FNAL instrumentation: Lessons Learned

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Abstract. Experience gained during the recent commissioning of the Main Injector accelerator and the Recycler storage ring at Fermilab will be discussed. Some of the more interesting problems involve; ground differences, cabling for bpm and multiwire systems, electromagnetic noise, and magnetic shielding

LOCAL CURRENTS

"Ground"

According to Mr. Webster, definitions of "ground" include:

- The position or portion of an electric circuit at zero potential with respect to the earth.
- A conducting connection to such a position or to the earth.
- A large conducting body, as the earth, used as a return for electric currents and as an arbitrary zero of potential.

However, ohm's law requires "ground" to have different voltage potentials that depend on how currents flow from one part to another.

Main Injector Bending Magnet System

The Fermilab Main Injector uses conventional magnets to contain the beam as it accelerates from 8GeV to 150GeV. Twelve 1KV power supplies in series with 344 bending magnets are ramped to 9375 amps in about _ second. To build the desired waveform, each supply ramps up separately in about 30 milliseconds. Bending magnets have a series impedance of 0.8mΩ and 2mH with a coil to ground capacitance of 30nf.

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[1] Operated by Universities Research Association, Inc.

TABLE 1. Main Injector bending magnet system.

344 Bending magnets	0.8 mΩ and 2 mH each
capacitance to ground	30 nf each magnet
12 power supplies	1KV each supply
Maximum bend current	9375 Amps
1/2 second ramp overall	30 msec each supply

As the supplies ramp up, the changing voltage to ground induces "local currents" through the magnet capacitance to ground. These currents flow along the path of least resistance such as beam pipe, signal cables, and cable tray. Local currents make the bend buss current different for each supply and magnet. Generally, the bend magnet current at only one point is monitored and controlled. At Fermilab, orbit distortions lead to the realization that magnet current was not the same around the ring and depended on ramp waveform, power supply turn on order, and geometry of the bend magnet system. Local currents also produce significant potential differences in the ground system that result in problems with some instrumentation systems.

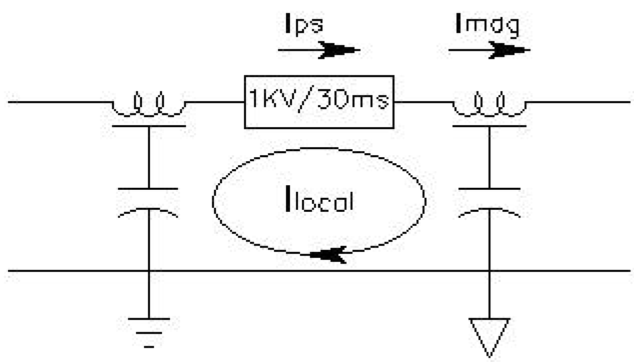


FIGURE 1. Power supply with two magnets in series. Local currents are driven by the changing voltage to ground. Even though all of the magnets and supplies are in series, they don't necessarily all have the same current.

Vacuum Chamber Impedance

If the vacuum chamber of the Main Injector were cut in one place, the impedance across the cut could be estimated as shown below.

$$
\begin{aligned}
&R_{tot} = \frac{C_M}{C_P\ t}\,\rho = 5.6\ \Omega \\
&C_M = \textit{machine circumference} = 3320\ \textit{meters} \\
&C_P = \textit{pipe circumference} = (0.0254) * 13.9'' \\
&t = \textit{wall thickness} = (0.0254) * 0.0595'' \\
&\rho = \textit{resistivity of stainless} = 9e-7\ \Omega - m
\end{aligned}
\tag{1}
$$

The inductance of the 2 mile diameter ring is estimated below:

$$
\begin{aligned}
&L = \mu_o \frac{\pi a}{2} N^2 = 1mH. \\
&\mu_o = 4\pi \times 10^{-7} \\
&a = radius \approx 528\ meters \\
&N = 1 = number\ of\ turns
\end{aligned}
\qquad (2)
$$

Magnet laminations surround the beam pipe and increase this inductance. With a typical "H" magnet lamination geometry, the reluctance for the path surrounding the pipe will be about 4 times that for the normal bending field. The beam pipe has only one turn compared to about 10 for the normal magnet coils. The increase in inductance attributed to the laminations of all 344 magnets is estimated below.

