TE Wave Measurements at CesrTA*

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Abstract

TE Wave measurement stations have been installed in the L0 and L3 regions of CesrTA. The L0 region has quasi-rectangular beam pipe and is the location of 6 superconducting wiggler magnets. The L3 region has round beam pipe with a chicane dipole magnet (from PEPII). At both locations, coaxial relays are used to multiplex an rf signal from a signal generator output, through the beam pipe, to the input of a spectrum analyzer. Software is used to monitor accelerator conditions and can be triggered to take data on demand, or on changes in conditions such as beam current or wiggler fields. This paper will describe the TE Wave measurement technique, the installation of hardware at CesrTA and some measurement examples. It will also outline some problems in the interpretation of data, specifically the results of reflections and standing waves.

INTRODUCTION

Microwaves that are transmitted through a waveguide will be phase shifted by the presence of a plasma. The beam pipe of an accelerator, although not an ideal waveguide, can also transmit microwaves and the electron cloud produced by a train of bunches will phase shift microwaves transmitted through the beam pipe. Since the cloud lifetime is a fraction of a revolution period at CesrTA, a phase modulation of the carrier is produced at the beam revolution frequency. This results in phase modulation sidebands of the received carrier frequency, spaced at the revolution frequency of 390kHz [1].

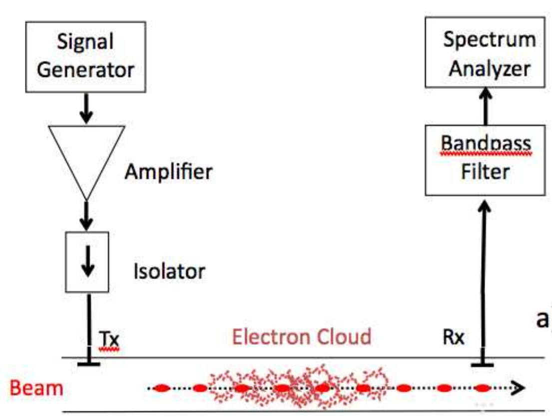

Figure 1: The basic TE Wave technique: a carrier is injected at Tx and the modulated signal detected at Rx.

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Beam position monitor (BPM) button detectors are used to couple microwaves into and out of the beam pipe. These detectors were originally installed at many location around CesrTA for the purpose of orbit and trajectory measurements. Some of these buttons were borrowed from the BPM system; others were installed specifically for TE Wave measurements. Thus far, we have only used the transverse electric $TE_{1,0}$ mode, since it is relatively easy to excite in the beam pipe and has a maximum electric field in the center of the pipe. A sketch of the method of coupling is given in figure 2. For convenience in making combinations of measurements, a transmitting and receiving pair are available at each location. While hybrid combiners can be used, many of the detectors at CesrTA use 0 degree combiners, with cable lengths chosen to give a differential signal at the desired frequency, usually at about 2GHz.

Notice that the button pairs are offset from the center of the pipe. Given this geometry, it would also be possible to excite the $TE_{2,0}$ mode, but this higher frequency has not been used. The $TE_{1,0}$ mode is sensitive to the electron cloud near the beam, in the center of the pipe, while the $TE_{2,0}$ mode is not. Also, the 5 watt amplifier that we are presently using is limited to a little over 2GHz.

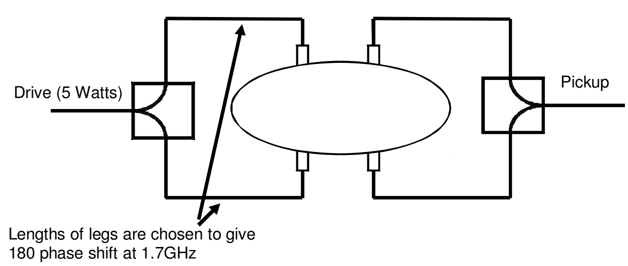


Figure 2: Top and bottom buttons are combined to give differential signals at the measurement frequency. This selects the TE microwaves while helping to reject direct beam signal sidebands. The button electrodes are ~1.7cm dia with a horizontal spacing of 2.8cm.

