Resonant TE Wave Measurement of Electron Cloud Density Using a Phase Detector*

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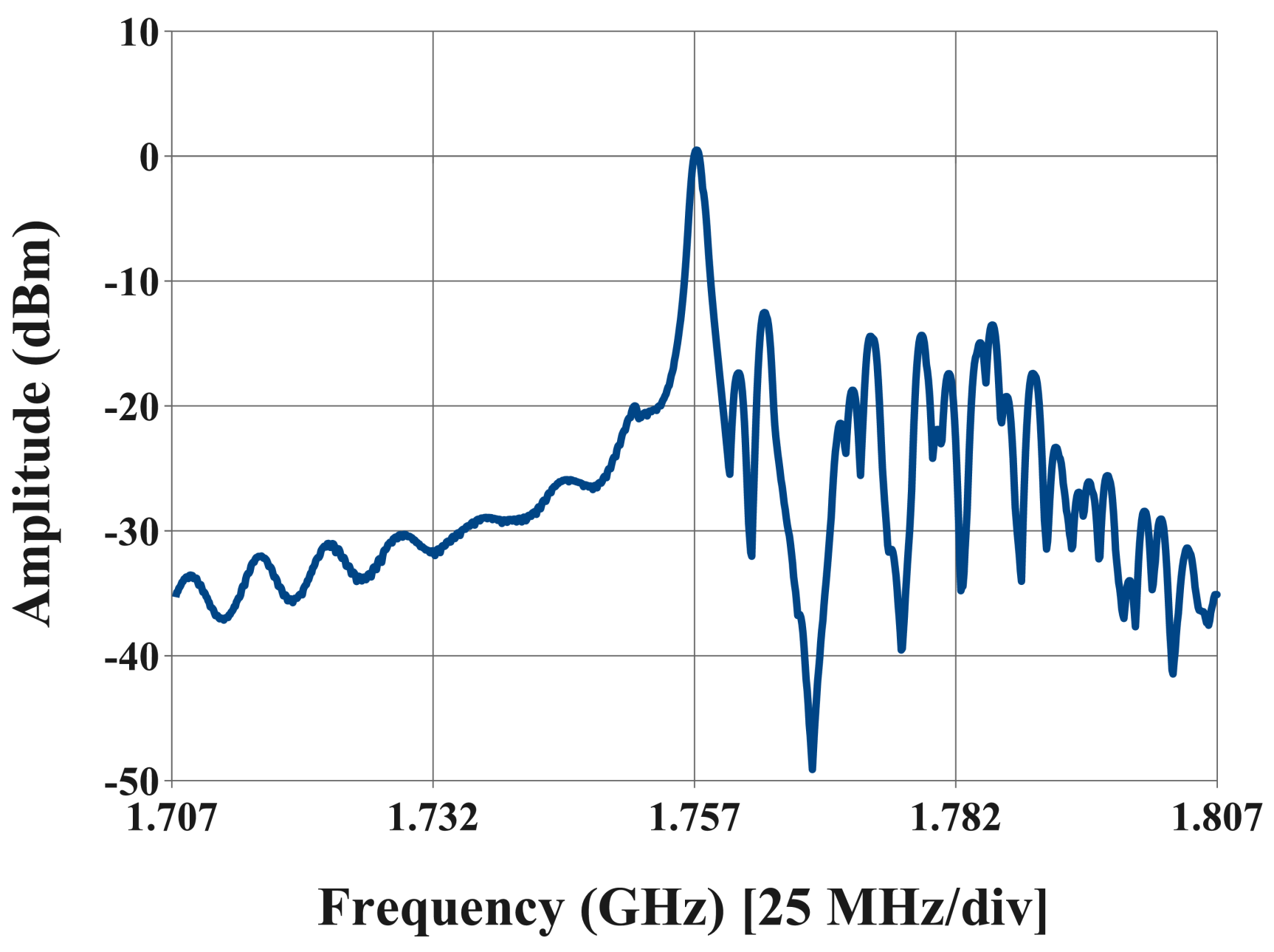
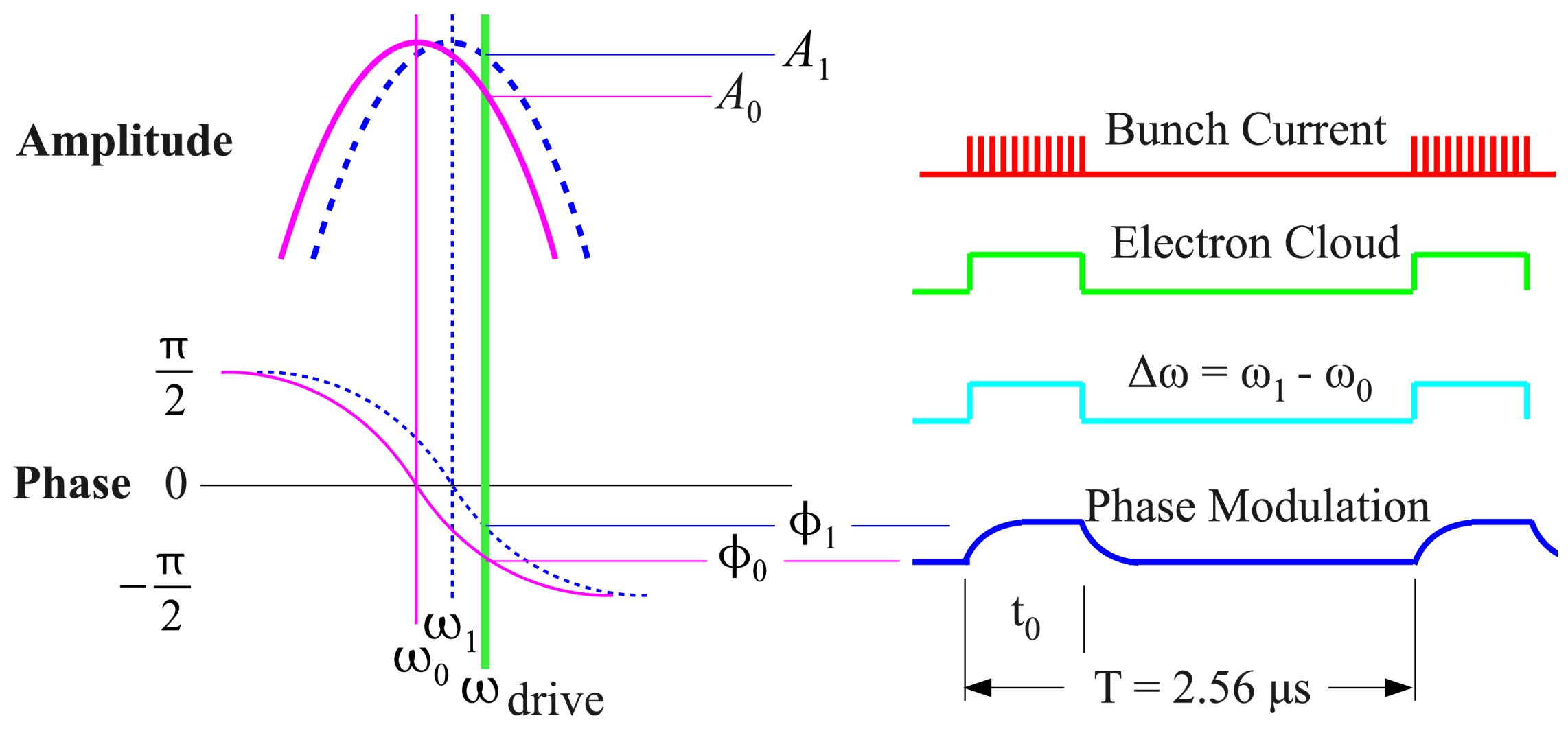
Abstract
The resonant TE wave technique can use the magnitude of modulation sidebands to calculate the electron cloud (EC) density in beam-pipe. An alternative is to mix the drive and received microwaves to form a phase detector. Using this technique, the phase shift across the resonant beam-pipe can be observed directly on an oscilloscope. The growth and decay of the EC density has a time constant of roughly 100 ns, while the resulting phase shift will include a convolution of the 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.