$$
L_{la\min ations} = 344\,(2\ mH)\frac{1}{4}\left(\frac{1}{10}\right)^2 = 1.7\ mH \qquad (3)
$$

The corner frequency defined by the ring resistance and inductance is R/2πL=11Hz (5.6Ω, 2.7mH). The ring is resistive below this frequency and inductive above. The inductance from the magnet laminations will tend to steer beam image currents through the beam pipe and local currents through other pathways such as instrumentation cables.

The stainless steel beam pipe wall thickness (.0595") is one skin depth at 100 KHz. At frequencies below this, the magnetic fields from the beam current will leak through the wall and begin to produce measurable potential differences that follow the beam around the ring. For 1e11 particles distributed within 1/7 of the circumference (1.6usec) the voltage to ground would be:

$$
V_{ground} = \pm\frac{1}{2}1e11\frac{1.6e-19}{1.6e-6}\frac{5.6\Omega}{7} = 4\ mV \qquad (4)
$$

Estimate of Local Current

For one power supply turning on, the voltage to ground on the magnet buss has a simple distribution. Symmetry suggests the average voltage to ground is about +_ of the supply voltage on _ of the ring and -_ on the other half. This voltage will induce currents through _ the capacitance and _ of the resistance. The resistance is assumed to be only that of the stainless beam pipe. The Fermilab Main Injector also has a ground conductor around the circumference. The capacitive coupling to ground through the magnets will make the ground voltage proportional to dV/dt as estimated below.

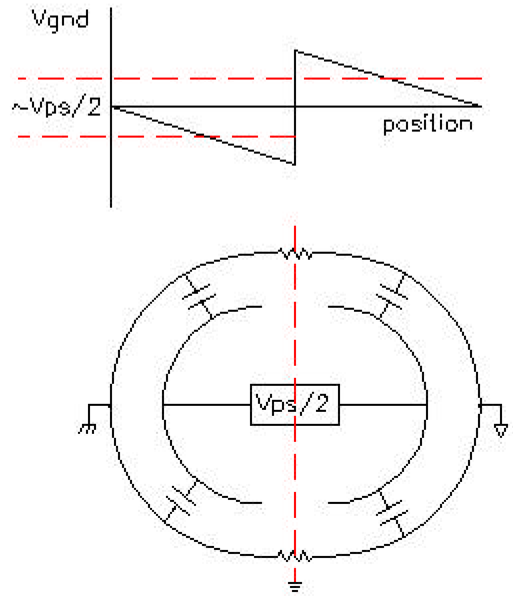


FIGURE 2. Voltage to ground of the magnet buss with one power supply. With a single power supply turning on, symmetry suggests the average voltage to ground is about +_ of the supply voltage on half of the ring and –1/4 on the other half.

$$
\begin{aligned}
&V_{ground} = \frac{1}{4}\frac{V_{ps}}{\Delta t}\frac{C_{tot}}{4}\frac{R_{tot}}{4} = 30\ mVolts \\
&V_{ps} = 1\ KV \\
&\Delta t = 30\ m\sec \\
&C_{tot} = 344 \leftrightarrow 30\ nf \\
&R_{tot} = 5.6\ \Omega
\end{aligned}
\tag{5}
$$

Measurement of Local Current Induced Voltages

The measured voltage between the tunnel ground and the service building ground is shown below. The measurement was made by connecting both the center conductor and the shield of a coaxial cable to the beam. The shield of the service building end was connected to ground through the chassis of the oscilloscope. The impedance of the test cable shield is large compared to all of the other ground connections and does not disturb the measurement.

