RESONANT TE WAVE MEASUREMENT OF ELECTRON CLOUD DENSITY USING PHASE DETECTION*

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Abstract

The resonant TE wave technique can use the magnitude of modulation sidebands to calculate the electron cloud (EC) density in beam-pipe. An alternative is to mix the drive and received microwaves to form a phase detector. Using this technique, the phase shift across the resonant beam-pipe can be observed directly on an oscilloscope. The growth and decay of the EC density has a time constant of 100 ns or less, while the resulting phase shift will include a convolution of the changing EC density with the impulse response of the resonant beam-pipe – typically about 500 ns. So any estimate of the growth/decay of the cloud requires deconvolution of the measured signal with the impulse response of the resonance. We have also used phase detection to look for evidence of EC density with a lifetime that is long compare to the revolution period of the stored beam. These measurements were made at the Cornell Electron Storage Ring (CESR) which has been reconfigured as a test accelerator (CESRTA) with positron or electron beam energies ranging from 2 GeV to 5 GeV.

INTRODUCTION

Electron cloud (EC) density in accelerators can be measured by coupling microwaves into and out of the beam-pipe, typically through buttons of the type that are used for beam position monitors [1, 2]. The effect of the EC density on microwaves in the beam-pipe can be observed on a spectrum analyzer. In the resonant TE wave technique, the response contains a number of resonances just above the cutoff frequency of the beam-pipe [3, 4]. These resonances are produced by changes in beam-pipe geometry especially horizontal dimensions or the inclusion of longitudinal slots in the chamber. The response of the Q0 detector at CESRTA is shown in Fig. 1.

The presence of an electron cloud (or other plasma) shifts the beam-pipe resonant frequency upward by an amount that is proportional to the EC density. There are several ways of observing this frequency shift. If the EC density is fairly constant in time, the frequency shift can be observed directly with a spectrum analyzer. However, the resonant frequency will also be shifted by temperature changes, and some means is needed to distinguish between thermal and plasma shifts. A technique that has been used at DAΦNE is to turn clearing electrodes on or off and record the change in resonant frequency under these different conditions [5].

A train of bunches in a storage ring will produce periodic changes in the local EC density and in the resonant frequencies of the beam-pipe. If the duration of the electron cloud is short relative to the revolution time of the bunch train, the EC density will vary between zero and the value produced by a single passage of the train.

If the beam-pipe is excited at one of its resonant frequencies, the shift in frequency results in a shift of the equilibrium phase across the resonator as illustrated in Fig. 2. On a spectrum analyzer, the result will be phase modulation sidebands that can be recorded and used to determine the EC density [4, 6]. There will also be some amplitude modulation, but this should be small when driving on resonance.

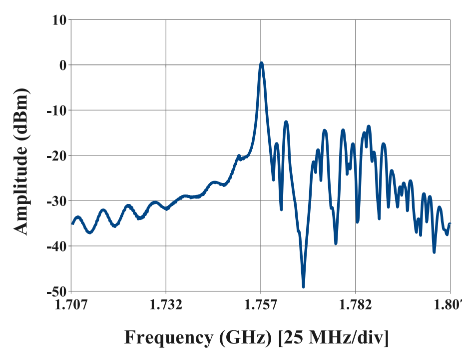

Figure 1: The resonant response of the beam-pipe at Q0, where the measurements of this paper were made, has its largest peak occurring at 1.757 GHz.

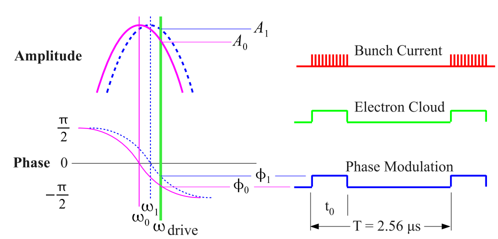

Figure 2: With a fixed drive frequency, a change in the resonant frequency will produce a change in the equilibrium phase and amplitude of the response signal.

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PHASE DETECTOR

A variation on the method outlined in the previous section is to measure the phase shift across the resonator directly by using a phase detector [7]. A fixed drive signal is split and sent to the beam-pipe and to a mixer. The response signal is routed to the second input of the mixer as shown in Fig. 3. The mixer output is routed to an oscilloscope so that the phase shift across the resonator can be observed directly. Along with other details of the setup, the amplitude of the response will depend upon how close the drive frequency is to the resonance. In order to use the mixer output directly, the response should be 0 dBm or higher. A simple calibration of the phase detector is carried out by varying the path length of one of the mixer inputs and noting the range of output voltages, which correspond to $\pm\pi/2$.