The resonant response of the beam-pipe was measured at Q0 with largest peak at this detector occurring at 1.757 GHz. The signal generator of the phase detector was set to this frequency.



With a fixed drive frequency, a change in the resonant frequency produces a change in the equilibrium phase and amplitude of the response signal. The dynamic phase modulation includes the convolution of the frequency change Δω with the impulse response of the resonance.

Detector Calibration

$$\frac{\Delta\omega}{\omega} \approx \frac{e^2}{2\varepsilon_0 m_e \omega^2}\,\frac{\int_V \overset{\text{Electron Cloud Density}}{n_e} E^2\,dV}{\int_V E^2\,dV} \rightarrow \frac{e^2}{2\varepsilon_0 m_e \omega^2}\,n_e$$

The shift in resonant frequency due to a low density plasma in the absence of magnetic field is given by the equation above, where for a spatially uniform plasma (EC density n_e) the density can be taken outside of the integral over the resonant volume.

$$\Delta\phi \approx 2Q\frac{\Delta\omega}{\omega} \approx 2Q\frac{e^2}{2\varepsilon_0 m_e \omega^2}n_e = 2Q\frac{1.59\times10^3}{\omega^2}n_e$$

The shift in equilibrium phase across the resonance is given above. Combining this with the equation for the frequency shift the relation between the EC density and the phase shift is obtained.