As an aid in analysis, the transmitted carrier is phase modulated at 410kHz with a depth of .001radian so that reference sidebands are visible near the cloud induced modulation sidebands. The carrier frequency is chosen to be somewhat above the cutoff frequency of the beam pipe's $TE_{1,0}$ mode, which at CesrTA is close to 2 GHz. As will be seen in a later section, the cutoff frequency for the beam pipe at CesrTA is not very clear and has many resonances. This feature has a significant effect on our ability to obtain a convincing calibration of the electron cloud density.

Figure 3 shows a typical spectrum. While the carrier is set to be somewhat above the cutoff frequency, the exact frequency is chosen so that the response is close to a local maximum and the modulation sidebands are between the beam induced revolution harmonics.

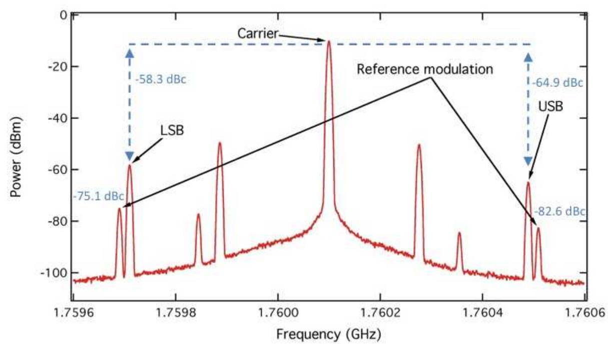


Figure 3: A spectrum of the received signal showing both reference modulation and cloud induced sidebands (labeled LSB and USB). The peaks closest to the carrier are the beam revolution harmonics, while the smaller peaks are from a noisy power supply for the 5 watt amp.

MEASUREMENT STATIONS

Figure 4 shows the location of two stations used for TE Wave measurement at CesrTA. At each station, there is an Agilent N5181A signal generator followed by a Mini-Circuits ZHL-5W-2G amplifier. As show in figure 5, the drive signal is routed with ½ inch heliax to a mechanical relay that can route the drive to the available detector locations. In the same way, the received signals are selected by a relay and routed with heliax to an Agilent MXA-9020A spectrum analyzer.

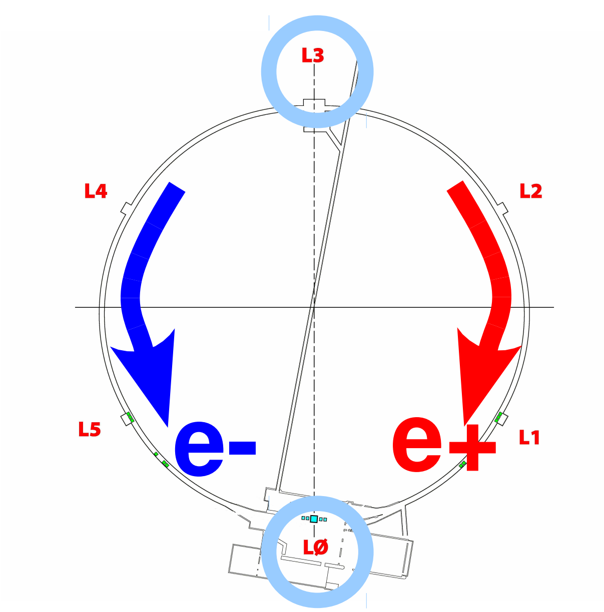


Figure 4: The L3 region is at the north end and the L0 region at the south end of the CesrTA storage ring. In L0, the positron beam travels from east to west.