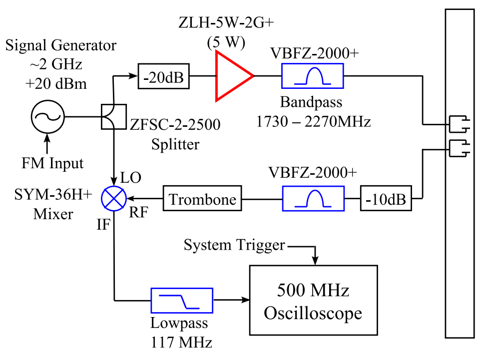

Figure 3: Signal path of the phase detector.

A step change in the phase shown in Fig 2 is only valid in equilibrium, when the changes in EC density are slow compared with the damping time of the resonance. At CESRTA this is generally not the case. The damping time of a resonance is typically 400 to 500 ns and rapid changes in the phase shift across the resonance will be limited by this damping time. For comparison, the rise time of the EC density can be tens of nanoseconds, its duration roughly the length of the bunch train and the decay time of the electron cloud is expected to be about 100 ns.

For measurements where changes in the EC density are similar or shorter than the resonance damping time, the phase shift should be proportional to the convolution of the changing EC density with the impulse response of the resonance. This is illustrated in Fig. 4 where the signal generator output has been frequency modulated with a deviation 20 kHz for 1.5 μs.

The bunch trains injected into the CESRTA storage ring are generally shorter than the 450 ns response time of the resonance. So the next test had the modulation length reduced to 400 ns with the FM deviation still at 20 kHz. The output of the phase detector was read into a MATLAB [8] script which applied a 4-pole 10 ns filter to the data, then deconvolved the data with the impulse response having a 450 ns damping time. Figure 5 shows the (filtered) input data in the upper trace and the deconvolved data in the lower trace which reproduces the 400 ns long modulation that had been applied to the resonator. The deconvolved voltage peak of about 6 mV is similar to the equilibrium value of Fig. 4. This is what would be expected since the FM deviation is the same in the two cases. So it is possible to extract the form of the original modulation by deconvolving the measured data.

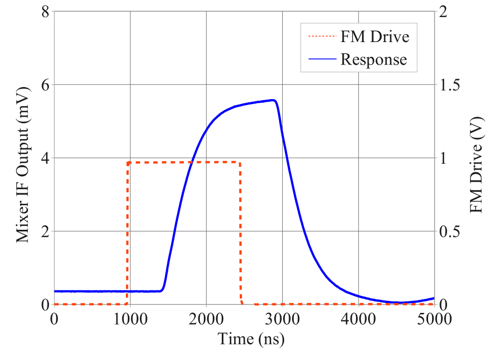

Figure 4: As a test, the drive frequency is modulated by 20 kHz for 1.5 μs. The response observed on the phase detector does not follow the frequency deviation exactly, but is convolved with the impulse response of the resonance. The time delay is due to cable lengths.

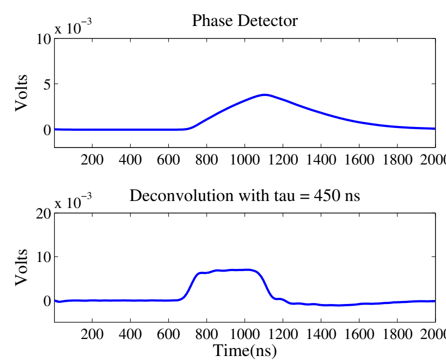

Figure 5: The 20 kHz FM duration was reduced from 1.5 μs to 400 ns. Data (upper trace) was deconvolved with the 450 ns resonator impulse response to obtain the original 400 ns modulation (lower trace) using a MATLAB script.

Detector Calibration

The trombone of Fig. 3 is varied in length to find the range of voltages produced by the detector which were $\pm$100 mV during the FM tests and $\pm$150 mV with beam. With the detector output near zero, the phase will be the ratio of the voltage output to the maximum output voltage. The voltage output during the FM test of Fig. 4 was approaching an equilibrium of about 6 mV. This gives a measured phase shift of 6/100 = .060 rad.