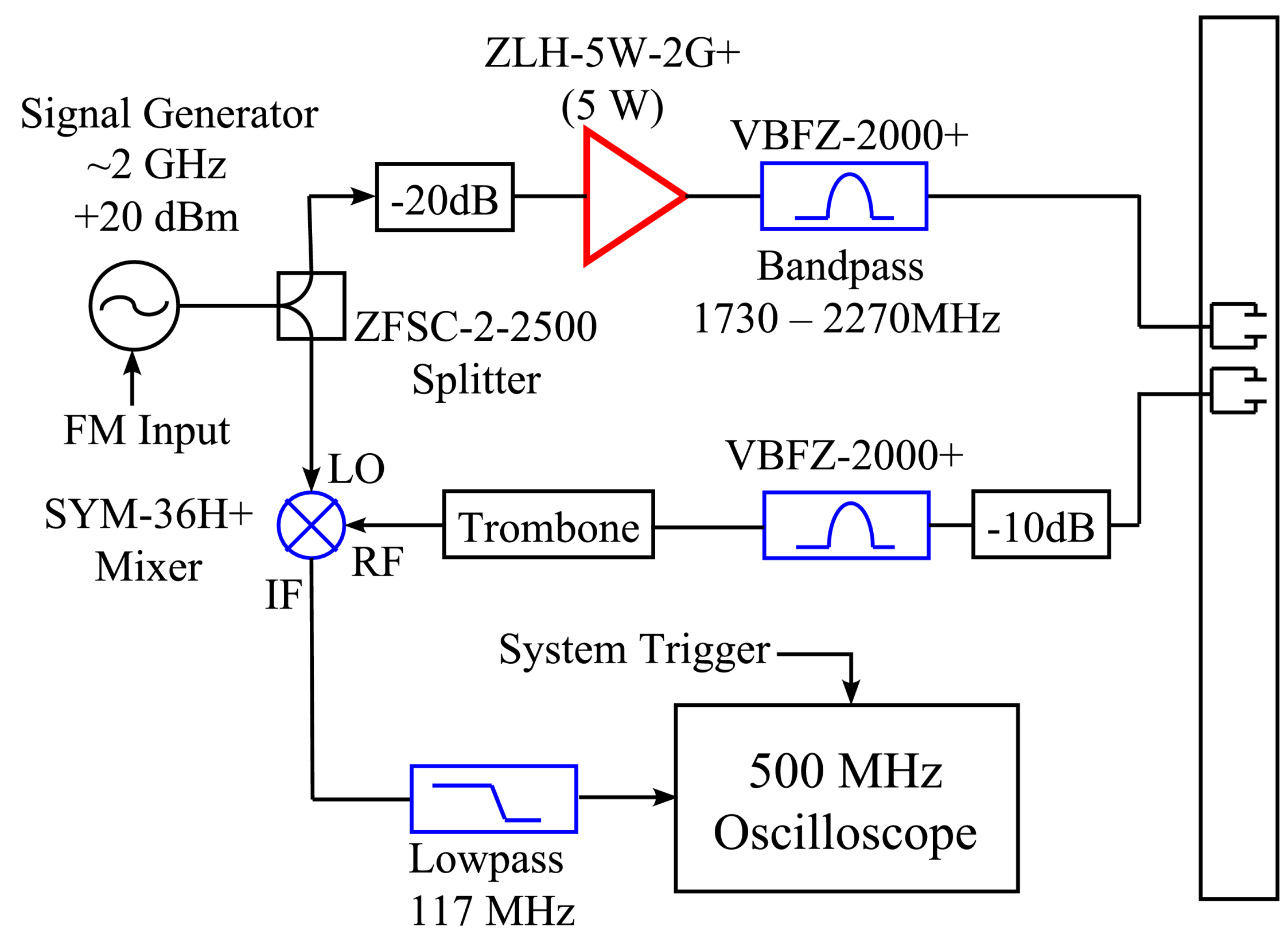
$$V = V_{max}\sin(\phi) \rightarrow dV = V_{max}\cos(\phi)\,d\phi$$

$$\Delta\phi \approx \frac{\Delta V}{V_{max}}$$

The detector sensitivity to phase shift is obtained by changing the length of the trombone and finding the maximum and minimum output of the phase detector. This was ±100 mV for the bench measurements and ±150 mV for beam measurements.

$$\boxed{n_e \approx \Delta\phi\cdot1.57\times10^{13} = \frac{\Delta V}{V_{max}}\cdot1.57\times10^{13}}$$

