USING TE WAVE RESONANCES FOR THE MEASUREMENT OF ELECTRON CLOUD DENSITY*

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Abstract

In the past few years, electron cloud (EC) density has been measured by means of its effect on TE waves propagated through the accelerator vacuum chamber. This technique has been used in several laboratories around the world (CERN, SLAC, FNAL, Cornell, INFN-LNF). Recent measurements at CESRTA and DAFNE show that the simple theory relating the phase shift of a propagating TE wave to the electron cloud density provides an inadequate description of the data. Standing waves set up between discontinuities in the vacuum chamber make the propagation length ill-defined and the standing wave pattern is not confined to the portion of beampipe between the input and output couplers. In this paper we present evidence that the response function near cutoff is the result of coupling to standing waves trapped in the vacuum chamber and that the analysis should be based on the response of a resonant cavity rather than waveguide transmission. This evidence includes measurements at DAFNE, CESRTA, a test waveguide, computer EM simulations, and analytical calculations.

INTRODUCTION

Electron clouds consist of relatively low energy electrons in accelerators that are a by-product of the beam. They can be initiated by synchrotron radiation and photoemission from the beampipe inner wall or by ionization of the residual gas. An electron cloud density of 10^{11} m^{-3} or higher can result in significant beam instabilities and emittance growth among other effects. One of the goals of the CESRTA program is to study the effectiveness of mitigation techniques as well as the validation of simulation codes of the evolution of electron clouds. The TE Wave technique can provide a relative measure of electron cloud density, as in the conditioning of vacuum chambers over time, as well as an absolute measurement of cloud density for comparison with simulation. The measurements are relatively easy to make using a signal generator and spectrum analyzer - the difficulty is in interpreting the measurements.

MICROWAVES AND BEAMPIPE

The original technique was to transmit microwaves through the beampipe and observe the output signal on a spectrum analyzer. Buttons from Beam Position Monitors (BPMs) are used to couple microwaves in and out of the beampipe. The electron cloud produced by the beam would give phase shifts in the transmitted signal and phase modulation sidebands on the spectrum analyzer [1, 2].

Waveguide has a cutoff frequency f_c that is determined by its transverse dimensions. Below f_c there is no transmission; above f_c the microwaves should propagate freely. Measurements of the transmission through the beampipe at CESRTA show that it is *not* an ideal waveguide. For example, microwaves were coupled into the beampipe at the BPM at 0E and the beampipe response measured at various detectors including at 0E itself (propagation length zero). Data taken in 2008 is shown in Fig. 1 where a number of resonances are seen in the response.
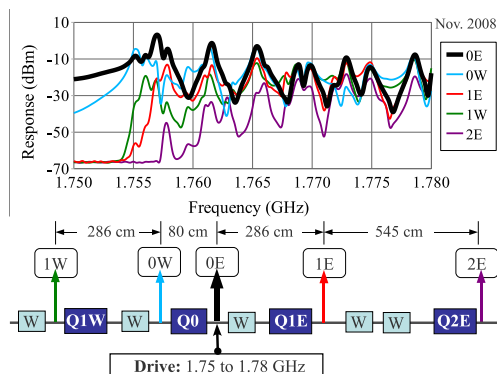

Figure 1: TE Wave response when exciting at 0E and receiving at other detectors in the region. The wide trace is the response when both driving and receiving at 0E.

The wide trace of Fig. 1 is the response when both driving and receiving at 0E. The response observed at other detectors generally follows this same envelope, although the relative amplitudes change with frequency. For example, both the detector at 2E and 0E show a resonance at 1.758 GHz, but their amplitudes are different by 40 dB or so. The lower frequency resonances tend to be confined to the region near the drive point, and the higher frequency resonances show significant overlap. Within this region, the various BPMs behave like coupling ports on the same

cavity. The resonances are presumed to be made by reflections that produce standing waves - the result of changes in beampipe dimension, longitudinal slots that connect vacuum pumps to the chamber, etc.

Testing the idea that the beampipe was behaving more like a cavity than a waveguide, a 2 μs burst of rf was coupled in/out of the beampipe at one of its resonant frequencies. The response observed on a scope was a typical cavity response having a rise and exponential decay with a time constant of about 500 ns - a Q of about 3000. So, treating the beampipe and its reflections as a cavity rather than a waveguide seems appropriate.