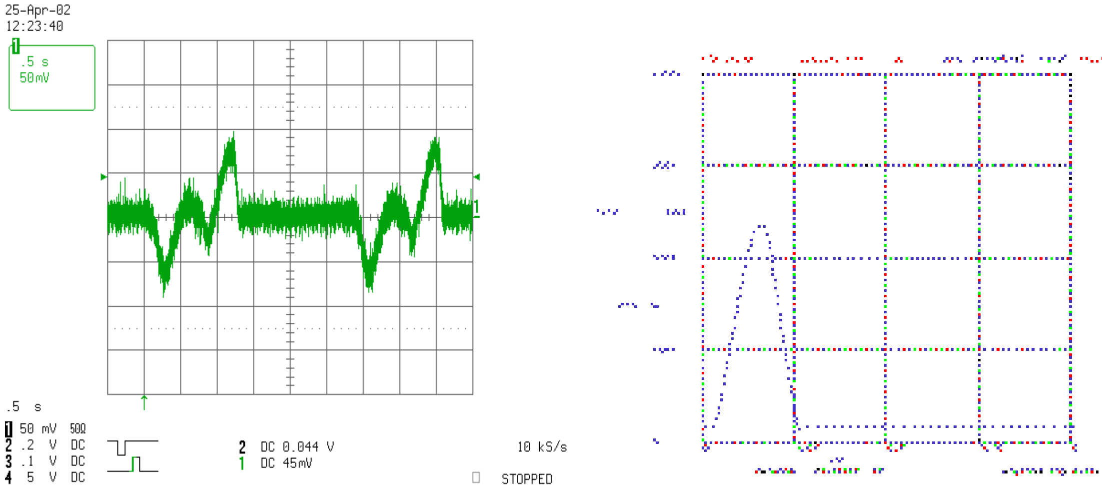


FIGURE 3. Measurement of the voltage between the tunnel and service building grounds during the magnet ramp. The voltage measured on the tunnel ground induced by two consecutive ramps is shown on the left (50mV, .5sec per division). One magnet ramp is shown on the right (3000Amps, 1.25 sec per division). The voltage is proportional to dV/dt.

Effects of Voltage Differences Between Grounds

The voltage between tunnel ground and building ground can induce errors into the signal path of instrumentation cables. The voltage will appear across the shield impedance. For equal source and receiving impedance, 1/2 of the noise voltage will appear across the load resistor as shown below.

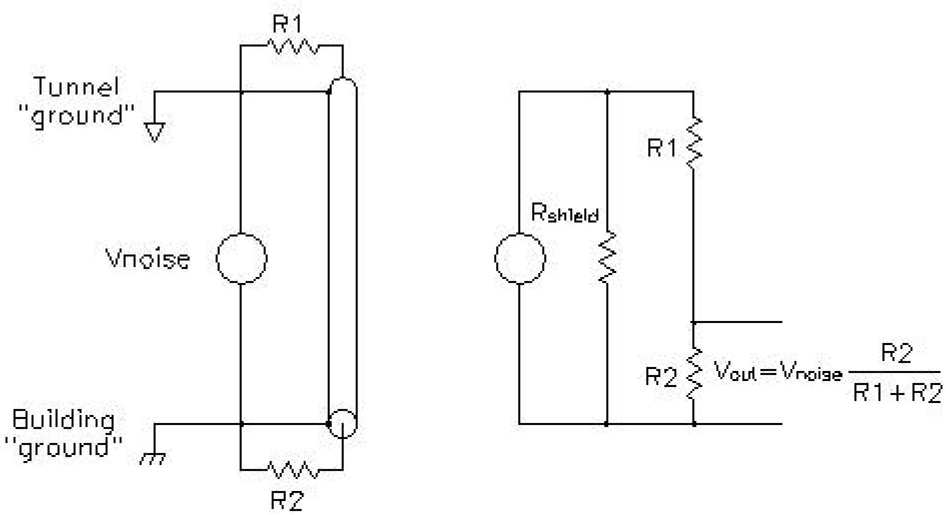


FIGURE 4. Schematic of a coaxial cable between the tunnel ground (or beam pipe) and the building ground.

The noise voltage across the load resistor can be reduced by inserting a transformer as shown below. Typically, these are made by wrapping as many turns as possible of coaxial cable on a torroidal tape wound core.

