RESONANT TE WAVE MEASUREMENTS OF ELECTRON CLOUD DENSITIES AT CesrTA*

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Abstract

The Cornell Electron Storage Ring (CESR) has been reconfigured as a test accelerator (CesrTA). Measurements of electron cloud (EC) densities have been made at CesrTA using the TE Wave transmission technique. However, interpretation of the data based on single pass transmission is problematic because of reflections and standing waves produced by discontinuities in the beam pipe - from pumps, sliding joints, etc. that are normally present in an accelerator vacuum chamber. An alternative model is that of a resonant cavity, formed by the beampipe and its discontinuities. The theory for the measurement of plasma densities in cavities is well established. This paper will apply this theory to electron cloud measurements, present some simplified measurements on waveguide, and apply this model to the interpretation of some of the data taken at CesrTA.

INTRODUCTION

As originally proposed, the TE wave technique was based on transmission and reception of microwaves from one point in the accelerator to another using the beampipe as a waveguide. Button detectors, normally used as part of the beam position monitor (BPM) system, are used to couple microwaves in/out of the beampipe. In the presence of a plasma (the electron cloud), transmitted microwaves will be phase shifted and the EC density along the path inferred [1-4].

However, in applying this technique to the data at CesrTA, it was noticed that transmission through the beampipe does not have a flat frequency response. In fact, the large variations in response suggest the presence of resonant excitation of the beampipe rather than single pass transmission. This interpretation was confirmed by the response when exciting and receiving at the same location, where very large resonances are often seen.

REFLECTIONS AND STANDING WAVES

The beampipe at CesrTA was not designed to be a waveguide. For devices such as vacuum pumps, longitudinal slots are used to provide a reasonable vacuum connection while minimizing the effect of beam-induced fields. However, these longitudinal slots present an obstacle to the propagation of a TE waves. A location was found at 43E in CESR where a BPM coupler/detector is located between two ion pumps (with slots). The response shown in Fig. 1 is consistent with a waveguide cavity of length L having a cutoff frequency f_c and n half-wavelengths in the distance L between the pumps [5, 6].

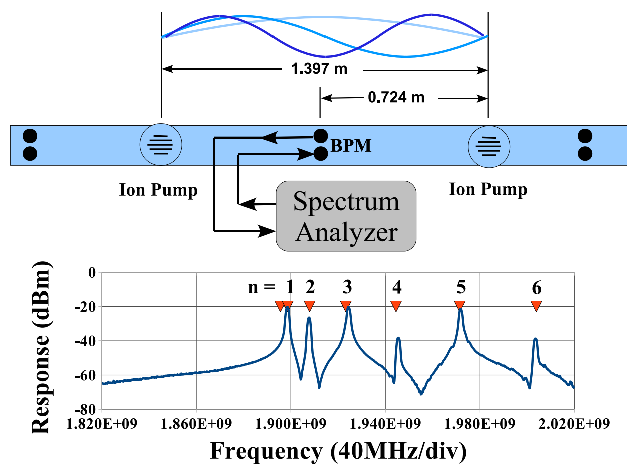

Figure 1: Sketch of 43E at CesrTA, where a BPM Detector is located between two ion pumps with longitudinal slots. The measured resonances follow the expected $f^2 = f_c^2 + \left(\frac{nc}{2L}\right)^2$ of a rectangular cavity.

The effect of dielectrics and plasmas on the resonant frequency of a cavity is well established [7]. The effect of small dielectrics on resonant frequency is very useful in mapping the fields of accelerating cavities, and plasma densities are routinely measured using resonant cavities [7, 8]. Perturbation techniques provide the following approximation for the shift in resonant frequency due to a dielectric in a resonant cavity [9].

$$\frac{\Delta\omega}{\omega} = \frac{\displaystyle\int_V (1-\varepsilon_r)\, E_0^2\, dV}{\displaystyle 2\int_V E_0^2\, dV} \tag{1}$$

The effective dielectric constant of a plasma has real and imaginary parts. The imaginary part gives a change in the Q of the resonance, the real part a change in its frequency. For low density plasmas ($\omega_p^2 \ll \omega^2$) with a small collision frequency ($\nu \ll \omega$) and no magnetic field, the real part of

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the dielectric constant of a plasma can be written as [8]

$$\varepsilon_r = \left[1 - \frac{\omega_p^2}{\omega^2\left(1+(\nu/\omega)^2\right)}\right]. \tag{2}$$