The instruments are connected to the accelerator control system with network cables for configuration and data taking. For each measurement, software configures the station hardware following a list of drive/detector pairs, collects data for each pair and updates an html table. The table has links to the data files that contain the station configuration, spectra, and relevant accelerator data such as bunch current, beam energy, wiggler fields, etc., as well as links to plots of the spectra. The table allows easy browsing of the data, but additional software is required for further analysis. In a typical plot shown in the next section, each data file represents a single point. Work is now underway to load relevant data summaries into a database that can be more easily searched.

Data has been routinely collected using both the standard transmission measurements - where different detectors are used for drive and received signals - as well as resonant measurements where the drive and detection are at the same location.

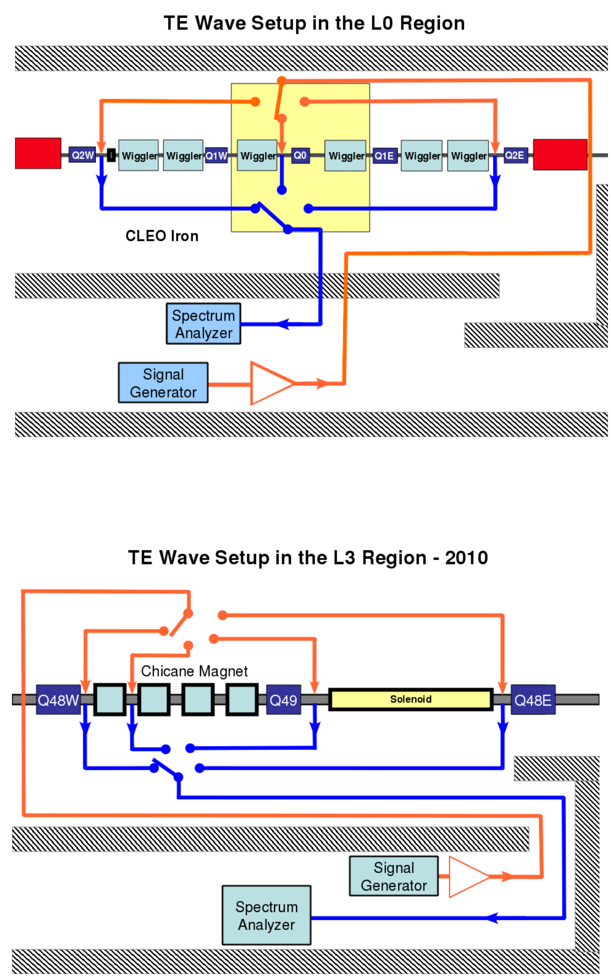


Figure 5: The layout of measurement stations at L0 and L3 is given above. In the L3 region with round beam pipe, the detectors are often oriented to give a horizontal electric field. This allows the rf to excite cyclotron resonances of electrons in the Chicane's dipole magnets.

MEASUREMENT EXAMPLES

Below are examples of some recent measurements made at CesrTA. Figures 6 and 7 show the general behavior of the electron cloud induced phase modulation sidebands at 2GeV and at 5GeV.

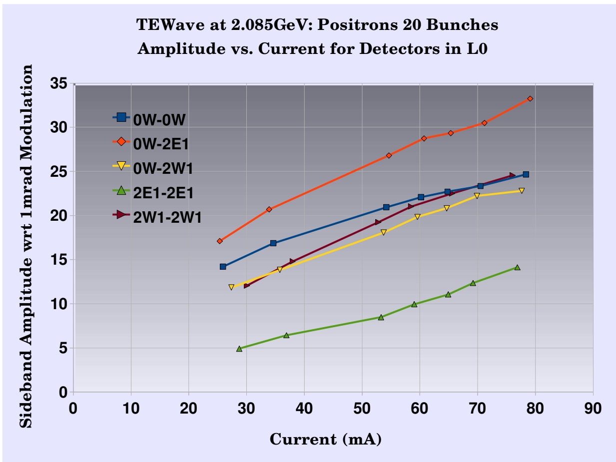


Figure 6: At 2 GeV, six superconducting wigglers are on in the L0 region. There is a general increase in cloud intensity for measurements that are further downstream (westward) along this series of wigglers.

