ELECTRON CLOUD STUDIES IN THE FERMILAB MAIN INJECTOR USING MICROWAVE TRANSMISSION*

J. C. Thangaraj#, N. Eddy, B. Zwaska, J. Crisp, I. Kourbanis, K. Seiya, Fermi National Accelerator Laboratory, Batavia, IL 60510, U.S.A.

Abstract

In this paper, we present recent results from our measurement at the Fermilab Main Injector through microwave transmission in a beam pipe. We present three types of measurement techniques. In the first technique, we use time-resolved direct phase shift measurement to measure the e-cloud density. In the second and third techniques, we look for side bands in the frequency spectrum with or without frequency span by collecting turns of data. We present experimental results taken from MI40 and MI52 test section of the main injector.

INTRODUCTION

Project X is a multi-megawatt proton facility planned for construction at Fermilab. To achieve this goal, high current proton beam will have to be transported through the main injector [1]. The main injector is a synchrotron that accelerates 53 MHz proton bunches from 8 GeV to 120-150 GeV. During the passage of a high intensity proton bunch, low energy background electrons can interact with the proton bunch and develop instabilities. This could potentially limit the performance of the accelerator by increasing the vacuum pressure, emittance growth, shifting the tune of the machine among other things. Hence it is important to measure, model and mitigate electron cloud in such machines.

In this work, we report our results from measuring electron cloud density using microwave techniques in the main injector at the Fermilab. We begin with a brief introduction to the principle behind the measurement and then discuss three different techniques to measure e-cloud density. Finally, we summarize our results and conclude by suggesting future plans.

Microwave measurement Principle

By sending EM waves through an electron cloud of uniform distribution and measuring the phase shift of the EM waves, the electron cloud density can be measured. The phase shift φ of an electromagnetic wave of frequency ω through a uniform, cold plasma (of plasma frequency ω_p and density ρ) per unit length is given by [2]:

$$\frac{\emptyset}{L} = \frac{\omega_p^2}{2c\sqrt{\omega^2 - \omega_c^2}}; \quad \omega_p^2 = 4\pi\rho r_e c^2$$

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 main injector and other machines, the e-cloud density varies as a function of time. The reason being the proton bunch which generates the electron cloud has a time pattern. Hence, the e-cloud density varies as a function of time. So, sending a carrier wave into the cloud should result in a phase-modulation of the carrier wave. In other words, in frequency spectrum, we expect to see sidebands to the carrier [3]. By measuring the amplitude of the sideband, in theory, we can estimate the electron cloud density.

Here we summarize three different techniques used to measure e-cloud density in the main injector. The three techniques are called as direct phase shift, sideband spectrum and zero span measurement. All these techniques are based on the same general principle of measuring the phase shift of the carrier wave. In the sideband spectrum measurement, we send a carrier wave (1.5 GHz) and any phase modulation will show up as a side band. In the zero span measurement, we set the spectrum analyzer to the expected side band frequency (measured using the sideband spectrum technique) and collect data over the full injector cycle. In other words, we make power measurement at a single frequency. Any increase in the amplitude of the signal at this frequency will then indicate phase modulation. The direct phase shift measurement is similar to microwave interferometry. The carrier is split into two paths: one is sent through the e-cloud and to the receiver while the other is sent directly to the receiver. At the receiver, both the signals are demodulated to baseband, mixed and the mixer output recorded in a scope and time averaged to yield the phase shift. We use a filter to minimize the beam induced AM. Additionally, as this signal occurs at random phase each turn with respect to the microwave carrier, it simply averages away out many turns.

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jtobin@fnal.gov

EXPERIMENTAL SETUP

Figure 1 shows the experimental setup of our experiments. The source consists of a signal generator, an amplifier while at the receiver the mixer detects the phase modulation. The details are mentioned in here [4].

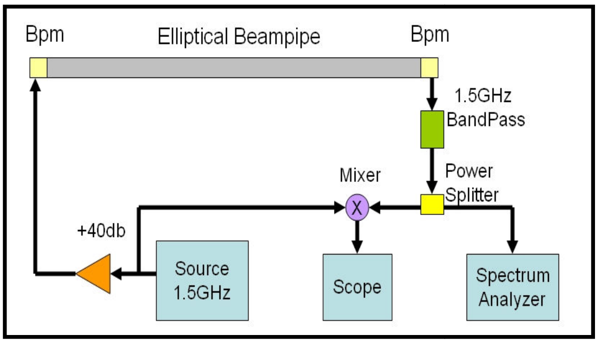


Figure 1: The experimental test setup showing the BPMs, which act as our antenna. The source is E4428C signal generator.

The BPMs used in our experiments are 25 cm long shorted stripline pickups. Fig 2 shows how they are connected to drive a TE11 mode.

