IMPEDANCE SPECTRUM FOR THE PEP-II RF CAVITY*

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Abstract

The impedance spectrum presented by the PEP-II RF cavity to the beam is calculated using a 3D MAFIA model which includes the damping waveguides and the input coupler. The simulation assumes that all the ports leading out of the cavity, including the beam pipes, are terminated in matched loads. The effect of the external loading on the longitudinal impedances will be examined. This study takes into account the input coupler damping which has not been considered in previous calculations [1].

I. INTRODUCTION

There is an ongoing program at SLAC to minimize the ring impedances in the PEP-II B Factory [2]. PEP-II is a high-current storage ring in which both longitudinal and transverse coupled modes will be excited. These are wakefields generated by the narrow-band (high-Q) impedance in the ring that can cause different beam bunches to interact. The coupled-bunch motion if left uncontrolled, can drive the beam unstable at high beam currents. Most of the high-Q resonances in the ring are attributed to the Higher-Order-Modes (HOMs) of the RF cavities. A distinct feature in the PEP-II cavity design is a set of damping waveguides to couple the HOMs out to external loads. By heavily loading these modes, their contributions to the ring impedance budget can be greatly reduced.

II. PEP-II RF CAVITY

The HOM damping scheme for the PEP-II RF cavity consists of three symmetrically placed waveguides around the cavity wall and connected with the cavity volume through iris apertures (Fig. 1). The positioning of the apertures are such that they interrupt the current flow of the most harmful HOMs. The waveguides are dimensioned to allow the HOMs to propagate while cutting off the fundamental mode so that it is minimally perturbed. This design was tested on a low-power prototype cavity. In Fig. 2, we show the transmission (S_{21}) data between probes on opposing beam pipes up to 1.4 GHz (reproduced from Ref. [1]). When compared with the undamped response, the fundamental mode at around 480 MHz is relatively unchanged (waveguide cutoff is at 600 MHz). The HOM Q's, however, are significantly lowered; for example, the TM_{011} mode at around 750 MHz is loaded to a Q of 28, down from a calculated unloaded Q_o of around 40000. Because the probes couple differently to different modes, one cannot take the relative amplitudes of the peaks of the modes as a good measure of their relative impedances. An impedance spectrum, however, is essential for detail studies of the collective effects to determine beam instabilities.

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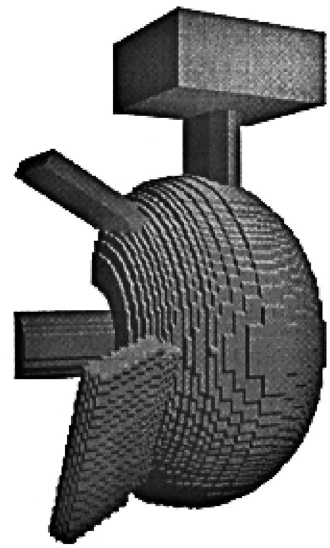

Figure 1. MAFIA model of the PEP-II RF cavity.

III. PREVIOUS IMPEDANCE ANALYSIS

The impedances of the longitudinal and transverse HOMs in the undamped (axisymmetric) PEP-II cavity have been calculated with the 2D URMEL code. HOMs with high impedances were targeted by the damping waveguides. The damping effect in the prototype cavity was studied with the Kroll-Yu method [3] which calculates the frequencies and Q's of the cavity modes by assuming the waveguides are terminated in matched loads. It made use of the eigenmodes provided by fully 3D codes such as MAFIA, but with the waveguides shorted at various lengths. This indirect method is necessary because the eigenmode solver cannot easily handle complex frequencies when loss is included.

There is generally good agreement between the analytical results and measured data up to 1.2 GHz. Above that frequency, the second waveguide mode is not cut off and the Kroll-Yu method, which assumes a single waveguide mode, may not give reliable results. The POPBCI [4] code does not have this limitation and uses similar numerical input to generate an impedance spectrum. It modeled the PEP-II cavity with some success but no further work with it was carried out.