Phase Detector

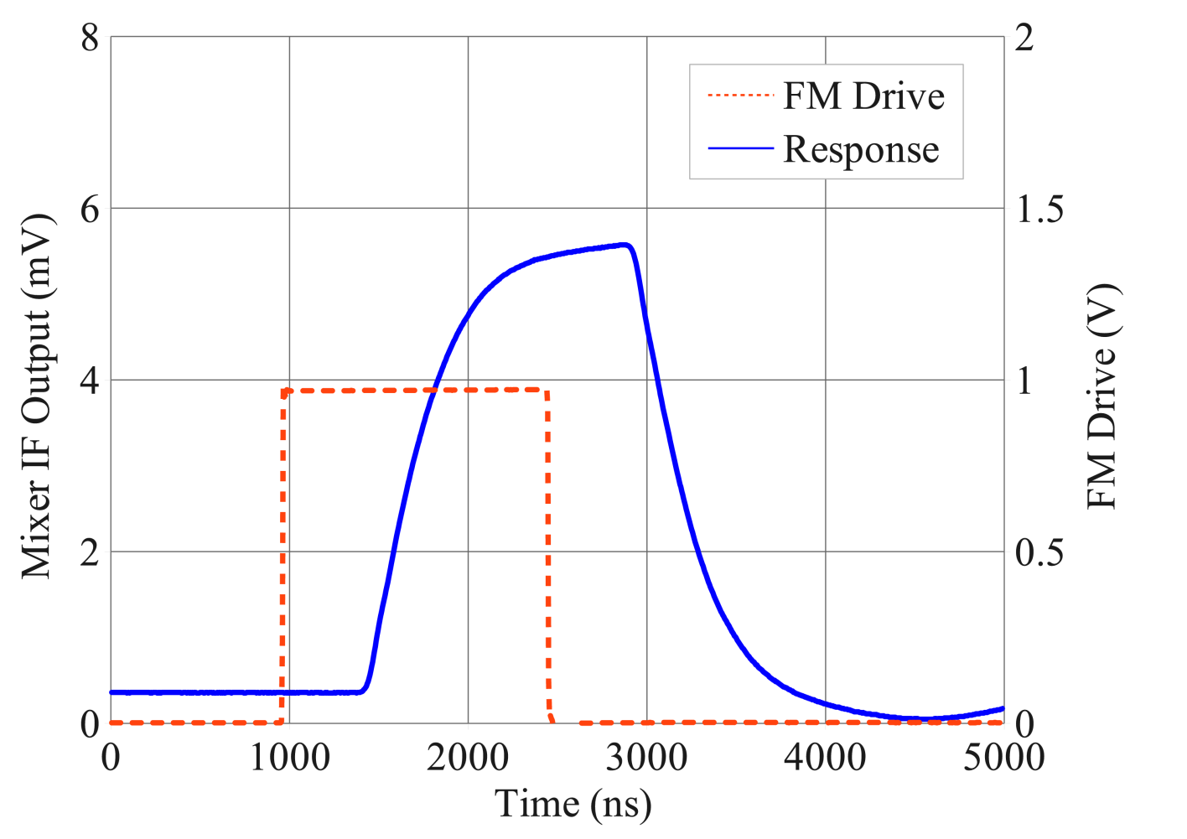


The signal path of the phase detector is shown above. A simple calibration of the phase detector is carried out by varying the trombone and noting the range of output voltages, which correspond to ± π/2. Near zero output, the phase will be the ratio of the measured voltage to the maximum voltage.

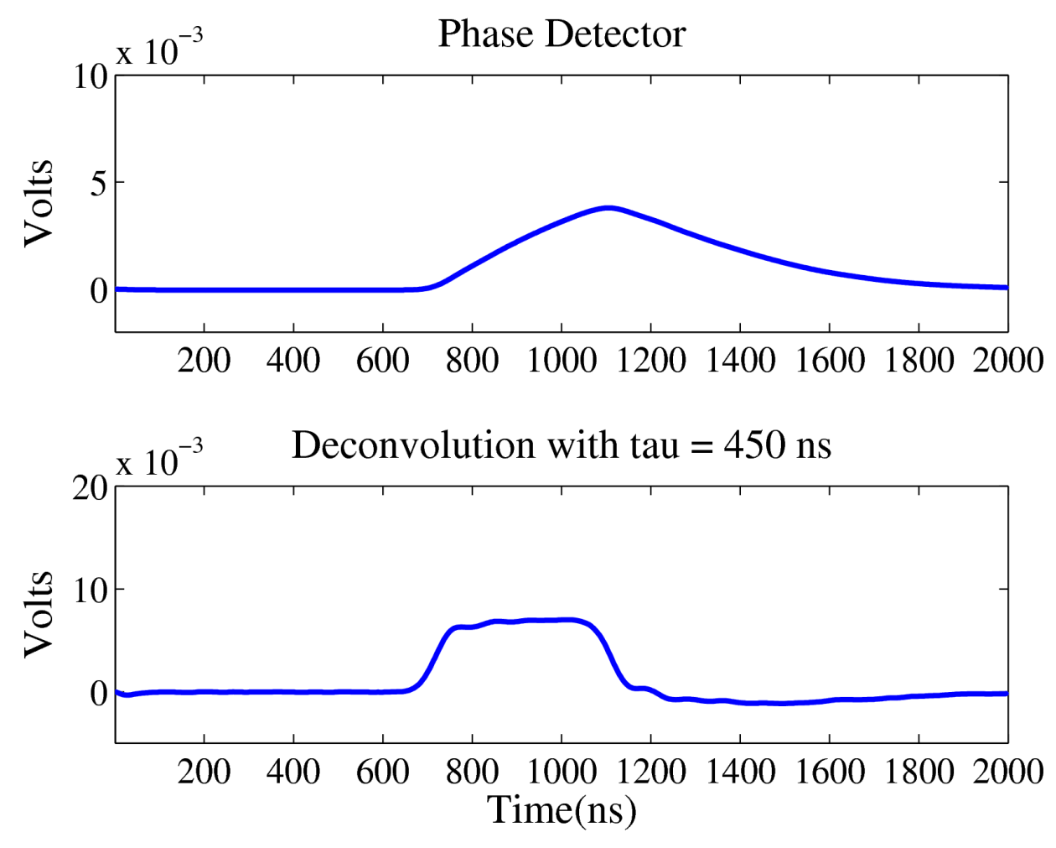
The presence of electron cloud will change the phase of signal to the RF port of the mixer, producing a change in voltage on the oscilloscope. The duration of the electron cloud (EC) density is short compared to the revolution period of 2562 ns.

