MICROWAVE RESONATOR DIAGNOSTICS OF ELECTRON CLOUD DENSITY PROFILE IN HIGH INTENSITY PROTON BEAM

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Abstract

A method for electron cloud detection in proton accelerators is reported through the measurement of the phase shift of microwaves undergoing controlled reflections within accelerator vacuum vessel. Previous phase shift measurement has a limitation in interference signals due to uncontrolled reflections from beamline components, leading to an unlocalized region of measurement and indeterminate normalization. The method in this paper describes controlled reflectors about the area of interest to localize the measurement and allow normalization. Analyses of the method are discussed via theoretical calculations, electromagnetic modeling, and experimental measurements with a bench-top prototype.

INTRODUCTION

The formation of a cloud of non-relativistic electrons in the vacuum chamber of an accelerator causes the electron cloud. A variety of factors seeds and amplifies the cloud through acceleration in the electromagnetic field of the beam and secondary emission from the vacuum chamber materials. With the intense amplification, the electron gas can induce a beam instability by interacting through electrostatic forces with a stored proton (or positron) beam. This instability is a particular concern for the proposed Project X [1], a multi-megawatt proton facility planned for construction at Fermilab. Project X will involve more than tripling the bunch intensity in the Main Injector (MI), which is a synchrotron that accelerates 53 MHz proton bunches from 8 GeV to 120 – 150 GeV. The electron cloud can be seeded in the MI either by residual gas ionization or beam loss on the vacuum chambers. The seed electrons are accelerated transversely by the electric potential of the proton bunches and are amplified upon subsequent collision with the vacuum chamber. The instability can limit the performance of the accelerator by increasing the vacuum pressure, inducing large coherent oscillations, emittance growth, and shifting the tune of the machine, among other things.

Fermilab initiated a program of investigation of the electron cloud to understand the issues concerning an upgrade MI and other high-intensity proton accelerators. One component of this program is to develop instrumentation for measuring the formation of the electron cloud. The electron cloud density can be measured by sending EM waves through an electron cloud of uniform distribution and measuring the phase shift of the EM waves [2]. The phase shift of an electromagnetic wave through a uniform, cold plasma per unit length is given by:

$$\frac{\Delta\varphi}{L} = \frac{\omega_p^2}{2c\sqrt{\omega^2 - \omega_c^2}} \quad \omega_p^2 = 4\pi\rho r_e c^2 \tag{1}$$

where c is the speed of light, r_e is the classical electron radius, and ω_c is the cut-off frequency of the pipe. The above formula assumes that the e-cloud density is static but in the MI and other machines, the e-cloud density varies as a function of time because the proton beam which generates the electron cloud has a time pattern of a bunch structure. Therefore, sending a carrier wave into the cloud results in phase-modulation, which can be measured at a receiver some distance from the transmitter. A previous test of an isolated region, surrounded by ferrite absorbers, resulted in phase shifts that were so small as to be nearly immeasurable [3]. Therefore, we need a technique that is localized and yet gives a strong phase-shift [4, 5]. Our aim in this work is to make the measurement both localized and increase the signal amplitude. We achieve this by installing reflectors on the beam pipe on either side of the region under study. By deliberately installing reflectors, the reflections are controlled and thereby increase the signal and localize it simultaneously. This paper reports our experimental study of microwave reflection for the specific case of the Fermilab MI beam pipe for various dielectric thickness, orientation and location for different sets of antennae. We begin by describing the experimental setup and then discuss the experimental methods we undertake using simulations and analytic calculations. Next, we discuss the results of the measurement from a bench-top prototype and some ideas for future work.

NUMERICAL MODELLING

The entire system configuration has been simplified to be the elliptical beam pipe blocked by the apertures that induce signal reflections at both sides of the pipe. In electron gas diagnostics, the phase of a carrier signal, while traveling along the beam pipe, is shifted by the presence of the electron cloud with gas density, n. Electron clouds energized by a proton beam are normally very dilute gas; densities range from 10^{11} – 10^{12} m^{-3}. The phase shift ratio ($\Delta\varphi/L$) of a traveling wave signal in the dilute gas would be too small to be properly identified; Even a 10 m long beam pipe may not enhance the phase shift large enough to be clearly measured by a signal detector (antenna) within the phase resolution. Due to the nature of the single path interaction through the

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waveguide, traveling waves also have nearly zero response to localized gases, which have no variation on their phase shifts. Therefore, this method is also limited in identifying the spatial location of the electron cloud. Multiple trips of a trapped eigenmode effectively increases the travel distance, L, which thereby enhances the phase shift. The feeble phase shift through a dilute plasma gas can be thus rapidly increased far beyond the resolution limit of a signal detector within a very short distance. Besides, since cavity eigenmodes respond more or less sensitively to electron gases depending upon their locations corresponding to trapped waveforms, the technique might be much more efficient for accurately specifying the spatial position and distribution of the electron cloud.