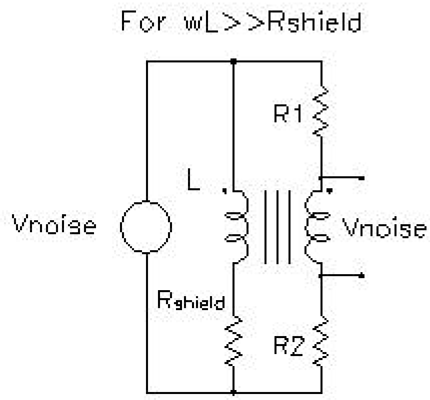


FIGURE 5. Schematic demonstrating the benefit of torroidal cores. For wL>>Rshield the noise well be removed from the load impedance.

For an inductance L of the core, and total cable shield resistance Rs, the amount of noise reduction is given below.

$$\frac{V_{out}}{V_{noise}} = \frac{R_S}{R_S + j\omega L} = \frac{1}{1 + \dfrac{j\omega L}{R_S}}$$

$$for \;\; f >> f_o = \frac{R_S}{2\pi L} \tag{6}$$

$$\frac{V_{out}}{V_{noise}} \cup \frac{f_o}{f}$$

The core has no effect below the corner frequency fo=Rs/2πL. Above this frequency, the noise is reduced by fo/f. Such a core was not effective above 50 KHz because of turn to turn capacitance and associated resonance's in the windings themselves. Common mode filters using such an approach can be effective but only for a limited frequency range. The core must be inserted into the signal cable between the tunnel and building grounds. Well intentioned, but less informed, people have inserted a transformer inside the relay rack with the cable shield grounded were it entered the rack. If the shield of the cable is grounded before the torroid, it does no good.

TABLE 2. Typical common mode filter using a torroidal core

Arnold T8027 tape wound Supermalloy core	3" OD, 2" ID, 1" Ht	104 uH/N^2
500 ft RG58 cable	4 Ω/1000ft	2 Ω
30 turns on core		94 mH
fo	R/2πL	3.4 Hz
60 Hz noise reduction	60/3.4	17.6 (or 25db)
Maximum frequency		50 KHz

Fast Kicker Magnets

Fast kicker magnets are another source of voltage differences between grounds. At Fermilab, fast kicker magnets have rise times of 20 to 100 nsec and pulse widths of 1.6 to 20 usec. Several RG220 cables are used in parallel with up to 600 amps in each cable to carry the pulse to the magnet in the tunnel. The impedance of the RG220 cable shield is 0.05Ω for a modest cable length of 200ft. The 600 amp return current will make 30 volts on it's way back to the power supply! The shield of the RG220 is tied to the building ground upstairs and to the magnet case in the tunnel. If the magnet case is connected to the tunnel ground or beam pipe, this 30 volt signal will drive currents through any instrumentation cables connected between the tunnel and the building.

If the magnet case is left floating, beam image currents will produce electromagnetic waves as they cross from one side of the magnet to the other. The kicker magnet becomes an antenna broadcasting the beam frequency with substantial power. This rf interference can induce substantial signals into nearby signal cables.

This is a difficult problem because the fast rising kicker currents have frequency components as high as the beam. The decision to ground kicker magnet cases has not been resolved at Fermilab.

Multiwires

Multiwire Signals and Ground

Multiwires are secondary emission profile monitors made from wire grids. The small charges induced on the wires by the passing beam are integrated and the relative amplitudes on the wires in the grid are measured to produce a transverse beam profile. A 50 um wire centered on the beam collects 1 charge for each 2000 protons. This depends on many things but is typical for the beam density at Fermilab. The 40 picocoulombs collected from 5e11 protons will produce a 0.4 volt signal in a 100pf integrator. The signal to noise ratio is often several hundred and results in good profiles.