Because the beam-pipe is resonant, the measured phase response will be the convolution of the changing EC density and the resonant impulse response. A deconvolution is required in order to obtain the time profile of the EC density.

Bench Tests

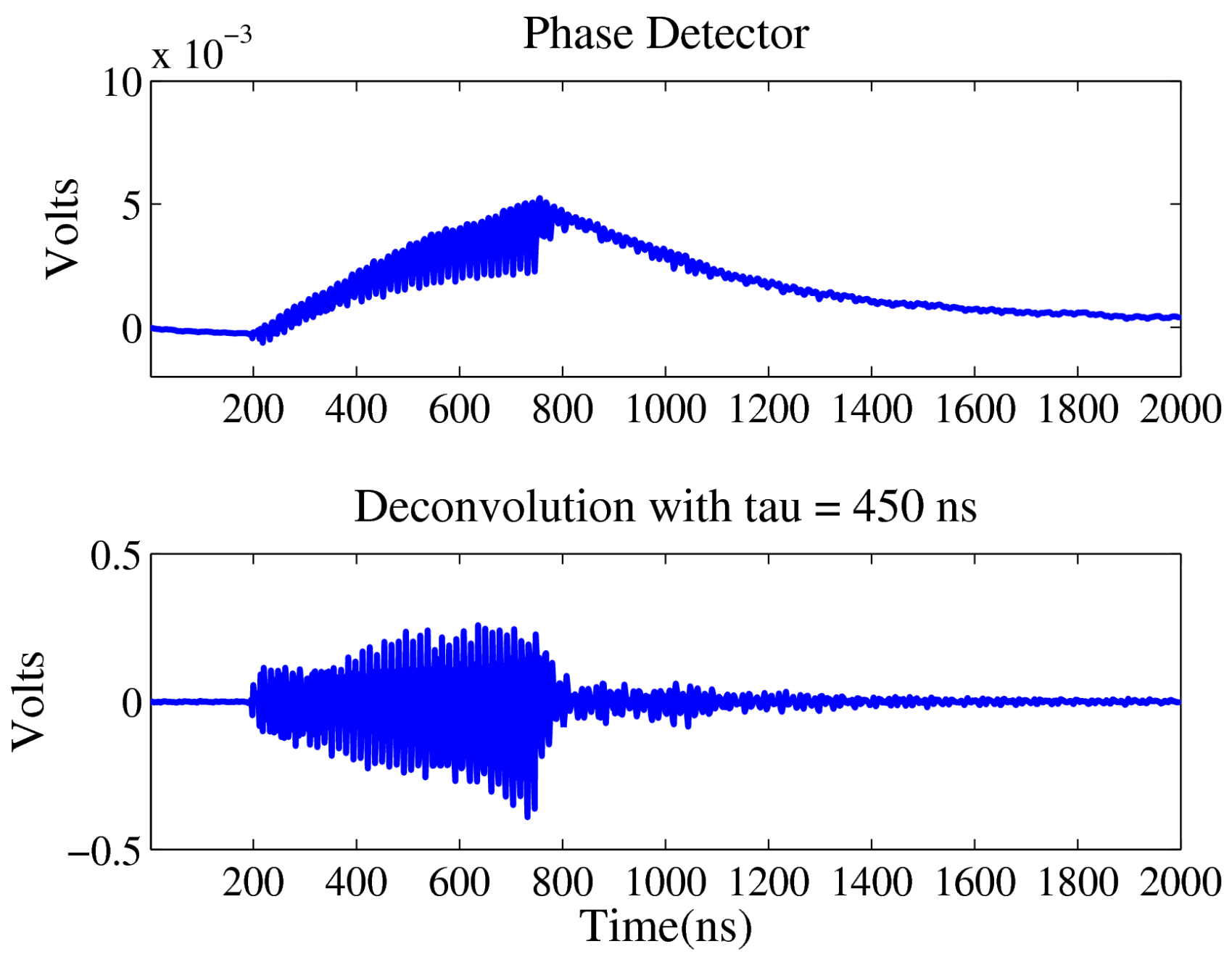


As a test, the drive frequency is modulated by 20 kHz for 1.5 µs. The response observed on the phase detector does not follow the frequency deviation exactly, but is convolved with the impulse response of the resonance. The time delay is due to cable lengths.

