MEASUREMENT OF ELECTRON CLOUD DEVELOPMENT IN THE FERMILAB MAIN INJECTOR USING MICROWAVE TRANSMISSION*

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Abstract

The production of an Electron Cloud poses stability issues for future high intensity running of the Fermilab Main Injector. Recent experiments have shown the presence of the electron cloud can be detected by the phase shift of a TE wave propagated along the beam pipe. This technique has been employed to provide very sensitive measurements of the electron cloud development in the Fermilab Main Injector.

INTRODUCTION

The Main Injector is a synchrotron which accelerates 53MHz proton bunches from 8GeV up to either 120GeV or 150GeV. It has a revolution frequency of 89KHz. While the Main Injector currently provides over 300KW of beam power, the plan is to eventually increase it up to 2.1MW with *Project X*[1]. At these beam currents, there is concern about electron cloud instabilities. It is necessary to rely upon simulations to predict what this effect will be. In this regard, it is very beneficial to have measurements of the current electron cloud development in the Main Injector to check the models 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 at Fermilab, 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[3].

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

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

The time response of the electron cloud is observed to be faster than the batch structure. 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 period of 89KHz results in the largest frequency component in the beam current spectrum. For a phase modulation of ±β radians the sideband amplitude relative to the carrier amplitude will be β/2. Thus, the amplitude of the 89KHz sidebands reveals the electron cloud density.

EXPERIMENTAL SETUP IN THE FERMILAB MAIN INJECTOR

The measurement makes use of existing Beam Position Monitor (BPM) stripline pickups. To configure the pickups, it is necessary to access the Main Injector tunnel. The filters for the existing BPM system are removed and the pickups are connected as shown in Fig. 1 to drive the TE_{11} mode. Each BPM is located inside the downstream end of a quadrapole magnet. As it is necessary to remove the BPMs from operation to make the measurement, the choice of BPMs is limited.

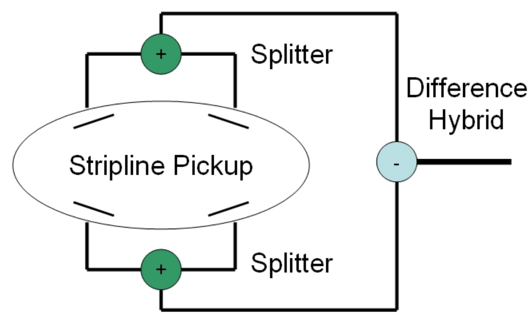

Figure 1: Connections at stripline BPM pickup to maximize coupling to TE_{11} mode and reduce beam signal. The coupling was measured at -30dBm for both pickups.

The basic experimental setup is shown in Fig. 2. A high quality Agilent E4428C analog signal generator is used as the source and amplified by a mini-circuits ZHL-10W-2G wideband amplifier. Measurements have been performed at two locations in the Fermilab Main Injector.

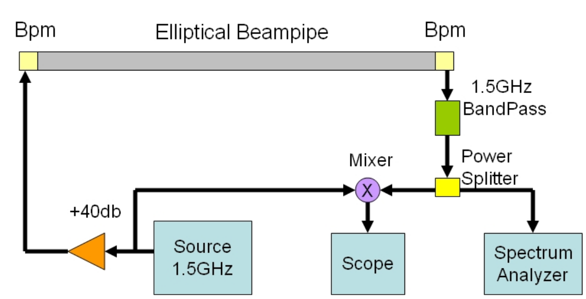

Figure 2: Basic experimental setup.

* Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy
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Bend Region

The first two BPMs selected were located in a bend region. They were 12.6m apart and separated by two dipole magnets and the associated quadrupole. These BPMs have the advantage of spare high quality ½" heliax cables available to transport the signals from the MI60 service building to the pickups.

The high quality cables at this location provide for very good transmission. The total transmission due to amplifier, cables, pickup coupling, and transmission through the beam pipe is shown in Fig. 3 (red). While there is slightly better transmission at higher frequency, 1.538GHz was chosen as it is close to cut-off to enhance the phase shift.

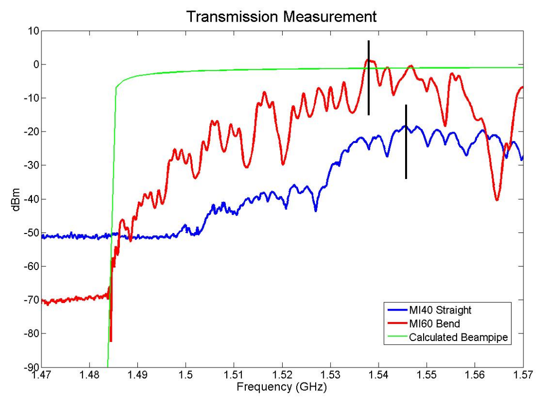

Figure 3: Update this to show transmission from MI60 Bend (red), MI40 Straight (blue), and Calcuated transmission for our beampipe. The lines denote the carrier frequency chosen at each location.

Straight Section

For comparison, two BPMs in a dipole free straight section were also used. The BPMs in this region were separated by 17.6m and a quadrapole magnet. Unfortunately, at this location only the RG8 foam BPM cables were available to transmit the cables to the MI40 service building.

The RG8 cables have poor transmission at 1.5GHz. To recover some of this loss and mitigate cable coupling, the amplifier was moved into the tunnel. The total transmission for this location is shown in Fig 3 (blue).

MEASUREMENTS

Traditionally, the sensitivity of the electron cloud measurements have been limited by reduced coupling into and out of the beam pipe. The stripline BPMs in the Fermilab Main Injector provide strong coupling resulting in improved sensitivity. This allows a direct time domain measurement of the electron cloud induced phase modulation revealing growth and decay rate of the electron density.