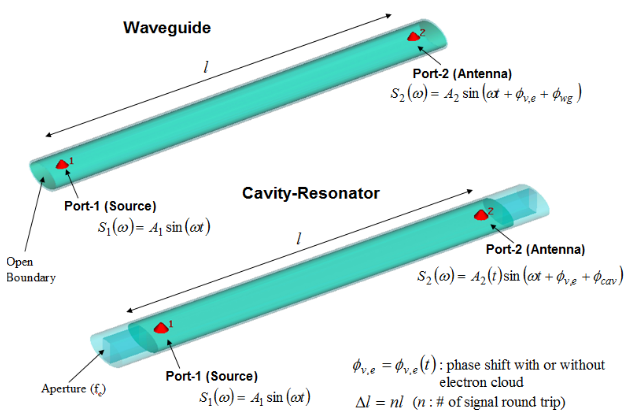

Figure 1: Finite-integral-technique (FIT) simulation models (a) elliptical waveguide and (b) elliptical cavity.

In the given experimental system, the beam pipe is assumed to be filled with an electron gas, with a density (n), produced by a high intensity proton beam. Although density distribution of a real gas state has a spatial dependence, $n = n(\mathrm{r})$, for simplicity, we first consider a constant density, $n = n_0$. $= \varepsilon\mu^{1/2}$. A plasma gas with a constant density can be thus simply approximated as a dielectric medium by a Drude model, as follows.

$$\varepsilon(\omega) = \varepsilon_0 \left(1 - \frac{\omega_p^2}{\omega^2}\right) \quad \text{and} \quad \mu = \mu_0 \tag{2}$$

This dielectric approximation very effectively reflects the typical response of a uniformly distributed plasma gas since the gas strongly resonates with an incident wave as ω approaches ω_p.

Figure 2 shows the phase-shift versus time graphs of the cavity and waveguide models with the 2π-mode carrier ($f = 1.5416$ GHz) with charge density, $n_e = 10^{11}$ m^{-3}. The comparative analysis result ended up showing a noticeable improvement: phase shift seems to be enhanced 10 times more by the cavity than the waveguide. In Fig. 2, the carrier signal in the waveguide quickly reaches the maximum phase shift (Δφ ~ 2.3 mrad) at $t = 2$ μs. However, it continuously rises in the cavity beam pipe up to Δφ ~ 23 mrad until $t = 6$ μs when the cavity reaches a steady state.

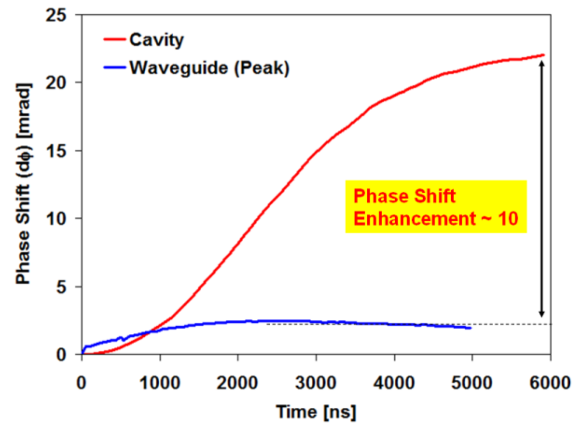

Figure 2: Phase shift versus time graphs of waveguide (blue) and cavity (red) beam pipe models. The cavity enhances the phase-shift by a factor of 10. (ear length/width = 60 mm/6mm)

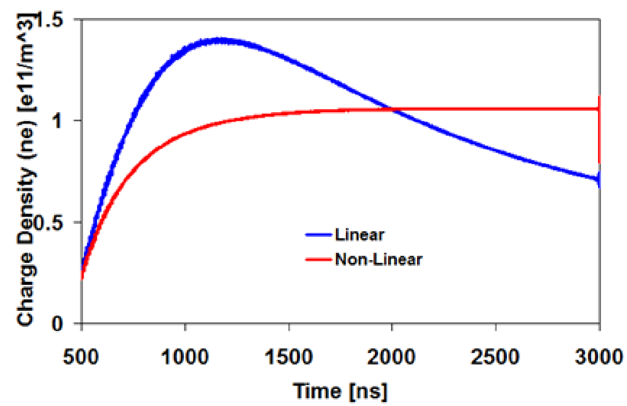

Figure 3: Electron cloud charge density versus time graphs from two different assumptions on the wave traveling distance in the cavity: linear- (blue) and non-linear (red) increases.

Figure 3 shows the time-dependent charge density graph. The input parameters for the density calculation are given as the 2π-mode carrier frequency of $f = 1.5416$ GHz, f_c = 1.516 GHz, and $n_e = 10^{11}$ m^{-3}. The charge density linearly increases until t = ~ 2 μs and gradually decreases after the stationary state since the travel distance of the carrier signal is assigned to continuously increase in the definition, whereas the phase shift is saturated after RF filling time. Figure 8(b) shows that the charge density at ~ 2 μs, corresponding to the saturation time of phase shift in Fig. 8(a), is ~ 10^{11} m^{-3}, which is exactly matched with the theoretically pre-assigned density to the dielectric Drude model. The red curve is the corrected charge density versus time graph, which clearly shows that the analytic curve converges to the defined density (10^{11} m^{-3}). In this model, the incremental rate of signal travel distance also gradually decreases with that of the phase shift. This calculation technique can thus provide an exact charge density after the simulation time of phase saturation. The comparative analysis verified that a cloud density can be still accurately calculated even from the enhanced phase-shift resolution of the cavity resonance diagnostics.

