MEASUREMENT OF ELECTRON CLOUD DENSITY WITH MICROWAVES IN THE FERMILAB MAIN INJECTOR*

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Abstract

Electron cloud density in the Fermilab Main Injector was measured by observing microwave transmission along the vacuum tube. Presence of the electron cloud reduces the velocity of the microwave signal. Both frequency and time domain methods reveal relative cloud density and time evolution. The effect of beam time structure is clearly evident. The accelerator magnetic field effects the distribution of electrons making it difficult to estimate density.

INTRODUCTION

The Main Injector is a synchrotron which accelerates 53 MHz proton bunches from 8 GeV to either 120 GeV or 150 GeV. It has a revolution frequency of 90 kHz. While the Main Injector currently provides over 300 kW of beam power, Project X [1] requires up to 2.1 MW . There is concern about electron cloud instabilities at these beam currents. It is necessary to rely on simulations or models to predict this effect. In this regard, it is prudent to compare measurements of electron cloud development with simulations before extrapolating to higher beam currents.

An electron cloud can be created and trapped in the electromagnetic fields originating from the positively charged proton beam. Depending on the emissivity of the surface and the energy of the electrons striking it, the charge density can increase until the beam fields are neutralized. With the increased beam intensities anticipated, the electron density could adversely affect operation.

Presence of the electron cloud can be measured by observing the propagation of microwaves along the beam pipe [2]. For a uniform distribution of electrons, the phase shift through length L can be estimated as shown below [3].

$$\phi \approx \frac{L}{c}\frac{\omega_p^2}{2\sqrt{\omega^2-\omega_c^2}}, \quad \omega_p \approx 2\pi\, 9\sqrt{\frac{N_e}{m^3}} \ \ plasma\ \ frequency \qquad (1)$$

$$\omega_c = beam\ pipe\ \ cut-off\ \ frequency$$

The time response of the electron cloud is observed to be faster than the batch structure (~100 nsec). Thus, the phase shift will be modulated with the electron cloud density which in turn follows changes in beam current each turn. The variation in beam current is provided by the gaps required to accommodate injection and extraction kicker rise times. The rotation frequency of 90 kHz results in the largest component in the beam current spectrum. For a phase modulation of ±β radians the sideband amplitude relative to the carrier will be β/2. The amplitude of these sidebands reveals the electron cloud density.

EXPERIMENTAL SETUP

The measurement makes use of existing Main Injector Beam Position Monitors (BPMs) which are 25 cm long shorted stripline pickups. The BPMs and the beam pipe have a 50x120 mm elliptical aperture. BPMs are located inside the downstream end of each quadrupole magnet. The BPMs are connected as shown in Fig. 1 to drive the TE_{11} mode which has the lowest cut-off frequency (1.484 GHz). It is necessary to remove the BPMs from operation which limits acceptable locations.

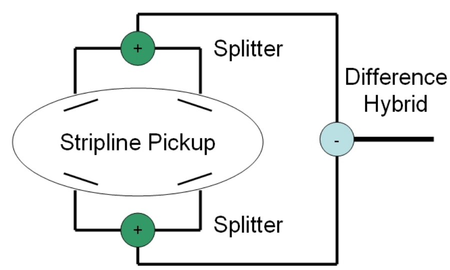

Figure 1: Connections at BPM pickups are configured to couple to the TE_{11} mode and cancel the common beam signal. The coupling was measured at -30 dB through both pickups and 17 m of pipe.

The experimental setup is shown in Fig. 2. An Agilent E4428C signal generator provides the source which is amplified by a mini-circuits ZHL-10W-2G power amplifier. To first order, the mixer detects phase modulation and rejects amplitude modulation. Measurements have been performed at two locations in the Fermilab Main Injector.

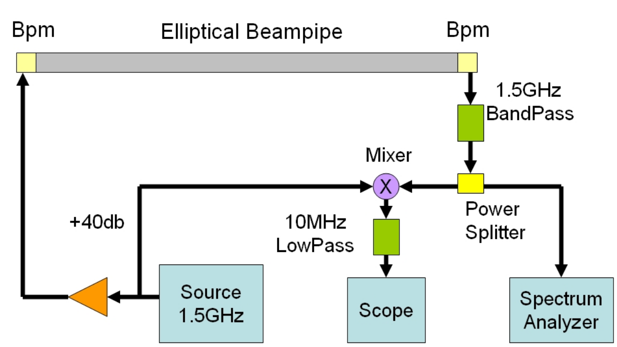

Figure 2: Basic experimental setup.

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MI60 Bend Region

The first two BPMs selected (Q532, 601) were located in a bend region near MI60 service building. They were 12.6 m apart and separated by two dipole magnets and their associated quadrupole. The bend field is 1.4 Tesla at 120 GeV. MI60 has the advantage of high quality ½" heliax cables available to transport the signals to/from the service building with good transmission.

The total transmission including the amplifier, cables, stripline pickups, and the beam pipe is shown in Fig. 3 (red). The peak at 1.538 GHz was chosen for good transmission and good sensitivity. The electron cloud induced phase shift increases near cut-off.