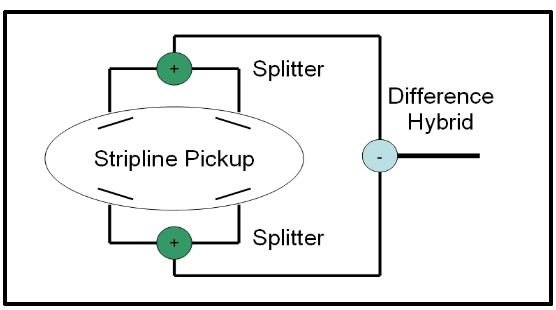


Figure 2: The BPM's connection are to cancel the common beam signal and couple TE11 mode.

Measurement location

The measurements for this work were done at several locations in the main injector. The locations were: MI 40 (Straight region), MI 52 Bend, MI 521(test). MI 40 is a straight section where the BPMs are separated by a drift region (15.1m). MI 52 is a bend region where the BPMs have two dipoles and their associated quads between them (12.9m). The bend field is 1.4T at 120GeV. Both these location have been upgraded to have high quality heliax cables for good signal transmission and reception. Both MI 40 and MI 52 have elliptical beam pipe and the cutoff frequency was just below 1.5 GHz. Recently, a test lattice (M521) of round beam pipe (6") of length 2m was installed for dedicated e-cloud studies.

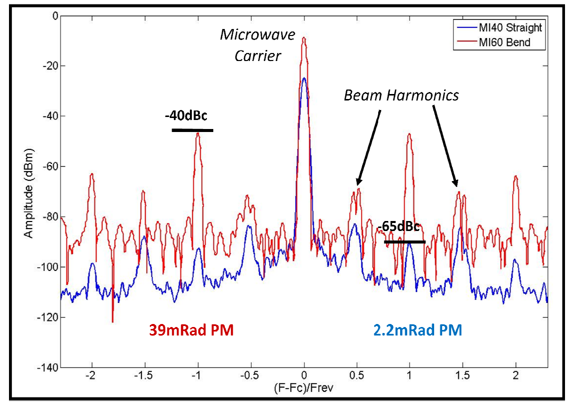


Figure 3: The figure shows the sideband spectrum measurement at MI 40 and MI 60 Bend region. The MI52 bend region shows a larger signal presumably due the strong e-cloud column due to the dipole fields.

Sideband spectrum measurement

Fig 3 shows the sideband spectrum measurement done at MI40 straight section and the MI 60 bend region. The proton beam signal and its harmonics constantly interfere with the measurements of the phase shift signal. So, the carrier frequency is chosen such that the signal is placed between the carrier and the 90 kHz beam harmonics. The increase in amplitude at the MI 60 bend may be due the presence of dipole which tends to increase the e-cloud density by trapping them along the field lines.

Zero span and Direct phase shift measurement

In the zero span measurement, the spectrum analyzer is set to the zero span mode. The phase shift signal from ramp to the extraction cycle of the main injector is recorded. This is shown in Fig 4. The transition indicates the time at which the bunch length of the proton bunch is at the minimum. The extract arrow indicates the end of the MI cycle. The lower trace shows the measurement without the carrier wave.

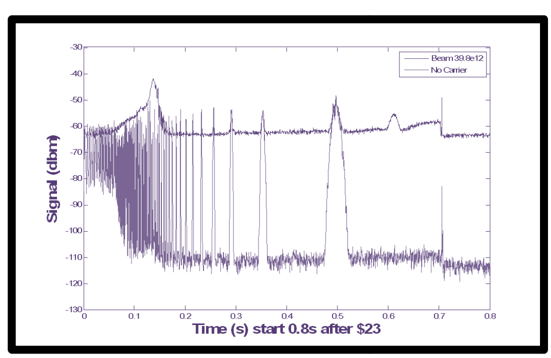


Figure 4: The upper trace shows the zerospan measurement at MI 52 Bend region.

At MI40 and MI60, direct phase shift measurements were done. The results are discussed elsewhere [5]. For our discussion we restrict ourselves to Fig 5, where we see that the phase-shift follows the proton beam signal and also indicating the growth in electron density in time.