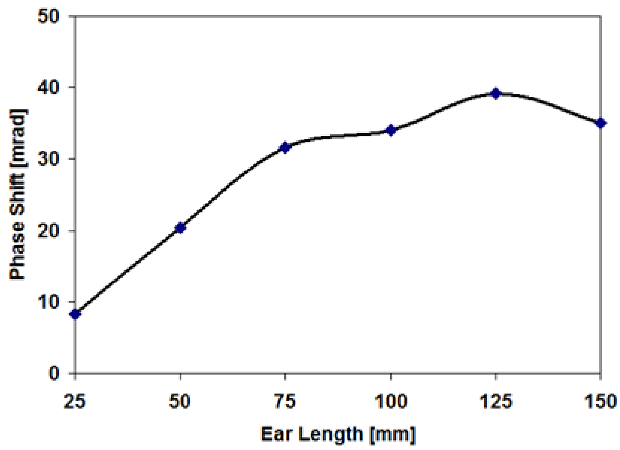

Figure 4: Saturated phase-shift versus ear-length graph (carrier signal: f = 1.5224 GHz, π-mode.

Figure 4 shows phase-shift graphs in terms of the ear lengths that are calculated with the fixed ear width (= 20 mm). The width of the beam pipe aperture was chosen to be ~ 80 mm with the consideration of the maximum proton beam diameter. Sweeping the ear lengths ranges from 25 mm to 150 mm with a 25 mm step. The phase-shift graphs in time domain clearly depicts that the shortest aperture with the longest penetration depth of an evanescent leakage field has the smallest phase-shift resolution with the short saturation time. The converging shift resolution is gradually increased from 8 mrad to 40 mrad as the saturation time moves from ~ 2 μs to ~ 8 μs, but it does not increase above the ear length = 125 mm. The beam pipe apertures with ≥ 100 mm lengths appear to have significantly small amounts of external energy losses, which thereby need a few thousand round trips for a π-mode standing wave to be completely coupled out with the 1 m long beam pipe cavity.

EXPERIMENTAL TEST

In order to test the effectiveness of the reflector 'ears', we performed a series of bench-top experiment with the MI pipe of 1 m length and a cross section 11.8 cm by 5.4 cm. We set up the network analyzer to generate microwave signal with a frequency span from 1.5 GHz to 2.4 GHz with a bandwidth of 10 kHz, and measure the phase of S_{21} transmission. Two 5.08 cm half-wave dipoles in transverse orientation are used to transmit and receive even TE_{11} mode with cutoff frequency at around 1.516 GHz. To model the e-cloud, we placed the 2.7 cm dielectric (Teflon) at the center of the waveguide. The phase data were collected with and without the dielectric inside the waveguide. We calculated the phase shift of the signal due to the dielectric by subtracting the phase data without the dielectric from the phase data with the dielectric. Reflectors of three different thickness, 80 μm, 2.1 cm, and 4.3 cm, were designed. Fig 5 shows the phase-shift due to three different reflector thicknesses. As predicted by the simulation, the thicker the reflector-ears, the higher the phase-shift. A separate experiment using distributed dielectric also indicates phase-shift improvement when thick ears are used as reflectors.

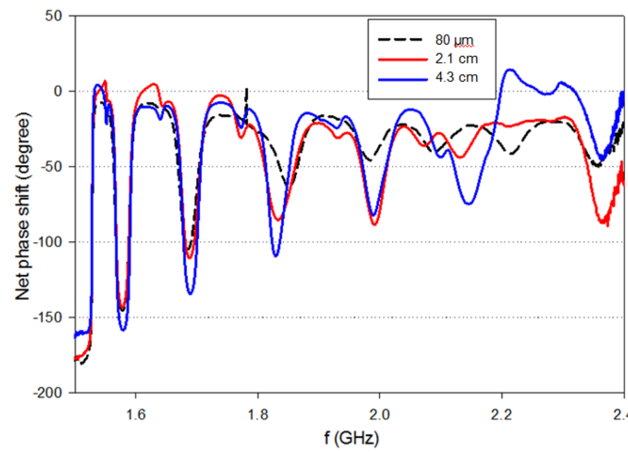

Figure 5: Saturated phase-shift versus ear-length graph (carrier signal: f = 1.5224 GHz, π-mode.

CONCLUSION

We have developed an effective method to accurately measure the density of dilute electron clouds generated by high intensity proton beams. The strong phase shift enhancement from multiple reflections of standing waves in a resonating beam pipe cavity has been demonstrated with numerical modeling using dielectric approximation and microwave S-parameter measurements. The equivalent dielectric simulation showed a ~ 10 times phase shift enhancement (2π-mode, 1.5416 GHz) with the cavity beam pipe compared to the waveguide model. Preliminary experimental studies based on a bench-top setup confirm the simulation showing that thicker reflectors enhance the phase-shift measurement of the electron cloud density.

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