A good estimate of the effective impedance can be obtained from the R/Q calculated with URMEL and from the Q measured in the damped cavity. The results indicate that the damped modes are reduced to a level that is within the capability of the broad-band feedback system. The possibility of further damping these modes through the drive port for example, is being considered. We point out that the fundamental shunt impedance loss due to the HOM damping scheme is 10% from the MAFIA analysis.

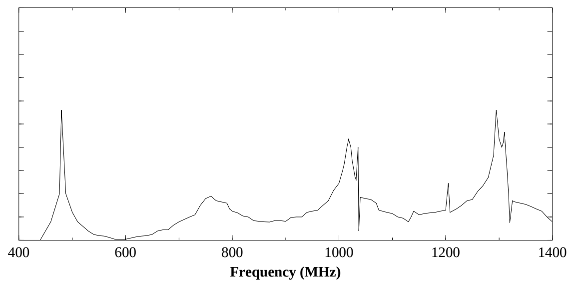

Figure 2. Mode spectrum of low-power test cavity with damped waveguides.

IV. THE MAFIA TIME-DOMAIN MODEL

A straightforward way to calculate the impedance is through the Fourier transform of the wake potential. One moves a bunch charge along the beam axis of the cavity and from the wakefields it generates, it is possible to obtain the wake potential by numerical integration. For cavities of arbitrary shape, codes like TBCI in 2D and MAFIA in 3D are commonly used for such calculations. Normally in an accelerator cavity, the impedance spectrum consists of narrow-band contributions below the beam-pipe cutoff and a broad-band portion that extends above it. The narrow-band impedance comes from cavity resonances which contribute to the long-range wake potential. Without loss, they are delta functions which are best evaluated in the frequency domain using eigenmode solvers. The spectrum above cutoff is due to a continuum of beam-pipe modes, and contributes to the short-range wakes that time-domain calculations can treat more effectively.

In this paper, we describe a time-domain approach to calculate the impedance spectrum for the PEP-II damped cavity, including the narrow-band contributions, with the following justifications. First, the frequency domain methods have been successful in analyzing only a small number of modes. Second, as seen in Fig. 2, most of the HOMs no longer have sharp peaks but are broadened by damping. Since the frequency spacing in the spectrum varies as the inverse of the total wake distance, it is possible to resolve many of the reasonably low Q modes if we calculate the wakefield out to large enough distance. Third, broad-band waveguide boundary conditions are now available in the MAFIA time-domain module, so that not only the standard beam pipes can be modeled. The damping waveguides as well as other 3D insertions such as the input coupler can also be properly treated with matched terminations at their end planes. A passing bunch charge then comes very close to interacting with the realistic cavity, and one can calculate the impedance spectrum from the wakefields it generates in a direct and straightforward manner.

V. WAKEFIELD CALCULATION

We model one half of the geometry to take advantage of symmetry. The symmetry plane splits the cavity, the top waveguide and the iris coupler but leaves the side waveguide intact (hence also the one on the opposite half). The wakefield calculation requires driving a bunch charge along the beam axis. The PEP-II nominal bunch length σ_z is 1 cm and numerically it is preferable to have at least 5 mesh points per bunch length or a .2 cm mesh size. For the half cavity dimensions of 30cmx15cmx50cm, this translates to many millions of mesh points, even without the waveguide and coupler attachments. Furthermore, the time step would accordingly be small (the Courant condition) so simulation time would be very long, especially when we calculate wakes out to large distances.

In the simulation, we used about six mesh points per bunch length and a σ_z of 2 cm (the narrow-band impedance does not depend on the bunch length). The mesh constructed on this grid scale contains close to three million mesh points. The wakefield calculation was carried out to s=40 m, where s is the bunch coordinate. Two separate runs were made; one with and one without the iris coupler to distinguish any additional damping effect.