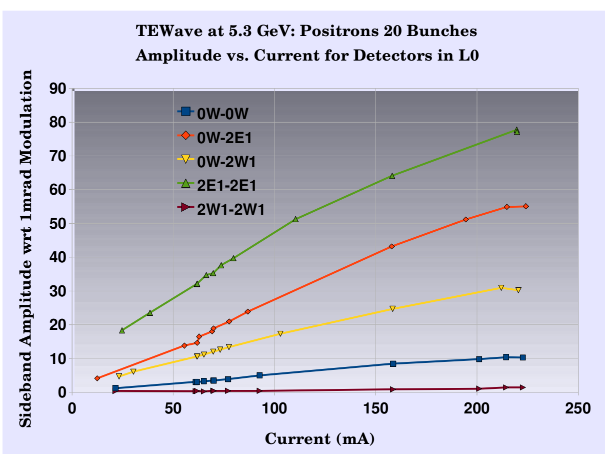


Figure 7: At 5 GeV with the wigglers off, there is a general decrease in cloud intensity for measurements that are further downstream of the positron beam. The source of light is the last dipole magnet in the east before the wiggler straight section.

The next two measurements are more specialized. Figure 8 shows the change in sideband amplitude of detectors in L0 as the superconducting wigglers are ramped up from zero to a full field of 1.9 Tesla. This data was taken with 45 bunches of positrons, whose trajectory is from east to west. Notice that the eastern resonant detector 2E1-2E1 shows no change in amplitude with wiggler field because the wigglers are all down stream of this detector. Figure 9 shows another very specialized measurement, where the magnetic field of the Chicane magnet in L3 was ramped through the value that corresponds to the electron cyclotron resonance. Across this resonance, there is a nearly 30dB increase in the magnitude of the phase modulation sideband. At the same magnetic field, there is a small (0.5dB) decrease in the amplitude of the carrier frequency.

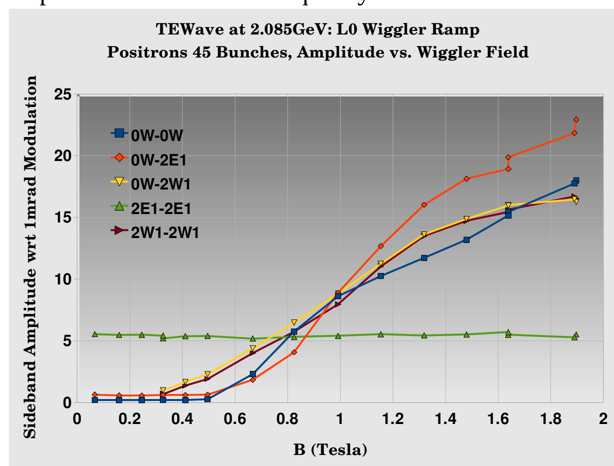


Figure 8: During a ramp of wiggler fields there is an increase in the cloud intensity with increased field. This increase begins slightly earlier at the 2W1 which is furthest downstream. The 2E1 detector signal is unaffected since it is upstream of all wigglers.

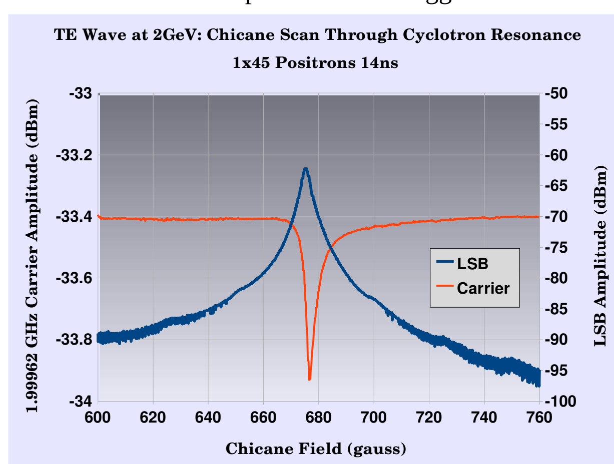


Figure 9: During a scan of the chicane magnet in L3, a strong resonance is seen both in the sideband and carrier amplitudes of the TE Wave signal. This occurs at a field corresponding to the electron cyclotron resonance.

