	E/M
2A	<ELQ>	Future electric quadrupole	<.090+>	E/G
2A	SEP	Separating plates	.140	M
2A	VALV	6" gate valve (VAT)	.006	M
2A	RED/VQ2/VO1/VQ1	See note 3	.040	E/G
IR 2	IP 2	TPC/2γ - PEP 9/4	.220+	E/M
2B	VQ1/VO1/VQ2/RED	See note 3	.040	E/G
2B	VALV	6" gate valve (VAT)	.006	M
2B	SEP	Separating plates	.140	M
2B	<ELQ>	Future electric quadrupole	<.090+>	E/G
2B	HZ36	High Z mask	.025	E/M
2B	VALV	6" gate valve (VAT)	.006	M
2B	SM1/TR1/SM2	Synch. rad. masks & transition	.042	E/M
3A	VALV	6" gate valve (VAT)	.006	M
3 SYMM	V21/22/T3	Drift pipes <ceramic pipe> & transitions	.036<+>	M

REGION	NAME ¹	COMPONENT DESCRIPTION	k(V/pC)	DETER- MINED BY ²
3B	VALV	6" gate valve (VAT)	.006	M
4A	SM2/TR1/SM1	Synch. rad. masks & transition	.042	E/M
4A	VALV	6" gate valve (VAT)	.006	M
4A	HZ36	High Z mask	.025	E/M
4A	SEP	Separating plates	.140	M
4A	VALV	6" gate valve (VAT)	.006	M
4A	RED/VQ2/VO1/VQ1	See note 3	.040	E/G
IR 4	IP 4	MAC - PEP 6	.105+	E/M
4B	VQ1/VO1/VQ2/RED	See note 3	.040	E/G
4B	VALV	6" gate valve (VAT)	.006	M
4B	SEP	Separating plates	.140	M
4B	RFC (3)	Three RF cavities	(3.150)	M
4B	HZF	High Z mask	.025	E/M
4B	RFC (5)	Five RF cavities	(5.250)	M
4B	VALV	6" gate valve (VAT)	.006	M
4B	TR1/SM2	Synchrotron radiation mask	.027	E/M
5A	<VALV>	Future 6" gate valve (VAT)	<.006>	M
5 SYMM	TSB/TSW/WIG	WIGGLER	.060	E/M
5 SYMM	FFC	Fast feed back cavity	1.000	E/M
6A	SM2/TR1/SM1	Synch. rad. masks & transition	.042	E/M
6A	VALV	6" gate valve (VAT)	.006	M
6A	HZ36	High Z mask	.025	E/M
6A	<ELQ>	Future electric quadrupole	<.090+>	E/G
6A	SEP	Separating plates	.140	M
6A	VALV	6" gate valve (VAT)	.006	M
6A	RED/VQ2/VO1/VQ1	See note 3	.040	E/G

REGION	NAME ¹	COMPONENT DESCRIPTION	k(V/pc)	DETER-MINED BY ²
IR 6	IP 6	QUARK - PEP 14	.140	M/E
6B	VQ1/VQ1/VQ2/RED	See note 3	.040	E/G
6B	VALV	6" gate valve (VAT)	.006	M
6B	SEP	Separating plates	.140	M
6B	CUR	Current monitor	~.000	G
6B	<ELQ>	Electric quadrupole	<.090>	E/G
6B	HZ36	High Z mask	.025	E/M
6B	VALV	6" gate valve (VAT)	.006	M
6B	SM1/TR1/SM2	Synch. rad. masks & transition	.042	E/M
7A	<VALV>	Future 6" gate valve (VAT)	<.006>	M
7 SYMM	SLM	Synchrotron light monitor	.100	M
7B	<VALV>	Future 6" gate valve (VAT)	<.006>	M
8A	SM2/TR1	Synchrotron radiation mask	.027	E/M
8A	VALV	6" gate valve (VAT)	.006	M
8A	RFC (5)	Five RF cavities	(5.250)	M
8A	HZF	High Z mask	.025	E/M
8A	RFC (3)	Three RF cavities	(3.150)	M
8A	ELQ	Electric quadrupole	.090	E/G
8A	SEP	Separating plates	.140	M
8A	VALV	6" gate valve	.006	M
8A	RED/VQ2/VQ1/VQ1	See note 3	.040	E/G
IR 8	IP 8	SUPER DELCO (PEP 15)	.055	E
8B	VQ1/VQ1/VQ2/RED	See note 3	.040	E/G
8B	VALV	6" gate valve (VAT)	.006	M
8B	SEP	Separating plates	.140	M
8B	KI1	First injection kicker	.100	E/G
8B	BI1	First beam bump magnet	.030	E/M
8B	ELQ	Electric quadrupole	.090	E/G
8B	PPS	Personnel protection stopper	.015	M