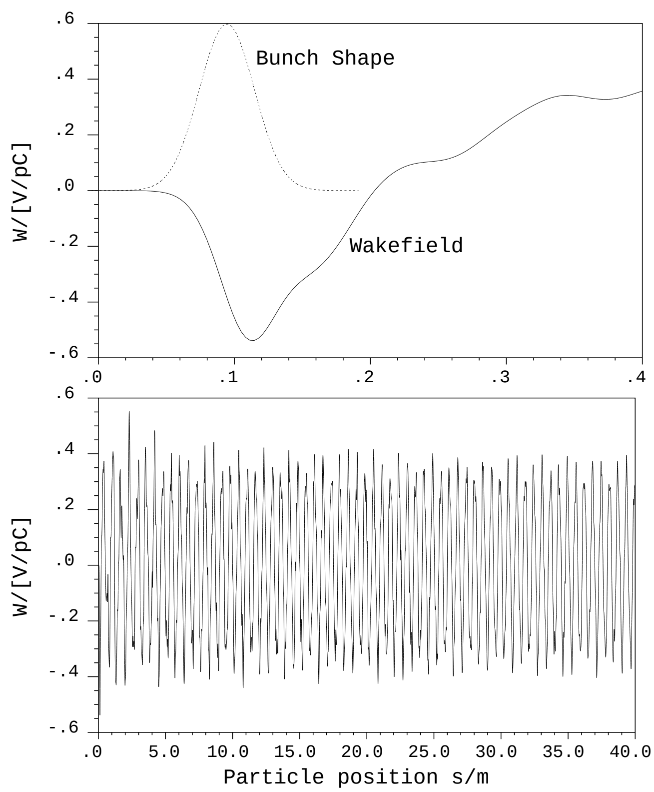

Figure 3. Short-range and long-range wakefields in the PEP-II RF cavity.

The top plot in Fig. 3 shows the short-range longitudinal wakefield up to s =.4 m, while the bottom plot shows the wake over the full range (40 m). The short-range wakefield is not affected by the damping waveguides and agrees with previous TBCI results on the undamped cavity. The longe-range wakefield exhibits persistent oscillations, indicating the presence of high-Q resonances in the cavity. A snapshot of the electric field distribution in the symmetry plane of the cavity at large time is given in Fig. 4. It shows predominantly the fundamental mode which is undamped and is responsible for the large persistent oscillation in Fig. 3. We also see fields in the beam pipes, the damping waveguide and the iris coupler as well. A series of similar snapshots will verify that these are outgoing waves leaving the cavity. In MAFIA, one can monitor the fields crossing the waveguide boundaries so that the power spectrum can be found at each of the ports also.

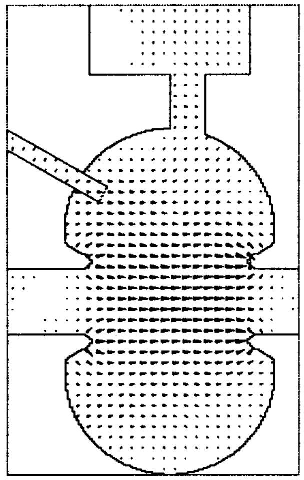

Figure 4. Electric field distribution at large time.

VI. IMPEDANCE SPECTRUM

From the wakefield of Fig. 3, one obtains the impedance spectrum by Fourier transform and then divides by the bunch spectrum. The top plot in Fig. 5 shows the result for the no coupler case whereas the bottom plot is with coupler included. In both spectra, we easily identify three familiar peaks in the frequency range up to 1.5 GHz. These are the modes with the three highest effective impedances, and correspond to the fundamental mode near 480 MHz, the TM_{011} at 760 MHz and the TM_{021} near 1.3 GHz respectively. Note that the TM_{020} peak that was visible around 1 GHz in Fig. 2 is not present because it has negligible residual impedance. The primary interest here is not in the fundamental mode although it constitutes the main contribution to the long range wakefield. Since it is not damped, the resonance broadening of the peak is due to artificial damping introduced by applying the Fourier transform.