The phase shift across a resonator with a fixed drive frequency depends on the difference between the drive and

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resonant frequencies $\omega - \omega_0$. Near resonance, a small change in resonant frequency $\Delta\omega$ will give a change in phase $\Delta\phi$ of approximately

$$\Delta\phi \approx 2Q\frac{\Delta\omega}{\omega}. \quad (1)$$

The Q of the resonance was obtained by recording the frequency response with a spectrum analyzer. The resonance used for all of the measurements presented here is at 1.75699 GHz. The -3 dB point is at f = 355 kHz below resonance giving $\tau = 1/2\pi f \approx$ 450 ns and Q = $\omega\tau/2 \approx$ 2475. Using Eq. 1, a 20 kHz difference in frequency would give a phase shift of 0.056 rad, in rough agreement with the measured value.

To connect the measured phase shift to an EC density, the relative frequency shift $\Delta\omega/\omega$ due to the presence of a uniform low density plasma in the absence of a magnetic field is given by Eq. 3 [3, 9] where a spatially uniform EC density n_e can be brought outside of the integral over the resonant volume.

$$\begin{aligned}\frac{\Delta\omega}{\omega} &\approx \frac{e^2}{2\varepsilon_0 m_e \omega^2}\frac{\int_V n_e E^2 dV}{\int_V E^2 dV} \rightarrow \frac{e^2}{2\varepsilon_0 m_e \omega^2} n_e \\ &\approx \frac{1.59 \times 10^3}{\omega^2} n_e. \quad (2)\end{aligned}$$

Combining equations 1 and 2, for the stated values of Q and ω,

$$n_e \approx \Delta\phi \cdot 1.57 \times 10^{13}. \quad (3)$$

RESPONSE WITH BEAM

A 40-bunch train of 2.1 GeV positrons bunches was injected into the CESRTA storage ring with 14 ns spacing, giving a train length of 546 ns. The revolution period is 2.562 μs and a synchronous timing system trigger was used in averaging the phase signal data on an oscilloscope. Figure 6 shows unfiltered data from the phase detector as well as the deconvolution of that data. The direct beam signal adds high frequency components that obscure the phase shift to some extent and the deconvolution of that signal is not usable. Digital filtering was applied to the input signal – the same 4-pole 10 ns filter that was used in the test of Fig. 5. With this filtering, the phase modulation produced by the electron cloud is revealed as shown in Fig. 7. The deconvolved phase detector output is about 8 mV, corresponding to a EC density of 8.4×10^{11} m^{-3}.

While the phase detector signal has an amplitude that decreases somewhat slowly over the 2.562 μsec turn, the deconvolution shows that the actual change in EC density is relatively short lived. Figure 7 also shows that the EC density reaches equilibrium fairly quickly and there appears to be a brief increase in EC density after the passage of the last bunch of the train.

Data was also taken at a bunch spacing of 4 ns with a 30-bunch train of of 2.1 GeV positrons. The bunch intensity was 9.6×10^9 positrons/bunch, similar to that of the

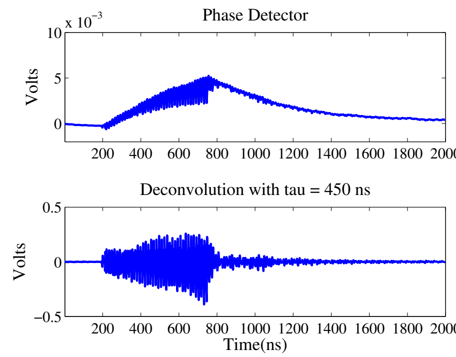

Figure 6: Unfiltered data (upper) is shown with a 14 ns spaced 40-bunch train of 2.1 GeV positrons at 0.5 mA/bunch (8.0×10^9 positrons/bunch) as well as the deconvolved data (lower).The phase signal includes high frequencies from the direct beam signal; the deconvolution is extremely noisy.

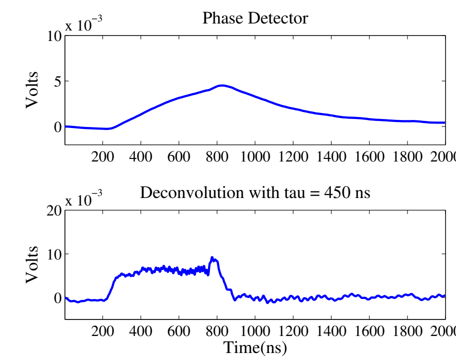

Figure 7: After filtering, the data from the 40-bunch train (upper) shows less high frequency (beam induced) signal. The signal can then be deconvolved to obtain a signal proportional to the EC density (lower).