REGION	NAME ¹	COMPONENT DESCRIPTION	k(V/pC)	DETER- MINED BY ²
8B	BM2	Second beam bump magnet	.030	E/M
8B	HZF	High Z mask	.025	E/M
8B	KI2	Second injection kicker	.100	E/G
8B	LAM	Lambert septum	.100	G
8B	BM3	Third beam bump magnet	.030	E/M
8B	PPS	Personnel protection stopper	.015	M
8B	SCR	Scraper (vert. and horiz.)	.003	M
8B	BM4	Fourth beam bump magnet	.030	E/M
8B	KI3	Third injection kicker	.100	E/G
8B	VALV	6" gate valve (VAT)	.006	M
8B	SM1/TR1/SM2	Synch. rad. masks & transition	.042	E/M
9A	<VALV>	Future 6" gate valve (VAT)	<.006>	E/M
9 SYMM	WST/TSW/WIG	WIGGLER	.060	E/M
10A	SM2/TR1/SM1	Synch. rad. masks & transition	.042	E/M
10A	VALV	6" gate valve (VAT)	.006	M
10A	KI3	Third injection kicker	.100	E/G
10A	BM4	Fourth beam bump magnet	.030	E/M
10A	BM3	Third beam bump magnet	.030	E/M
10A	LAM	Lambert septum	.100	E/G
10A	KI2	Second injection kicker	.100	E/G
10A	HZF	High Z mask	.025	E/M
10A	BM2	Second beam bump magnet	.030	E/M
10A	<ELQ>	Electric quadrupole	<.090+>	E/G
10A	BM1	First beam bump magnet	.030	E/M
10A	KI1	First injection kicker	.100	E/G
10A	SEP	Separating plates	.140	M
10A	VALV	6" gate valve (VAT)	.006	M
10A	RED/VQ2/VQ1/VQ1	See note 3	.040	E/G

REGION	NAME ¹	COMPONENT DESCRIPTION	k(V/pC)	DETER- MINED BY ²
IR 10	IP 10	MAGNET MONOPOLE - PEP 2	.090	E
10B	VQ1/VQ1/VQ2/RED	See note 3	.040	E/G
10B	VALV	6" gate valve (VAT)	.006	M
10B	SEP	Separating plates	.140	M
10B	<ELQ>	Electric quadrupole	<.090>	E/G
10B	HZ36	High Z mask	.025	E/M
10B	VALV	6" gate valve (VAT)	.006	M
10B	SM1/TR1/SM2	Synch. rad. masks & transition	.042	E/M
11A	<VALV>	Future 6" gate valve (VAT)	<.006>	M
11 SYMM	TI1S/BEX	Beam excitation & pickup electrodes	.090	M
11B	<VALV>	Future 6" gate valve (VAT)	<.006>	M
12A	SM2/TR1	Synch. rad. masks & transition	.027	E/M
12A	VALV	6" gate valve (VAT)	.006	M
12A	RFC (5)	Five RF cavities	(5.250)	M
12A	HZF	High Z mask	.025	E/M
12A	RFC (1)	Three RF cavities	(3.150)	M
12A	SEP	Separating plates	.140	M
12A	VALV	6" gate valve (VAT)	.006	M
12A	RED/VQ2/VQ1/VQ1	See note 3	.040	E/G

REGION	NAME ¹	COMPONENT DESCRIPTION	k(V/pC)	DETERMINED BY ²
DISTB'D		~300 PM shield pump ports	<0.900	E/M
DISTB'D	BL1,2	~240 6" & 8" shielded bellows	<1.440	E/M/C
DISTB'D	VO8,9	~96 Distributed ion pumps in 14 m chambers	<0.288	E
		TOTAL IR HALLS	0.710	
		TOTAL OF ITEMIZED RING COMPONENTS EXCLUDING RF CAVITIES	6.316	
		TOTAL OF DISTRIBUTED COMPONENTS	<2.628	
		CONTINGENCY FOR MISCELLANEOUS DISCONTINUITIES	<u>0.360</u>	
		TOTAL VACUUM COMPONENTS (RF CAVITY EXCLUDED)	<u>/10.0/</u>	+ 29%
		24 RF CAVITIES (120 CELLS) - EXCLUDING FUNDAMENTAL MODE	<u>/24.0/</u>	+ 71%
		RING TOTAL HOM LOSS PARAMETER	<u>/34.0/</u>	+ 100%
		24 RF CAVITIES (120 CELLS) FUNDAMENTAL MODE LOSS PARAMETER	18.6	

For an electron and a positron beam, each consisting of three equally spaced bunches (six bunches total) and with an average current, I_0 , in each of the beams: $P = 2I_0^2 Z$, where $Z = kT_b$.

For PEP $I_0 = 55$ mA and $T_b = 2.446 \times 10^6$ ps; therefore,

$$P(\text{kW}) = 14.8 \text{ k(V/pC)} \text{ and } Z(\text{M}\Omega) = 2.446 \text{ k(V/pC)} \\ = 6.05 Z(\text{M}\Omega)$$

For the current configuration:

$$Z_{\text{vac}} = 24.5 \text{ M} ; \quad Z_{\text{RFC}} = 58.7 \text{ M}\Omega ; \quad Z_{\text{TOT}} = \underline{83.2} \text{ M}\Omega ; \\ P_{\text{vac}} = 148 \text{ kW} ; \quad P_{\text{RFC}} = 355 \text{ P}_{\text{TOT}} ; \quad P_{\text{TOT}} = \underline{503} \text{ kW} .$$

NOTES:

1. The NAME is a cryptic form or acronym for the item and is the same as given in H. Wiedemann's computer list of the "Layout of the PEP Vacuum System."
2. The given k factor was obtained by: M = measured by simulated pulse tests; E = estimate based upon scaling from measurements; G = educated guess; and C = computer calculations.
3. This series consists of the vacuum chambers for Q1 and Q2, for the multipole chamber at Q1 - Q2, and for the bellows to Q2 chamber reducer.

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