To calculate the impedance and the Q of the HOMs, several factors have to be taken into consideration. First and foremost is the graininess of the frequency data which determines how well one can resolve a resonance peak. We will fit each peak with a Breit-Wigner resonant form to get improved accuracy. The other factor is the artificial damping we alluded to earlier and this has to be subtracted out from the Breit-Wigner solution. Yet another factor is the error incurred from mesh discretization, and this effect is especially pronounced in approximating the side waveguide and the iris opening into the cavity. As a result, the waveguide-cavity coupling is different from that in the physical cavity. However, one can correct for it from knowing the power ratio between the top and side waveguides.

The results on the TM_{011} mode after these factors are included agree very well with previous analysis. We found a Q of 28.6 versus 28 from measurement and 26 from the Kroll-Yu method. The impedance is 1.3 kΩ versus 1.26 from the estimate. For the TM_{021} mode near 1.3 GHz, the error due to limited data points is large. The frequency spacing for a wake distance of 40 m is 7.5 MHz, so at 1.3 GHz this resolution limits to a Q of several hundred. The measured Q is 900 which means a smaller frequency spacing, and correspondingly a larger wake distance, is needed. MAFIA has a restart option so one can in principle extend the simulation indefinitely to get finer resolution provided that numerical errors are not a factor. Nevertheless with

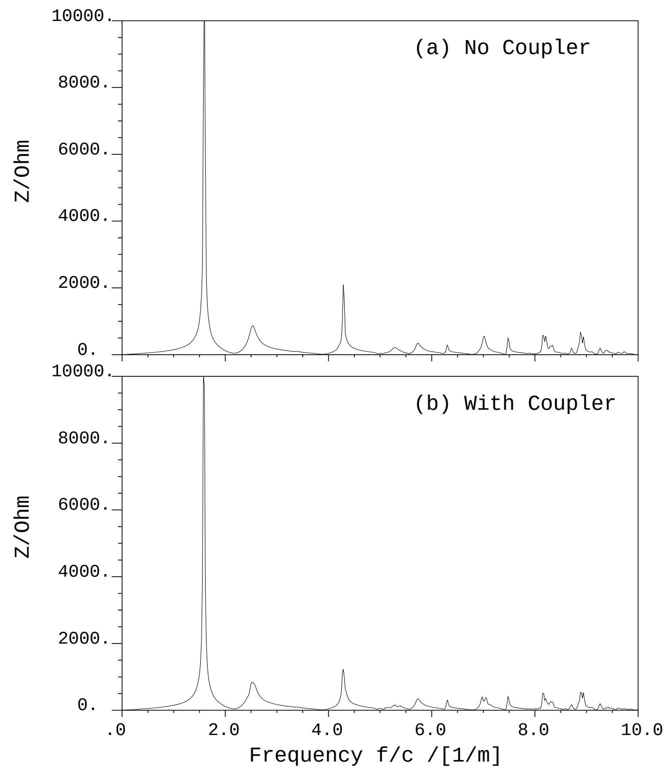

Figure 5. Longitudinal impedance spectrum as a function of frequency for the cavity with and without coupler.

the present data, we extracted a Q of 370 without coupler and 160 with coupler, which is a factor of two reduction. A separate analysis without the beam gives a reduction factor of three [5].

VII. DISCUSSION

We have presented a time-domain wakefield analysis of the PEP-II RF cavity which includes the effect of external loading directly. The longitudinal impedance spectrum for the waveguide-damped cavity is calculated with and without the input coupler. The agreement with previous results is good for low Q modes because of better resolution. We believe that by using a longer bunch to save in total mesh size, and calculating to larger wake distance, even higher Q modes can be adequately resolved. This approach has the potential of providing a more complete model for the narrow-band impedance than was done previously.

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