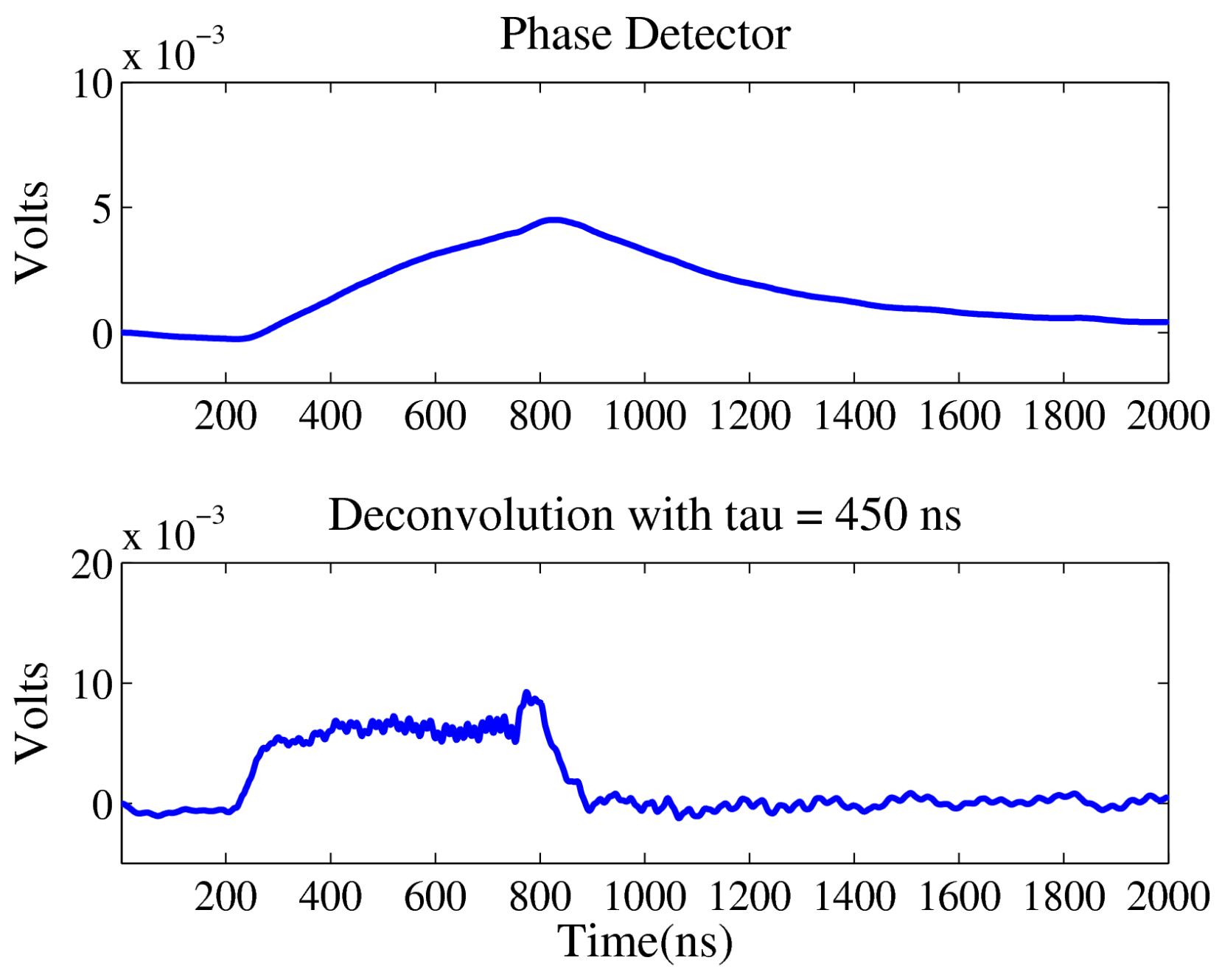


The 20 kHz FM duration was reduced from 1.5 µs to 400 ns. Data (upper trace) was deconvolved with the 450 ns resonator impulse response to obtain the original 400 ns modulation (lower trace) using a MATLAB script. A 4-pole 10 ns filter was applied to the data before being displayed and deconvolved.