The plasma frequency ω_p is related to the electron cloud density by $n_e = \omega_p^2\varepsilon_0 m/e^2$ [7]. For $\nu \to 0$, the change in resonant frequency becomes

$$\frac{\Delta\omega}{\omega} = \frac{e^2}{2\varepsilon_0 m_e\omega^2}\frac{\int_V n_e E_0^2\,dV}{\int_V E_0^2\,dV}. \tag{3}$$

If there are high local densities, they will not have an effect on $\Delta\omega$ where the cavity electric field is zero. If the density is uniform, $\Delta\omega$ is independent of the details of the electric field, since the same integral appears in the numerator and denominator [10]. An EC density of $10^{12}(m^{-3})$ would give a frequency shift of about 20 kHz. Simulations using Vorpal are in agreement with this analytic expression for uniform electron cloud densities.

With a train of bunches in the storage ring, the electron cloud will grow and decay at the revolution frequency f_{rev} (390 kHz at CesrTA). The quantity $\Delta\omega$ is the modulation in the resonant frequency of the waveguide cavity produced by the electron cloud. We now need to determine the effect that this modulation has on the observed signals.

EFFECT ON SIGNALS

For most of the TE Wave measurements made at CesrTA, the resonant beampipe is driven at a fixed frequency (~2 GHz) and its response measured with a spectrum analyzer. The steady state solution for a driven oscillator is given in equations (4-6) and illustrated in Fig. 2.

$$x(t) = A_n sin(\omega t + \phi_n) \tag{4}$$

$$A_n = Q\frac{A}{[(\omega_n^2-\omega^2)^2+\omega^4]^{1/2}} \tag{5}$$

$$\phi_n = tan^{-1}\left[Q\frac{(\omega_n^2-\omega^2)}{\omega^2}\right] \tag{6}$$

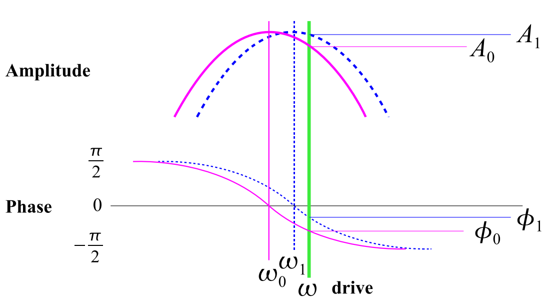

Figure 2: Steady state amplitude and phase response as the cavity resonant frequency changes from ω_0 to ω_1.

To obtain an estimate of the EC density, a number of approximations are made: that the steady state solution above applies; the drive frequency ω is close to resonance; the phase modulation - from Eq. (6) using the measured Q of about 3000 - is small; and a cw modulation would give a ratio of the first sideband to carrier amplitude of $\frac{1}{2}\Delta\phi$. Also, the phase modulation is not sinusoidal. So for our rough estimate, we make the approximation that the duration of the EC density *and its effect on the phase* is of fixed amplitude for the length of the bunch train and zero otherwise. Given these crude approximations, Fig. 3 is a plot of the EC density measured in the wiggler region at 2 GeV during a wiggler ramp. The stored beam was a 45 bunch train of positrons spaced at 14 ns with a total current of 35 mA.

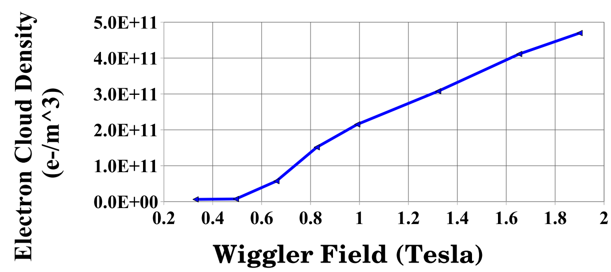

Figure 3: Estimate of EC density during a ramp of wigglers.

One concern with this approximation is that the beampipe cavity has damping time of about 500 ns. So the duration of the cloud and the damping time of the cavity are of the same magnitude. We are working on a more detailed analysis that would include transient effects. For example, a step in the resonant frequency of the cavity at $t = 0$ would be described by.

$$x(t<0) = A_0 sin(\omega t + \phi_0) \tag{7}$$

$$\begin{aligned} x(t\geq 0) = {} & A_1 sin(\omega t + \phi_1) \\ & + e^{-\gamma t}[A_0 sin(\omega_1 t + \phi_0) \\ & -A_1 sin(\omega_1 t + \phi_1)] \end{aligned} \tag{8}$$

For $t \gg 0$, the exponential vanishes and only the first term (steady state) remains. In the steady state solutions for $t < 0$ and $t \gg 0$ there is a difference both in the amplitude $A_0 \to A_1$ and in phase $\phi_0 \to \phi_1$. But, especially near the resonant frequency, the amplitude change will be quite small and the phase difference will dominate the signal. For small t (and small $\Delta\omega$), the term in the brackets of Eq. (8) appears to play the role of changing the phase from the initial ϕ_0 to the new ϕ_1 during the cavity damping time.

