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HOM Power Propagation and Attenuation in PEP-II B-Factory

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HOM power propagation and attenuation in PEP-II B-factory*

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Abstract

Most of the higher-order-mode (HOM) power that propagates in the PEP-II rings is generated in the RF cavities but its content in terms of TE and TM components has not been accurately determined. For purpose of shielding beamline components such as bellows and BPMs from TE power penetration and determining the heating on the cavity HOM absorber, this HOM power content and its distribution profile around the rings are needed. This paper calculates the TE and TM contributions of the RF cavities to the circulating HOM power and their transmission properties at another cavity downstream. By considering both the generation in, and scattering by the cavities, as well as the attenuation along the vacuum chamber, a complete distribution profile for the TE and TM HOM power can be obtained.

1 HOM POWER GENERATION IN PEP-II

The PEP-II B-factory is a high current machine that generates enormous amount of RF energy in the vacuum chamber. The total HOM power for all beamline elements is estimated to be $P_0 = 200$ Kilowatts[1]. Assuming that the HOM power is uniformly generated around a storage ring and the attenuation length l is constant for all the propagating modes of the vacuum chamber, the HOM power P at any location of the ring is given by the equilibrium condition

$$dP/dz + P_0/L = -P/l + P_0/L = 0, \tag{1}$$

where L, the PEP-II ring circumference, is 2200 m. The straight sections of the PEP-II rings consist of stainless steel pipes with a diameter of 9.525 cm. The attenuation length of the TM_{01} mode in these pipes is about 60 m at 5 GHz, the roll-off frequency of the PEP-II nominal 1 cm bunch. Thus the resulting HOM power at any ring location is roughly given by

$$P = \frac{l}{L} P_0 = 5.5\,\text{KW}. \tag{2}$$

2 MULTIPLE REFLECTIONS

The above calculation assumes no reflections by beamline elements. On the contrary, multiple reflections may happen even in a two-element network. To illustrate the significance of multiple reflections, we study the cascade of two simple 2-port elements as shown in Fig. 1. Here, S represents the scattering matrix of the two identical elements,

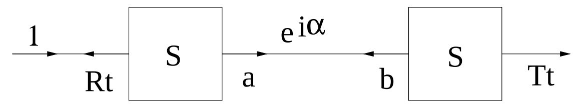

Figure 1: Cascade two 2-port elements with one unit of power incident from left.

and $e^{i\alpha}$ indicates the propagation through the beampipe between the two elements. The amplitudes of the right-going and left-going waves between the two elements are represented by a and b, respectively. We parameterize the S-matrix in the form of

$$S = \begin{bmatrix} r & i\sqrt{1-r^2} \\ i\sqrt{1-r^2} & r \end{bmatrix}, \tag{3}$$

where r represents the reflection coefficient. The particular form is chosen to satisfy symmetry and unitarity. With one unit of power incident from the left, the total transmission T_t is obtained by summing over all the reflections as follows:

$$T_t = Te^{i\alpha}T(1 + re^{i\alpha}re^{i\alpha}(1 + re^{i\alpha}re^{i\alpha}(1 + ...))), \tag{4}$$

where $T = S_{12} = i\sqrt{1-r^2}$. The first term is the direct transmission, and the second term has two extra reflections on the network interfaces and two extra phase propagations. Summing the geometric series, we obtain

$$T_t = -(1-r^2)\frac{e^{i\alpha}}{1-r^2e^{2i\alpha}}. \tag{5}$$

Following the same procedure, we also have

$$R_t = r\frac{1-e^{2i\alpha}}{1-r^2e^{2i\alpha}} \tag{6}$$

$$a = \frac{i\sqrt{1-r^2}}{1-r^2e^{2i\alpha}} \tag{7}$$

$$b = re^{i\alpha}a. \tag{8}$$

In Fig. 2, the transmission coefficient and amplitudes a and b are plotted as a function of the phase α. One prominent consequence of multiple reflections is the power enhancement with respect to the input power at certain α. It can be seen that resonant transmissions are evident at $\alpha = 0^o, 180^o, 360^o$. At resonance, due to coherent addition, the amplitudes a and b can be substantially higher than the input amplitude. For example, for $r = 0.8$, as much as $a^2 + b^2 = 4.56$ times of the input power flows in the beampipe between the elements at resonance.