The frequency of a cavity can be changed by the presence of a plasma. The change in resonant frequency ω is proportional to the integral of the EC density n_e over the cavity volume V weighted by the electric field squared as shown in Eq. (1) . When the beampipe is driven at one of these resonances, a train of bunches will produce a time periodic EC density and phase modulation sidebands [3, 4].

$$\frac{\Delta\omega}{\omega} \;=\; \frac{e^2}{2\varepsilon_0 m_e \omega^2}\frac{\displaystyle\int_V n_e E_0^2 \, dV}{\displaystyle\int_V E_0^2 \, dV}. \qquad (1)$$

If the EC density n_e is spatially uniform, it is easy to calculate the density from the measured phase modulation sidebands since the integral is equal to n_e. But n_e will generally not be a constant. At CESRTA there are variations in the amount of synchrotron radiation and beampipe geometry as well as several short test chambers for the study of mitigation techniques with coatings of carbon or TiN. So it is important to know the electric field pattern in the beampipe cavity in order to understand where the EC density measurement is being made.

SIMPLER GEOMETRIES

The beampipe response in the region around Q0 (Fig. 1) was not easy to interpret. A much simpler geometry was found at 43E in CESRTA where there is a BPM between two ion pumps with longitudinal slots. Driving and receiving at this single BPM, the response is what would be expected of a rectangular cavity. There are a series of resonances following $f^2 = f_c^2 + \left(\frac{nc}{2L}\right)^2$, with a cavity length L, having a cutoff frequency f_c and n half-wavelengths in the distance L between the pumps [5].

A chamber near 15E in CESRTA also has simple geometry, except that there is a gate valve near the center of the region between the two ion pumps as shown in Fig. 2. The TE wave resonances at 15E do not match those of a rectangular cavity quite as well as 43E. In particular, the lowest resonance is shifted downward considerably. This may be due to the gate valve body having a somewhat larger cross-section that the surrounding beampipe.

Some of the data from 15E is plotted in Fig. 3. The EC density was calculated using the first five major resonances of Fig. 2. The data from the first three resonances are close

to each other, but resonances four and five give a much lower EC density. Further analysis will be needed in order to understand this difference. The data from L3 will be discussed in a later section.
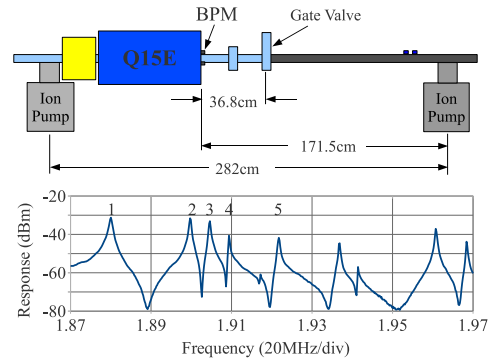

Figure 2: The physical layout of 15E, showing the (gray) carbon coated chamber in the right half of the section.
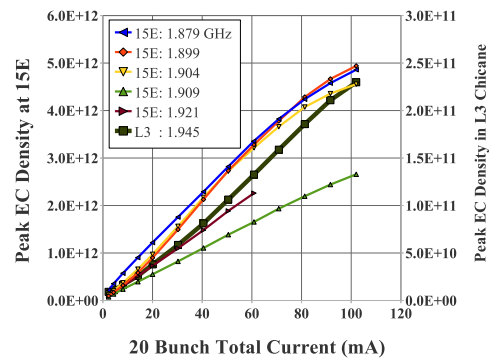

Figure 3: Data from 15E with 20 bunches of positrons, 14 ns spacing at 5.3 GeV. The first five major resonances of Fig. 2 are used to calculate the EC density. Data from the L3 Chicane dipole was taken with zero magnetic field.