THE CUTOFF RESONANCE

Bench measurements were made using WR284 waveguide which has a cutoff frequency very similar to the beampipe of CesrTA near 2 GHz. A 4 m long section was driven near its longitudinal center using buttons similar in geometry to those in CesrTA. Using metal blocks near the waveguide ends to generate reflections, cavity modes were excited. By moving a dielectric bead along the waveguide axis and measuring the consequent shift Δf in the resonant frequency (Eq. (1)), the electric field intensity E^2 vs. longitudinal position can be measured. In a uniform waveguide, the measurements showed E^2 varying as multiples of half wavelengths, including the lowest $n = 1$ mode.

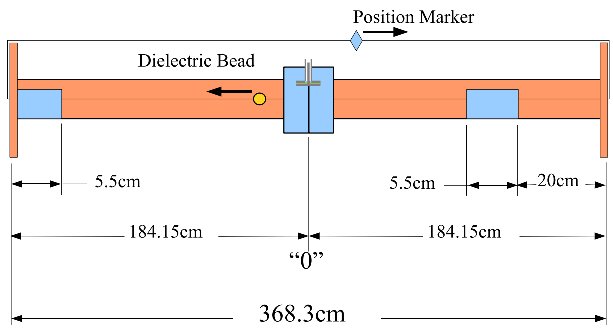

Figure 4: For bead pull measurements, a thin monofilament line varies the position of a dielectric bead in WR284 waveguide. The center flange has BPM-like buttons that are used to couple microwaves in/out of the waveguide.

However, a slight modification of the flange used at the drive point resulted in a significant change in the lowest resonance of the bead pull measurement as shown in Fig. 5. The inside width of the drive point flange was made 3 mm wider than the waveguide. This portion of the flange is about 2cm long. The lowest '$n = 1$' resonance was then shifted slightly below the cutoff frequency. Rather than a half-sine wave, it has a response consistent with an exponential decrease in E, as with an evanescent wave.

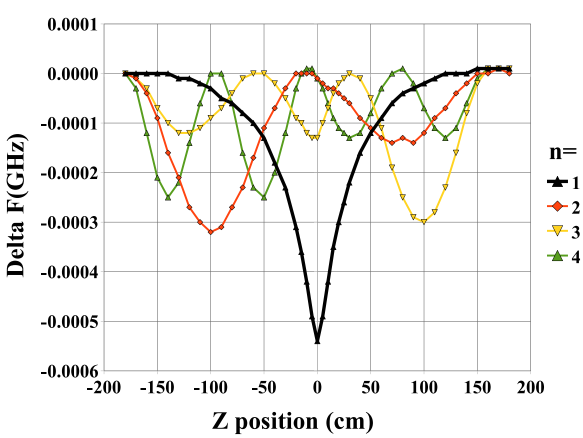

Figure 5: The cutoff resonance was observed using a modified drive flange in a measurement with WR284 waveguide.

If excited in this mode, the response to the EC density will occur over a distance of only about two meters and provide a very localized measurement, following Eq. (3). This can be a great advantage, especially when trying to cross calibrate with other localized EC density measurement techniques.

There are many details about this cutoff mode that we need to understand. Primarily, we need to be able to tell - without performing a bead pull experiment in the storage ring - whether or not we have excited this resonance vs. the usual half wave $n = 1$ cavity mode. One indication should be the effect on the sequence of resonant frequencies and the extent to which they are different from $f^2 \propto n^2$. For example, the $n = 1$ resonance should be lower than normally expected.

CONCLUSIONS

Interpreting TE wave signals as those from a resonant waveguide cavity gives reasonable electron cloud densities, but further analysis work remains. The transient response and its effect on sideband amplitudes needs to be fully evaluated. This will include simultaneous phase, frequency and amplitude modulation.

The response functions are generally much more complex than the example given in Fig. 1. The treatment of the beampipe as a single cavity is a good first step, but to fully understand the observed response functions, this approach will probably need to be extended to coupled cavities.

The cutoff resonance should be very useful in enabling localized measurements, so it will be the subject of further study. A method to identify it *in situ* is also needed.

Generally, simulation will help in the understanding of the observed signals, where the detailed geometry of the beampipe can be varied and its effects studied.

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