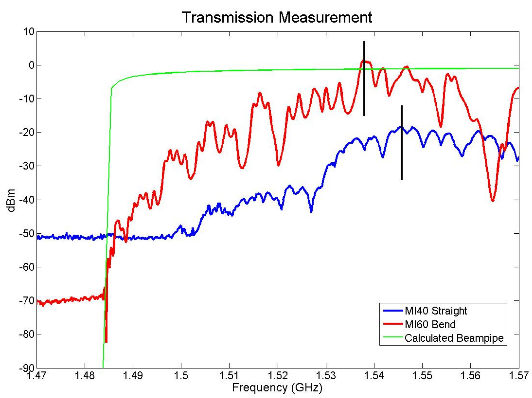

Figure 3: Transmission from MI60 Bend (red), MI40 Straight (blue), and Calculated transmission for our beam pipe. The lines denote the carrier frequency chosen at each location. Measurement includes amp, cables, pickups, and beam pipe.

MI40 Straight Section

For comparison, two BPMs in a dipole free straight section (Q403, 404) were selected near service building MI40. They were separated by 17.6m and a quadrupole magnet. Unfortunately, only RG8 foam cables were available at this location resulting in lower transmission. To drive a larger signal into the beam pipe and mitigate coupling between the cables as well as loss, the power amplifier was moved into the tunnel. The total transmission for this location is shown in Fig. 3 (blue). The carrier frequency of 1.545 GHz provided the best transmission at this location.

MEASUREMENTS

Traditionally, the sensitivity of the electron cloud measurements have been limited by reduced coupling with the beam pipe provided by button style BPMs. The Fermilab Main Injector stripline BPMs provide strong coupling resulting in improved sensitivity. This allows a direct time domain measurement of the phase modulation revealing growth and decay rate of the electron density. Measurements in both the frequency and time domain were taken and compared.

Frequency Domain

One difficulty is the presence of direct beam induced signals in the detector. Harmonics of the 90 kHz revolution frequency are observed above the 1.484 GHz cut-off frequency of the beam pipe. This was not expected for the 1.1nsec sigma gaussian bunches. The carrier frequency is chosen to place the 90 kHz electron cloud induced sidebands between the direct beam harmonics, Fig. 4. The -38 dbc amplitude at MI60 suggests 90 kHz phase modulation of about 50 mrad and at MI40 -65 dbc corresponds to 2.2 mrad peak to peak.

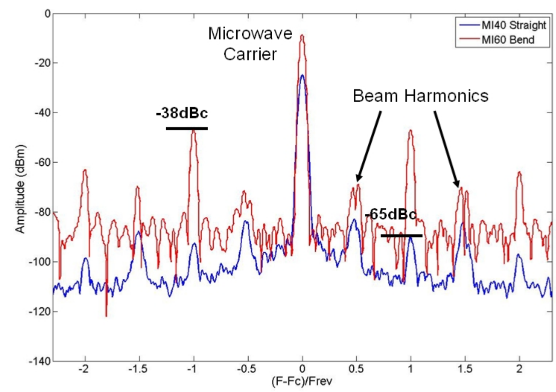

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Figure 4: Spectrum of transmitted microwave signal for MI60-red and MI40-blue.

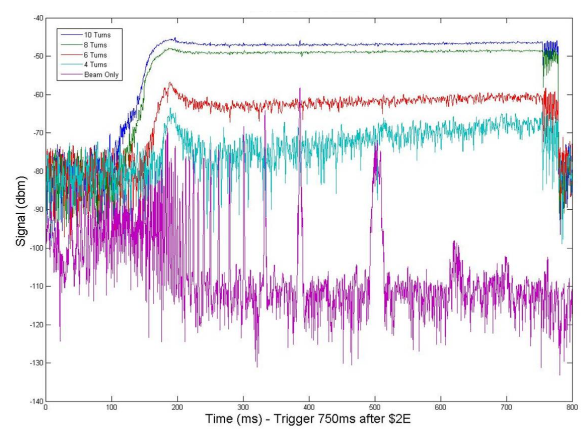

Figure 5: Zero Span Data for MI60. Bunch intensity is about 1e10 for each Booster turn.

The frequencies of the electron cloud induced sidebands are determined by the fixed carrier and are essentially constant throughout the acceleration cycle. However, the direct beam induced rotation harmonics at 17000 times the rotation frequency sweep through the microwave carrier as the beam is accelerated. Figure 5 shows the amplitude at one of the electron cloud induced sidebands from the start of ramp until extraction. The measurement was done by placing the spectrum analyzer in zero-span mode. The lowest trace was taken with no microwave signal and simply shows the direct beam induced harmonics sweeping through the detected frequency. The other traces show how the amplitude of the electron cloud induced sidebands change through the acceleration cycle at 4 different beam intensities. The peak observed just before 200 msec corresponds to transition, when the bunches are short and have the highest peak current. The last 50 msec of beam is affected by a 'bunch rotation' process that modulates the peak bunch current.