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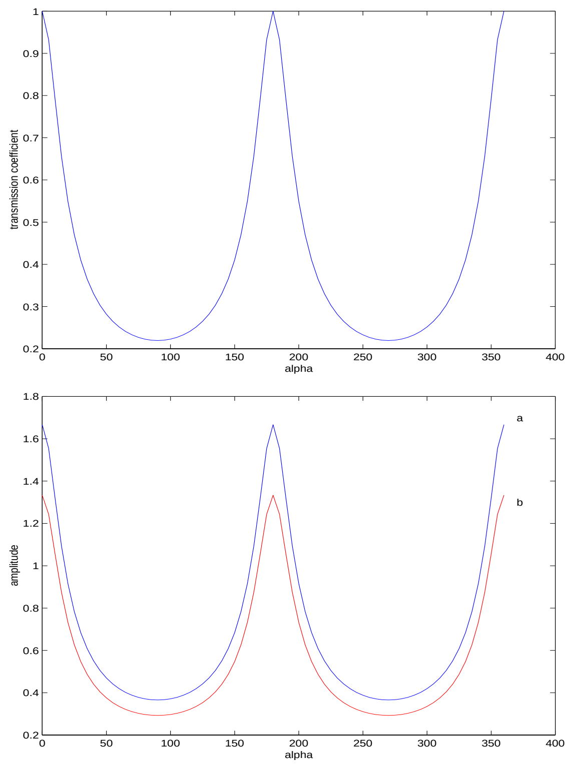

Figure 2: Amplitude T_t (upper figure), a and b (lower figure) as a function of α. The r is 0.8.

3 APPLICATIONS TO PEP-II

Several factors need to be considered in applying the simple two 2-port elements model to the PEP-II rings. First, the power generation in a PEP-II ring is not uniform. The layout of the PEP-II rings is illustrated in Fig. 3. There are 6 straight and 6 bending regions numbered according to the clock face. The HOM power is mainly generated by the RF cavities which are located in some of the straight sections. For the High Energy Ring (HER), the RF cavities are located in Region 8 and Region 12. Currently 8 cavities have been installed in Region 12 as shown in Fig. 4.

Second, the model described above is for simple two-port elements with only one propagating mode. The RF cavity has 6 external ports, namely, the upstream and downstream beampipes, three HOM damping waveguides and an iris coupler. At a moderately small frequency of 2.856 GHz compared with the beam roll-off frequency, all the ports have more than one propagating modes. Thus a multi-mode S-matrix for a multi-port network needs to be calculated.

Third, the stainless steel beampipe connecting the cavities is lossy. Therefore, the phase delay α also has an imaginary part to account for the attenuation.

Last, the beam excites a broad frequency spectrum. For a 1 cm beam, the frequency spectrum extends to about 10 GHz. Thus, HOM power can propagate in the frequency range between the beampipe cutoff of 1.85 GHz to 10 GHz. However, the periodic nature of the bunch train in PEP-II

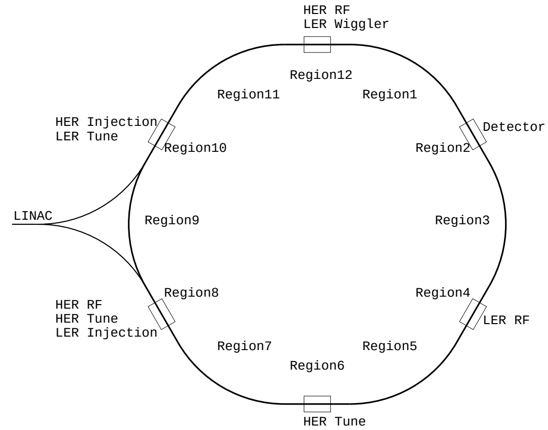

Figure 3: PEP-II ring layout.

suppresses all frequency contents except multiples of 238 MHz[1]. Therefore, about $\frac{10-1.85}{0.238} = 34$ beam harmonics in the frequency spectrum need to be considered

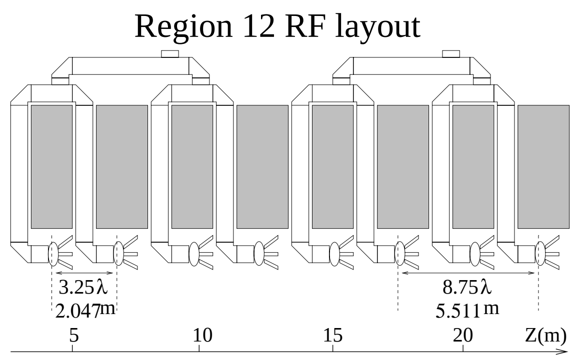

Figure 4: RF Cavity layout in Region 12.