Response with Beam: 40-Bunch Train 14 ns Spacing

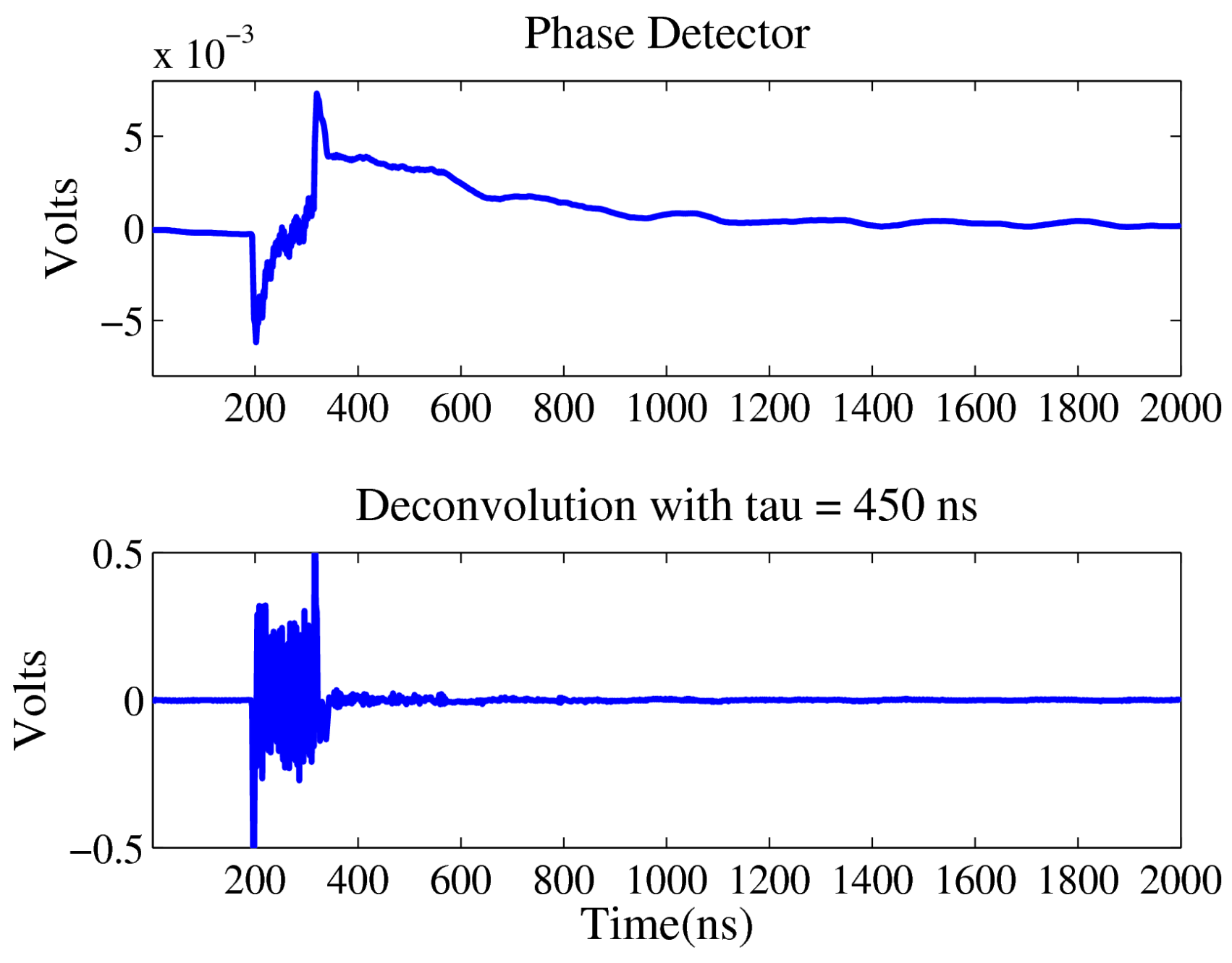


Unfiltered data (upper) is shown with a 14 ns spaced 40-bunch train of 2.1 GeV positrons at 0.5 mA/bunch (8.0 x 10^9 positrons/bunch) as well as the deconvolved data (lower).The phase signal includes high frequencies from the direct beam signal; the deconvolution is extremely noisy.