DATA FROM DAFNE

Data was taken at DAFNE where TE wave resonances have been observed [6]. The storage ring was filled with 100 positron bunches and a gap of 20. In this case, the combination of long cloud duration, high EC density and relatively low TE wave resonance frequency made it possible to observe the shift of the resonance directly - as shown in Fig. 4 - rather than as phase modulation sidebands. Clearing electrodes in the vacuum chamber were toggled off and on, and the response of the TE wave resonances recorded in each case. The change in EC density based on the maximum frequency shift of about 200kHz and using Eq. (1) is about 1.5×10^{12} m^{-3}. Not all of the resonances showed the same frequency shift and some showed no frequency shift at all. Further analysis would include a detailed understanding of the electric field pattern, electrode locations and an estimate or simulation of the EC distribution.
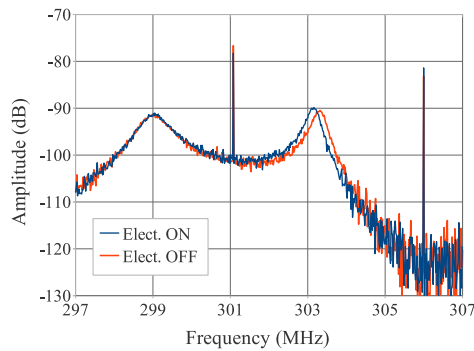
Figure 4: Data from DAFNE with 800 mA of positrons, showing the change in the TE wave resonant frequency as the clearing electrodes are turned off and on

BEAD PULL MEASUREMENTS

There are other situations where it is important to have detailed knowledge of the distribution of electric fields in the beampipe cavity. The data shown in Fig. 3 is an example. At 15E, about half of the region includes a chamber with a carbon coating for EC mitigation. Also included in that plot is data from the Chicane region of L3 where there are four chambers in dipole fields. Each of the chambers has a different type of mitigation applied to it: all the combinations of bare aluminum and TiN coating as well as chambers with or without grooved surfaces.

Bead pull measurements are a standard technique for measuring the electric fields of resonant cavities. A small dielectric bead is supported by a thin monofilament line and pulled along the length of the cavity. The change in resonant frequency is proportional to the electric field squared at the the bead using an equation similar to Eq. (1), but for a dielectric instead of a plasma. Measurements were made using both waveguide and short sections of beampipe.

Simulations using VORPAL [7] have given field patterns and frequency shifts that are in agreement both with bench measurements and analytic calculation. Simulations may become important in more complex geometries, once we obtain confidence in our ablitity to set them up correctly.

Bead pull measurements were made using beampipe similar to that in the L3 region of the storage ring. An example is given in Fig. 5 where microwaves are coupled in and out using single buttons of a BPM. Horizontal buttons were used in this measurement. The beampipe is round, roughly 9 cm diameter and each section is about 63 cm long. Three sections were joined together. In this case the beampipe with grooves on the top and bottom was the middle of the three sections. Aluminum plates were placed at both ends of the assembly to produce reflections there.

The measurement in Fig. 5 shows that the first two resonances are confined to the grooved section with exponential tails extending into the smooth sections to either side. The cutoff frequency of the grooved pipe is lower than that of the smooth pipe, which explains the effect.

There is a similar configuration of smooth and grooved beampipe in one of the Chicane magnets of the CESRTA storage ring. Data was taken there in November 2011, and is shown in Fig. 3 along with the data from 15E. The bead-pull measurement suggests that the EC density measurement in L3 is dominated by the grooved beampipe.
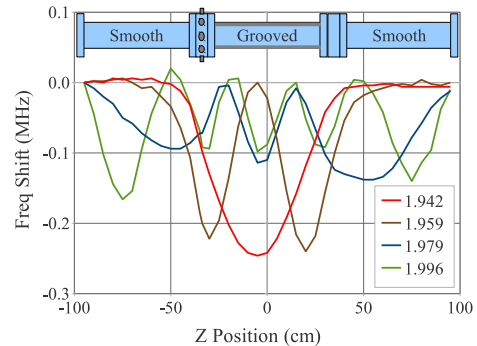
Figure 5: Bead pull with a section grooved beampipe between two smooth (round) pipes. The two lowest frequency resonances are confined to the grooved pipe.

CONCLUSIONS

The frequency response of the beampipe will determine whether it should be treated as a waveguide or as a cavity. TE wave resonances can be used to measure the EC density, but since this density is generally not uniform, the pattern of standing waves needs to be understood in order to determine *where* the measurement is being made.

ACKNOWLEDGEMENTS

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