So there is data available that shows a correlation between the sideband amplitudes and the expected relative density of the electron cloud. Treating the beam pipe as a wave guide, the phase modulation depth can be obtained through the relation below, that gives the phase shift of a $TE_{1,0}$ wave through a plasma, where ω_p is the

$$\Delta\varphi = \frac{L\omega_p^2}{2c(\omega^2-\omega_c^2)^{1/2}} \tag{1}$$

plasma frequency, ω_c is the cutoff frequency of the wave guide and L is the distance of propagation[1].

IMPERFECT WAVE GUIDE

Beam Pipe Response

In an ideal rectangular waveguide, there is a definite cut off frequency, below which there is no propagation and above which a wave can propagate freely. When using accelerator beam pipe as a waveguide, the response function is noticeably non-ideal with a large number of resonances as shown in figure 10, that are probably due to reflections. There are many discontinuities in the beam pipe: gate valves, longitudinal slots for vacuum pumps, transitions in dimensions, etc. Figure 11 shows the superposition of a number response functions, where the drive is applied to the center of L0 and observed at other detectors.

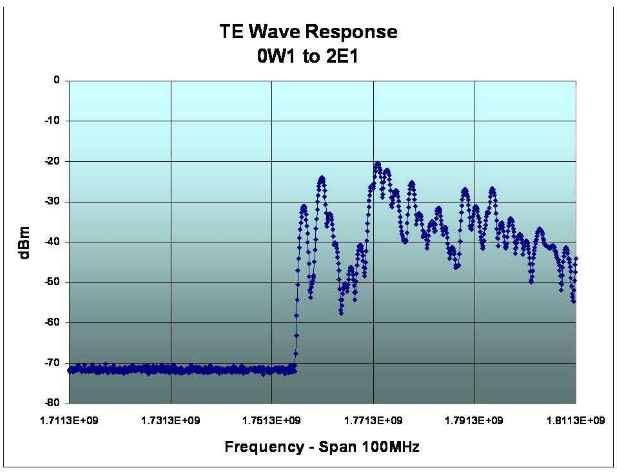


Figure 10: The response function of a TE wave transmitted through the beam pipe in the L0 region.

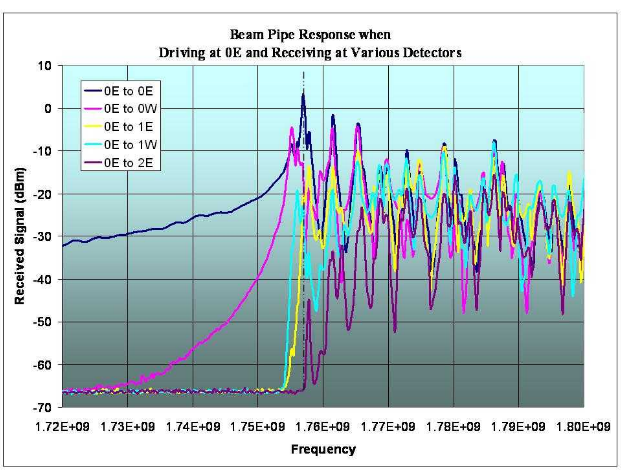
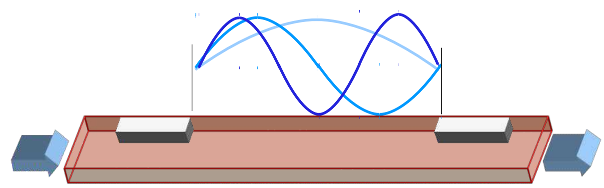


Figure 11: This is an overlay of the measured response functions from 0E to several other detectors in L0 (data from 2008). The complex pattern of resonances suggests that there is more than one set of reflections. However, there are frequencies where the resonances of several detectors coincide. Notice that the largest peak is 0E to 0E, where the drive and pickup are at the same location.