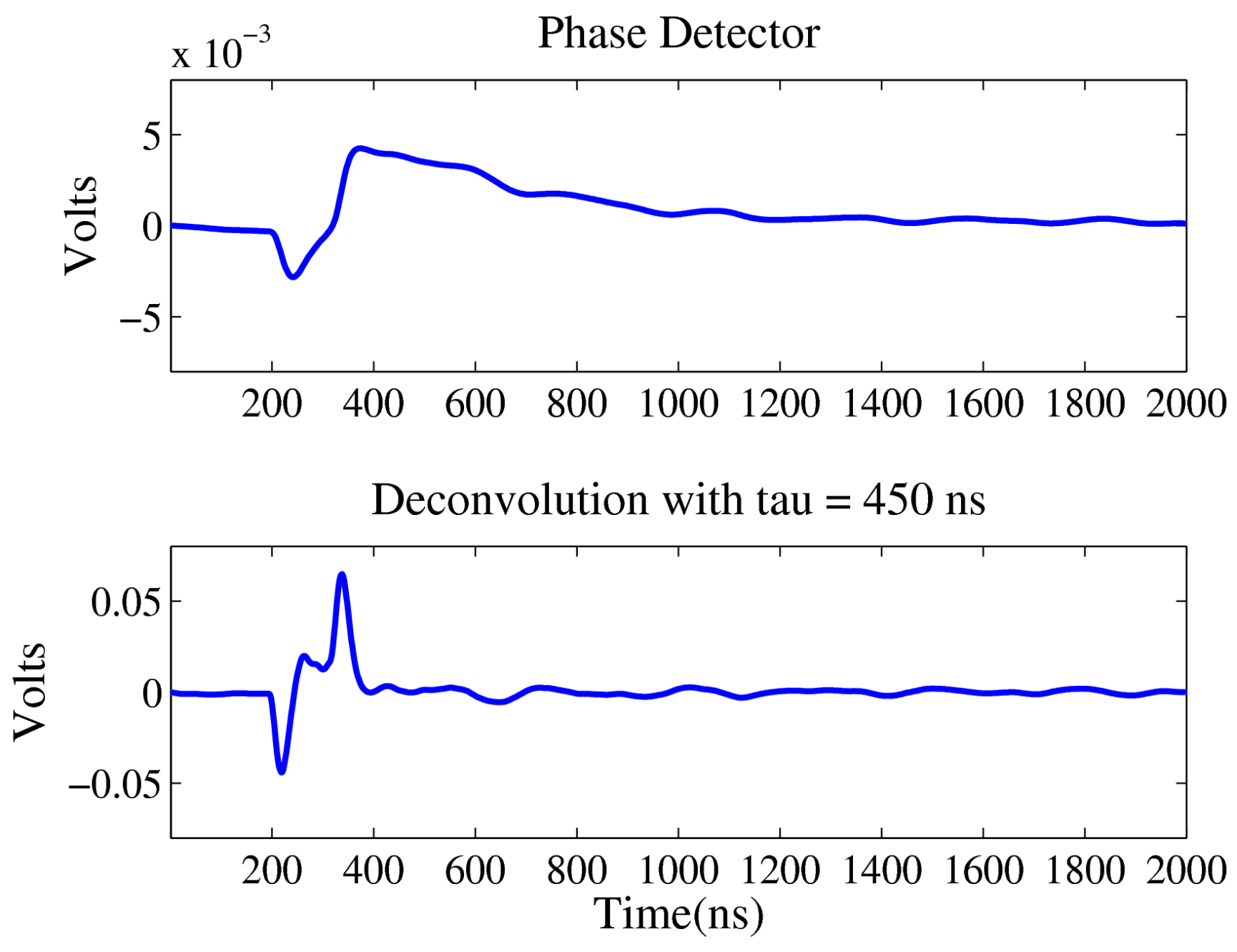


After filtering (4-pole 10 ns), the data from the 40-bunch train (upper) shows less high frequency (beam induced) signal. The signal can then be deconvolved to obtain a signal proportional to the EC density (lower). The deconvolved phase detector output is about 8 mV, corresponding to a EC density of 8.4 x 10^{11} m^{-3}.

Response with Beam: 30-Bunch Train 4 ns Spacing



Unfiltered 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 x 10^9 positrons/bunch)



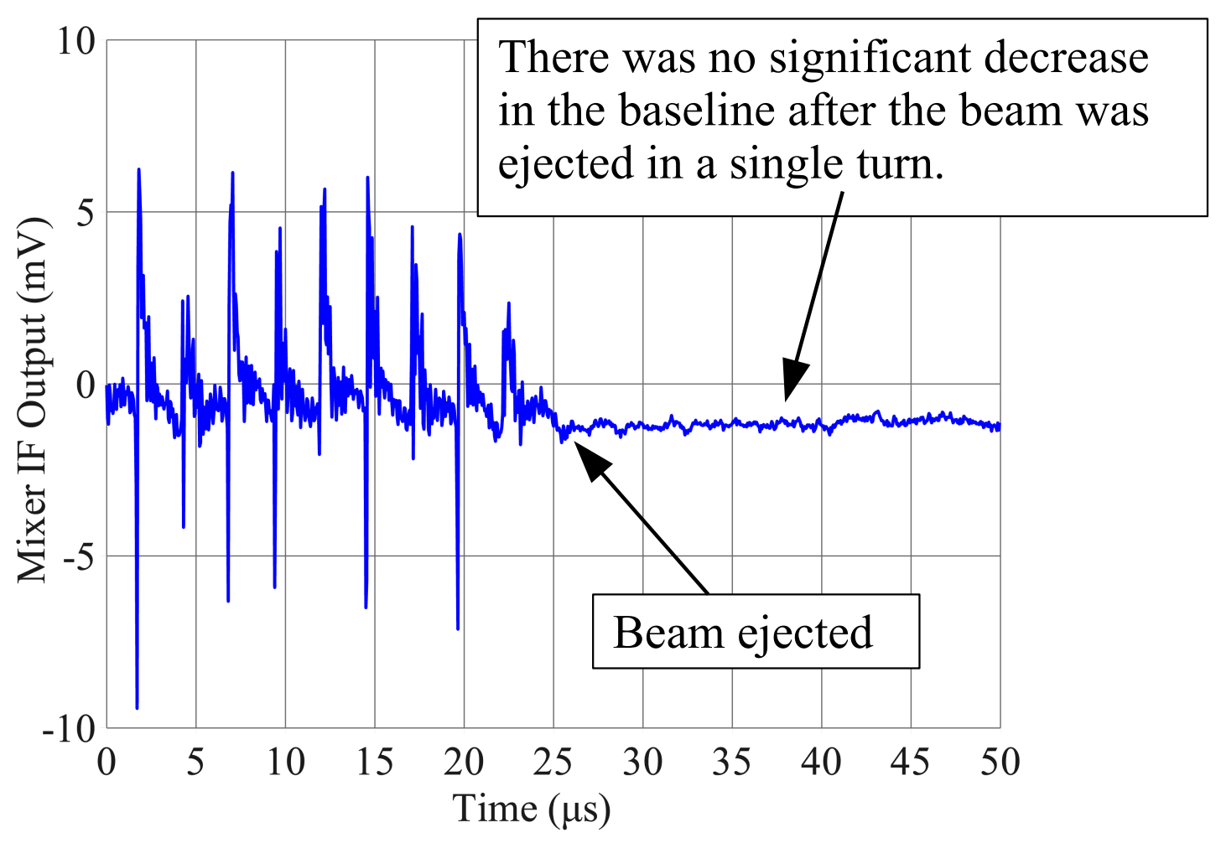
After filtering (4-pole 10 ns), the 4 ns 30-bunch data has some unusual features, such as the steps in the phase detector signal at the beginning and end of the train. We have not yet determined whether these features are an instrumentation artifact or a real signal.

Summary and Discussion

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.

Long Lived Cloud?



There was no significant decrease in the baseline after the beam was ejected in a single turn.

A 30-bunch train of 4 ns spaced 2.1~GeV positrons at 16.5 mA total current (8.8 x 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

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