4 HOM POWER DISTRIBUTION IN PEP-II

In this paper, we present the multiple reflection calculation at Region 12 only. Eight cavities and the stainless steel beampipes in between them are taken into account. Taking advantage of symmetry, we modeled half of the cavity (Fig. 5) by MAFIA. There are 2 beampipe ports (one is invisible in Fig. 5), 2 HOM ports and a coupler port on the top. MAFIA time domain simulations are used to calculate the S-parameters and the HOM power generated by a Gaussian charged beam. A couple of assumptions were made in the analysis. First, the HOM power generated by the cavity is assumed to propagate equally in the upstream and downstream beampipes in the form of TM_{01} mode. This is justified as the asymmetry of the cavity only generates a relatively small portion of TE power. Second, for sim-

[1] The 5% ion clearance gap is ignored here for simplicity. Because its contribution to the current at other frequency is less than 5%, the power induced by such current is negligible

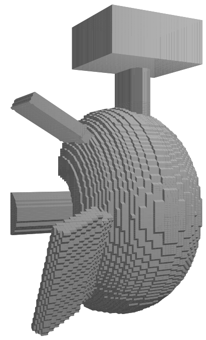

Figure 5: MAFIA model of RF cavity.

plicity, the S-parameter calculations are carried out for the TE_{11} and TM_{01} modes of the beampipe at 2856 MHz by allocating all the HOM power to this frequency.

The equilibrium distribution of the HOM power propagating in the beampipes is plotted in Fig. 6 as a function of longitudinal location in Region 12. Each discontinuity

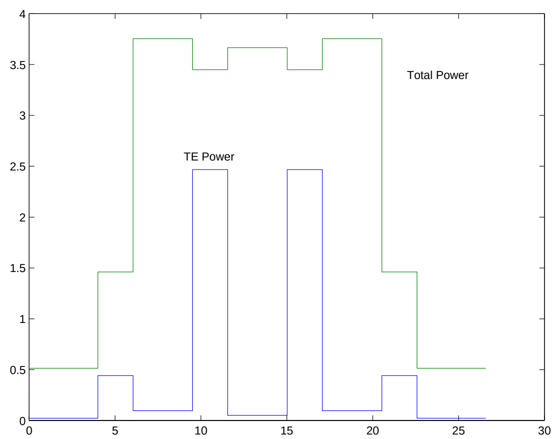

Figure 6: HOM power propagating in the beam pipe, normalized to one cavity HOM output(4 KW)

of the curve represents the location of a cavity. Generally, TM_{01} mode dominates in the beampipe. But in particular locations, for instance, between cavities 3 and 4, 5 and 6, TE_{11} power is high ($\sim$ 10 KW).

HOM power, in particular TE power, can penetrate through openings in beamline components. It was estimated that 0.01% of the TE power can penetrate through the bellow shield fingers[2]. This means that about 1 W is deposited in a bellows in the proximity of a cavity and this is small compared with 100 W design spec. For the BPM at the downstream of a cavity, about 0.12% for TE_{11} mode and 0.05% for TM_{01} mode couple to the buttons. The total power into the cable is therefore 14 watts maximum, which is well under 100 W designed for the BPM electronics.

We also obtained the HOM power going to the cavity load (Fig. 7). Without the coupler port, the three

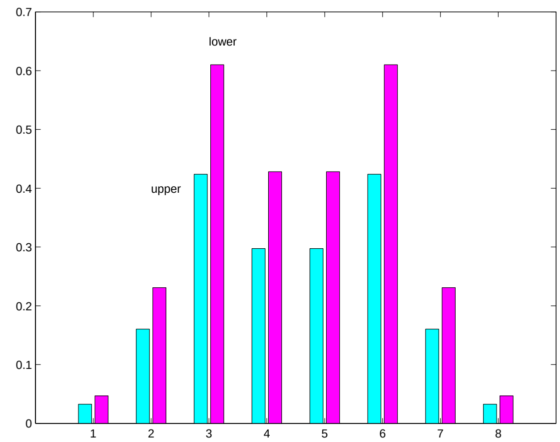

Figure 7: Power going into upper and lower HOM ports of each cavity, normalized to one cavity HOM output(4 KW)

HOM ports are symmetrically placed around the beam pipe. Therefore, with the beam on axis, each port will receive equal amount of HOM power. Since we only modeled half of the upper port, ideally, there are half as much power going into upper port as that going into lower port. But the coupler port breaks the symmetry, and Fig. 7 shows that the ratio of power going into half of the upper port and that into the lower port is 0.69:1 instead of 0.5:1. The total heating of upper port is still less than the designed 10 KW cooling capacity.

5 CONCLUSION

Multiple scattering of HOM by the beam line elements can substantially increase the local power density. Furthermore, TM to TE conversion is enhanced at particular locations, resulting in as much as 10 KW of TE power. The bellow heating and HOM power penetration through BPM cable turn out to be acceptable due to very small absorption coefficients.

This method can be scaled to the whole ring easily if S-matrix of other beam line elements are available. The resulting HOM profile is extremely useful in engineering design.

6 REFERENCES

[1] ‘Impedance Study for the PEP-II B-factory’, by S. Heifets et al. SLAC-AP-99. March 1995.

[2] ’Absorption of RF Power in the HER PEP-II Bellows’ By G.V. Stupakov, S.A. Heifets. SLAC-PEP-II-AP-NOTE-96-12, May 1996.