Model: A Waveguide with Reflections

If a wave guide contains two discontinuities, a standing wave is set up at particular frequencies. Because of the change in phase velocity near the cutoff frequency, the spacing of the resonances is not uniform but is given by the relation below where f_c is the cutoff frequency, L is the distance between discontinuities and n is an integer[2].



$$f^2 = \frac{c^2}{4L^2}n^2 + f_c^2$$

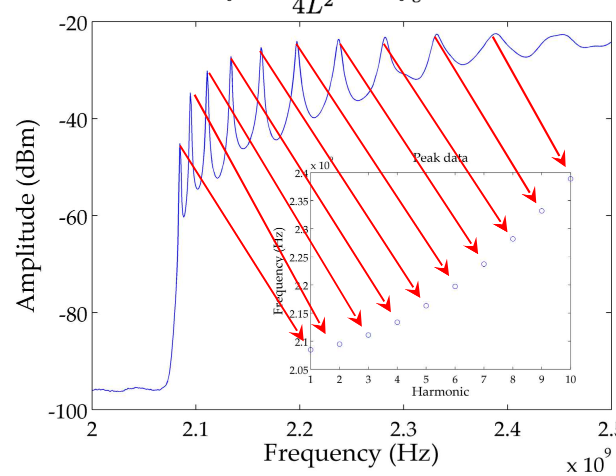


Figure 12: The measured response function of a waveguide with a single pair of discontinuities is given above (upper curve). Arrows connect the spectral peaks with the calculated resonances (circles).

The Effect of Reflections on the Calibration

The published relation between the sideband amplitude and the density of the electron cloud is based on a single pass transmission of the TE Wave between two points in the beam pipe[1]. However, reflections result in multiple passes of the wave through the plasma so that the phase shift becomes magnified. A more relevant model for electron cloud measurement would be the perturbation of the resonant frequency of a cavity by the presence of a plasma[3], where the shift in resonant frequency is proportional to the integral of E^2 over the volume of the dielectric. Work on this approach was carried out as a Research Experience for Undergraduates (REU) project (2009), where the resonant detector mode was modeled as wave guide that is excited at the cutoff frequency[4].

Using some lengths of wave guide, another REU (2010) project measured the amplitude and phase of transmission in a wave guide with discontinuities, where a dielectric could be inserted in the region of the standing waves[2]. The measurements of figures 13 and 14 show the phase *difference* with and without the dielectric inserted.

In figure 13 the dielectric is inserted at the midpoint between the two discontinuities. Although it is difficult to measure on this scale, there is a very small difference in phase shift anywhere in between the resonances. This would correspond to non-resonant wave guide transmission. On resonance, the phase difference