14 ns data. The filtered 4 ns data shown in Fig. 8 has some features that need further study. There is an initial decrease in the phase detector signal for this 4 ns data that is not present in the 14 ns data of Fig. 7. We have not yet determined whether this is an instrumentation artifact or an actual change in EC density.

LONG LIVED CLOUD

One of the motivations for setting up the phase detector was to look for EC density lifetimes that are long compared to the 2.5 μs revolution period of the bunch train at CESRTA. While the data of the previous section shows that the change in EC density is short lived, it doesn't show whether or not this change is on top of a persistent EC density. In the following experiment, the beam was removed from the storage ring in a single turn by activating pulsed magnets at large amplitude. If there is a long lived cloud, the phase detector should show a shift in the baseline signal that is lower than the value reached with stored beam.

The oscilloscope was reconfigured in the following way:

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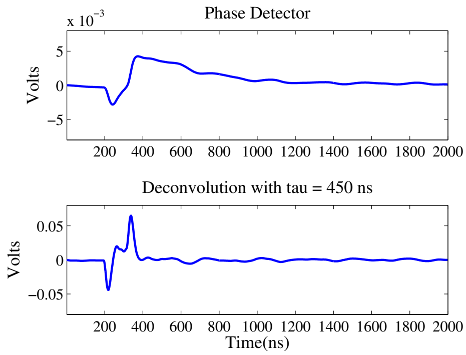

Figure 8: Filtered data for 4 ns spaced bunches in a 30-bunch train of positrons at 2.1 GeV and about 18 mA total current (9.6×10^9 positrons/bunch).

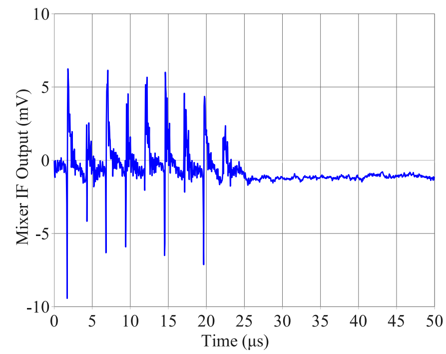

Figure 9: A 30-bunch train of 4 ns spaced 2.1 GeV positrons at 16.5 mA total current (8.8×10^9 positrons/bunch) The signal recorded after ejecting the beam in a single turn does not show signs of a significant long lived component of the cloud.

averaging was turned off; a 10 MHz lowpass filter was added to the scope input; a much longer time scale was used and a system beam loss detection trigger was used to trigger a single trace on the oscilloscope. A 30-bunch train of positrons was stored with 4 ns spacing and 8.8×10^9 positrons/bunch, similar to the 4 ns data of Fig. 8.

Figure 9 shows the phase detector output when the beam in the storage ring was removed in a single turn. On this timescale, nine turns are visible and there is not a large shift in the phase detector baseline output after removal of the beam.

In its present configuration, there are several limitations to the sensitivity of this technique for measuring long lived electron cloud. The signal levels are quite small, making it difficult to observed more subtle effects. The sensitivity of the measurement also depends upon the integral of Eq. 2 that is taken over the entire resonant volume. If the long lived cloud were in only a small part of the resonant volume (n_e not spatially uniform), the sensitivity of the measurement would be reduced by the volume ratio and scaled by the square of the electric field in the volume of persistent cloud. It has been suggested that long lived cloud may exist in quadrupoles and wigglers, which could occupy a small fraction of the resonant volume.

CONCLUSIONS

A phase detector can be used to observe phase shifts due to a rapidly changing EC density. The time evolution of the EC density can be extracted from the measured phase shift by deconvolving the signal with the impulse response of the resonant beam-pipe. Systematic studies will be needed to understand some of the features of the phase signal, especially with 4 ns spaced bunches.

This technique did not show evidence of significant long lived EC density, but the present sensitivity of a few millivolts could be improved. If the long lived cloud is highly localized, a better understanding is needed of the field distribution within the resonant volume in order to estimate the sensitivity of the measurement at that location.

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