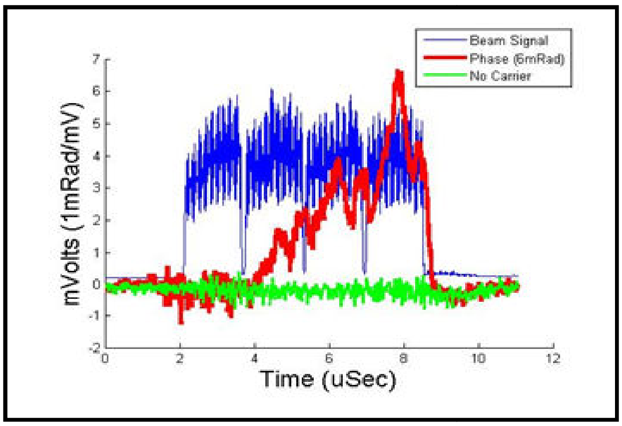
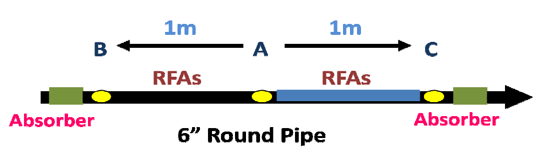


Figure 5: The red trace shows the phase shift signal while the blue trace shows the proton bunch structure. As time increases, the phase shift indicating increase in electron cloud density.

M521 TEST REGION



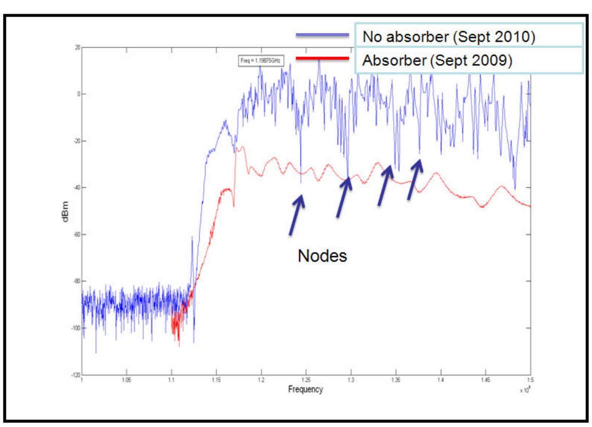


Figure 6: Showing the M521 test region (above) along with the transmission curve with and without the absorbers (below).

The top of Figure 6 shows the M521 test region. It consists of 2 m, 6 ‘’ round beam pipe with BPMs A, B, C. The cutoff frequency for this section of the beam lattice is about 1.2 GHz. The bottom figure in Figure 6 shows the transmission curve with and without the absorbers. Removing the absorbers not only increased the transmission but many reflection nodes were observed. This seems to indicate that the phase shift may be amplified due to spurious reflections and making the absolute electron density measurement difficult. Currently, experiments are being designed to take advantage of the reflection to make a localized density measurement [6]. By deliberately using reflection, we can setup an experiment to measure the amplification factor and thus calculate the electron cloud density. Without the absorbers, we get reflections leading to standing waves. The microwave sees a phase shift each time is passes through the e-cloud, so this can lead to an amplification of the phase shift. Note this is impacted by how the vectors add, but in general if there is an amplification of the carrier (constructive), then the phase shift will also be amplified.

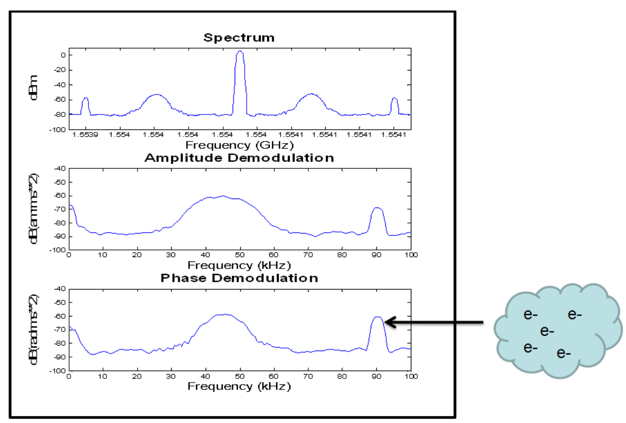


Figure 7: Side spectrum measurement at MI 521.The top plot shows the side spectrum, the middle plot shows the amplitude demodulation and the bottom plot shows the phase demodulation of the received signal

Fig 7 shows the results of the measurement done at M521. The sideband indicates that the signal has been modulated. Since we always have some AM modulation indicated by the middle plot, the plausible reason for the observed phase modulation (bottom plot) is due the presence of electron cloud.

SUMMARY AND CONCLUSION

Electron cloud density measurements using microwave techniques has been tested at three locations in the main injector using three different techniques. All the techniques show electron cloud formation in the main injector at transition and more specifically stronger electron cloud density at the bend region. A side band spectrum measurement on the e-cloud test lattice also indicated electron cloud formation. Though these techniques are successful in indicating electron cloud formation, it is still difficult to make an absolute measurement due to reflections. A reflection based technique based on resonance cavity is being developed at Fermilab and will be tested at a location in the main injector with longer path length.

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