Time Domain

For the time domain measurement, the mixer output is collected with a deep memory scope. At MI60, the scope sampled at 500 MS/s and the data was averaged for 100 turns. At MI40, the sampling rate was reduced to 100 MS/s allowing the data to be averaged over 1700 turns. The direct beam harmonics are larger than the electron cloud induced sidebands. However, they are not correlated with the microwave carrier and thus average away in the time domain, Fig. 6.

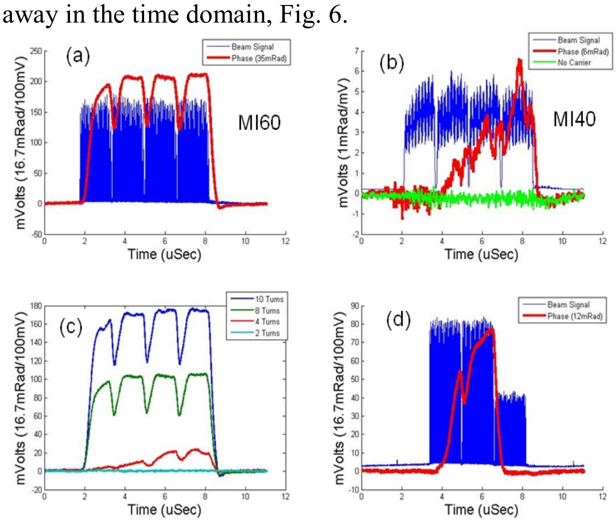

Figure 6: Direct Phase Shift measured at MI60 (a,c,d) for different batch structures and intensities and MI40 (b). Bunch intensity (blue) is 1e10 for each Booster turn.

The first set of measurements where done at MI60 and are complicated by passing through two main bending magnets and one quadrupole, Fig. 6(a,c,d). In Fig. 6(a), the 35mrad phase shift is approximately a square wave with 50% duty cycle and would produce a 45 mrad peak to peak phase shift at 90 kHz. This compares to 50 mrad measured in the frequency domain.

The test was repeated at MI40 through 17.6m of beam pipe, one quadrupole, and no bending magnets, Fig. 6(b). The 3 batch wide, 5 mrad peak 'clipped sawtooth' phase shift of Figure 6(b) would produce a 3.5 mrad peak to peak phase shift at 90 kHz. This compares to 2.2 mrad measured in the frequency domain.

It is believed the strong vertical bend field at MI60 traps the electron cloud in a narrow column centred on the beam [4]. This results in larger electron densities and associated phase shifts. The phase shift measured at MI40 without the bend field is 10 times smaller for the same beam current even with the longer beam pipe.

The development of the electron cloud can clearly be seen with a non-linear dependence on beam intensity Figure 6(c). Apparently, electrons left from previous batches seed the growth of subsequent batches allowing the electron density to reach equilibrium faster. It is interesting that the half intensity batch of Figure 6(d) is unable to sustain the electron cloud. Electron density rise times are 100-200 nsec at typical Main Injector intensities. At lower intensities it can take several μsec.

SUMMARY

From the basic theory, the microwave delay or phase shift is proportional to the electron cloud density. The observed phase shifts are not linearly proportional to beam intensity. For larger intensities, an equilibrium state is seen in the direct phase measurements in the dipole region. Due to a number of factors, the direct phase shift is significantly smaller in the field free straight section but no equilibrium is observed. The results of the direct phase shift in the time domain are in good agreement with the phase modulated sideband amplitude in the frequency domain.

An ideal mixer detects phase modulation and rejects amplitude modulation. A few percent asymmetry was observed between the upper and lower sidebands. This could be caused by a small amount of amplitude modulation suggesting the electrons absorb some of the energy attenuating the microwave carrier.

At this time, only the observed phase shift is reported. To infer the electron cloud density, requires understanding the effects of the magnetic fields and the non-uniform distribution of the electrons which develop. The direct phase data measured within a machine turn reveals how the electron cloud grows and decays. The relative changes observed can be directly compared with simulation results of this process [4, 5]. Evaluating simulations at the present intensities will allow extrapolating to the anticipated intensities to determine what electron cloud mitigation is necessary.

REFERENCES

[1] I. Kourbanis et al. "Current and Future High Power Operation of the Fermilab Main Injector", PAC09 proceedings.

[2] F. Caspers et al. "The CERN SPS Experiment on Microwave Transmission Through the Beam Pipe" PAC05 proceedings.

[3] J. Byrd, S. De Santis, K Sonnad, M. Pivi, "Measurements of the Propagation of EM Waves Through the Vacuum Chamber of the PEP-II Low Energy Ring For Beam Diagnostics", PAC07 Albuquerque, New Mexico, (2007).

[4] M. Furman et al., "Status of Electron-Cloud Build-Up Simulations for the Main Injector", PAC09 proceedings.

[5] P. Lebrun, "Microwave Transmission through the Electron Cloud at the Fermilab Main Injector: Simulation and Comparison with Experiment," PAC09 proceedings.