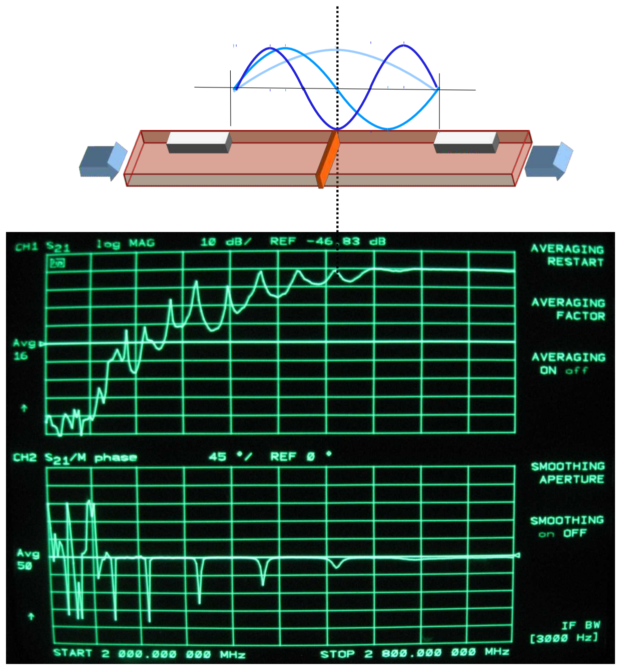


Figure 13: If the dielectric is inserted at the midpoint of the discontinuities, the even numbered harmonics will have no phase shift, since the dielectric will be at a voltage minimum. Frequency span: 2.0 to 2.8GHz.

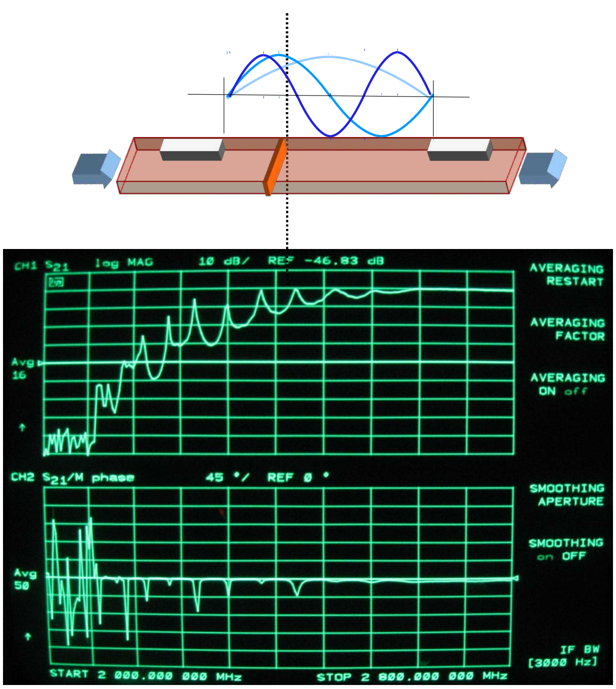


Figure 14: If the dielectric is inserted off center, the phase shifts for both the even and odd harmonics are visible, but their magnitudes vary. Frequency span: 2.0 to 2.8GHz

alternates between being large and being near zero, because the location of the dielectric is at a voltage maximum for odd *n* and a voltage minimum for even *n*. Where E is zero the resonant frequency shift is zero.

Another measurement was made with the dielectric displaced from the center of the discontinuities at a position that was roughly one third of the distance. In this case, all of the resonances show a somewhat enhanced difference in phase shift with the dielectric, as can be seen in figure 14.

From these simple examples, it seems clear that the phase shift can be enhanced by resonances. It also shows that the sensitivity can vary greatly along the length of the beam pipe – becoming zero at some locations – depending on which resonance is used for the measurement. This needs to be taken into account, especially when looking for highly localized electron cloud densities. In the example of the cyclotron resonance measurement of the previous section (figure 9), the effect was not visible at all with a carrier frequency of 2.00470Ghz, but was quite pronounced at 1.99962GHz .

SUMMARY

Data shows that the TE Wave technique is sensitive to the electron cloud density. However, given the typical response functions as shown in figures 10 and 11, it seems likely that almost *all* detectors pairs are resonant, whether the drive and pickup are at the same detector or not. These resonances are presumed to be from discontinuities in the beam pipe and can magnify the electron cloud induced modulation sidebands. So a quantitative analysis of reflections seems to be critical in order to obtain believable measurements of electron cloud densities. Once a field profile is obtained, calculations should follow the model of the *frequency modulation* due to a plasma in resonant cavities rather than the *phase modulation* of a plasma in single pass wave guide transmissions.

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