Frequency Domain

One difficulty is the presence of direct beam induced signals in the detector. Harmonics of the 89KHz revolution frequency are observed above the 1.484GHz cutoff frequency of the beam pipe. This was not expected for the 1.1nsec sigma gaussian bunches. The microwave frequency is chosen to place the 89KHz electron cloud induced sidebands between the direct beam harmonics, Figure 4. The -38dbc amplitude suggests an 89KHz phase modulation of about 50mRad and -65dbc corresponds to 2.2mRad.

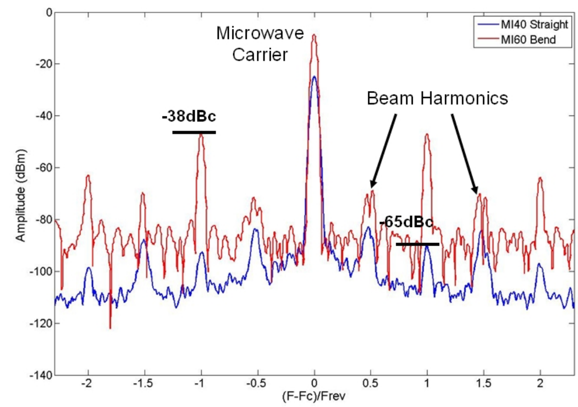

Figure 4: Spectrum of transmitted microwave signal for MI60-red and MI40-blue.

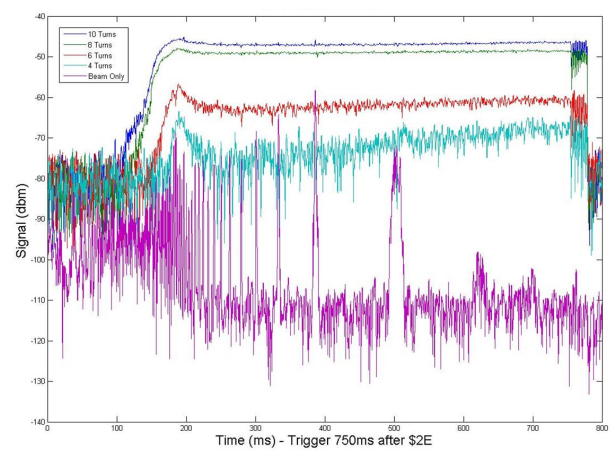

Figure 5: Zero Span Data for MI60. Bunch intensity is proportional to Booster Turns. (Remake plot with /bunch intensity?)

The frequencies of the electron cloud induced sidebands are constant throughout the acceleration cycle. However, the direct beam induced rotation harmonics at 17000 times the rotation frequency sweep considerably. 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 last 50msec of beam are affected by a 'bunch rotation' process suggesting the electron cloud is affected by peak beam current.

Time Domain

For the time domain measurement, the mixer output is collected with a deep memory scope. At MI60, the scope was sampling at 500MS/s. At MI40, the sampling rate was reduced to 100MS/s to collect more turns. The first set of measurements where done at MI60 and are complicated by passing through two main bending magnets and one quadrupole, Figure 6(a,c,d). The data shown from MI60 is averaged from 100 turns. The test was repeated at MI40 through 17.6m of beam pipe, one quadrupole, and no bending magnets, Figure 6(b). The data at MI40 is averaged for 1700 turns. The beam current shown in blue, indicates four of the seven batches where populated in the 11usec turn. 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 is roughly 6 times smaller for the same beam current, Figure 6(b). The measurement at MI40 is further compromised by 8db higher losses in the cables.

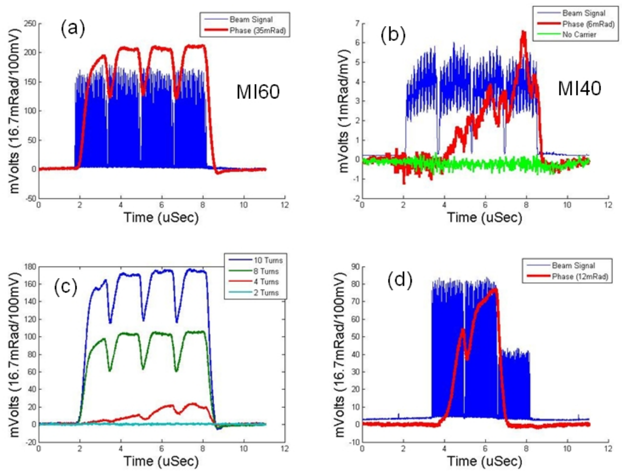

Figure 6: Direct Phase Shift measured at MI60 for different batch structures and intensities.

The development of the electron cloud density can be clearly 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, Figure 6(b,d). It is interesting that the half intensity batch of Figure 6(d) is unable to sustain the electron cloud. Electron density rise times are 100-200nsec at typical Main Injector intensities. At lower intensities it can take several μsec.

SUMMARY

From the basic theory, the phase shift is proportional to the electron cloud density. The observed phase shifts by both methods 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 very small in the field free straight section but no equilibrium is observed. To first order, the results of the direct phase shift within a single turn are in agreement with the phase modulated sidebands. This data interesting as it can be directly compared with the current simulations which are only capable of generating a few turns to do computational limitations.

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 particulars of the non-uniform distribution of the electrons which develop. The direct phase data measured within a machine turn shows how the electron cloud develops and decays. The relative changes observed can be directly compared with simulation results of this process [4,5]. The extrapolated electron cloud density from the simulations is needed to determine what electron cloud mitigation is necessary.

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