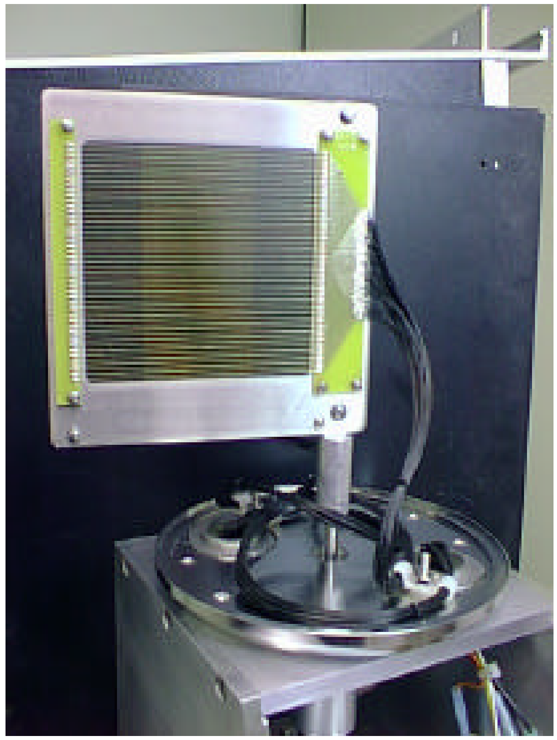
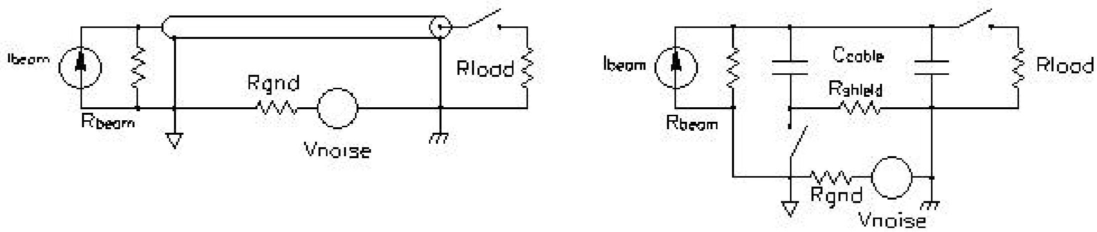


FIGURE 6. Multiwire (or secondary emission) profile monitor. Horizontal wires are placed on one side with vertical wires on the other. Each plane has 48 wires. This one has 2mm spacing.

The collected charge is stored in the cable capacitance and is later bleed into the integrating capacitor through a resistor. If the cable shield were connected to ground both at the tunnel and the service building the difference between grounds would swamp the signal. Just 1 mV difference between grounds would integrate to 5 volts with the 10KΩ 100pf integrator used.

The solution to this problem lies in exploiting the essentially infinite beam source impedance. The beam will induce the same secondary emission for any wire voltage within reason. Figure 7 indicates that with the shield grounded in the tunnel, AC noise can be induced in the load impedance above the corner frequency given by the cable capacitance and the load impedance. For a 500 foot 20pf/ft cable into 10KΩ the corner frequency would be 1.6KHz. If the shield is not connected to ground in the tunnel then noise voltage becomes Rload/Rbeam, essentially zero. The signal return currents will flow through what ever ground connections it can find. Because the beam source impedance is so large the return current path can have substantial impedance without affecting the profile measurement.

Unfortunately, cables are run through cable trays with many other conductors that can have substantial “signals” on their shields. Capacitive coupling between the shield of the multiwire cable and it’s environment can still induce noise.



$$for\ \omega C_{cable} \ll R_{load} \qquad (\omega > 1.6KHz)$$

$$\frac{V_{out}}{V_{noise}} = \frac{R_{load}}{R_{gnd} + R_{load}} \qquad switch\ closed \tag{7}$$

$$\frac{V_{out}}{V_{noise}} = \frac{R_{load}}{R_{gnd} + R_{load} + R_{beam}} \qquad switch\ open$$

FIGURE 7. Multiwire noise analysis.

Multiwire Cable

Originally Fermilab used custom bundles of RG174 coaxial cable to instrument multiwires. The original multiwires measured only the horizontal or vertical profiles using 24 wires. The latest design measures both horizontal and vertical profiles with 48 wires in each plane. The cost and burden of terminating these bundles precluded their use and it was decided to switch to a shielded ribbon cable. Figure 8 indicates how the ribbon is folded into a round shape and shows the braided shield. The "flat to round" cable is significantly cheaper and is much easier to terminate using mass connectors. The geometry constraints leads to a significant reduction in wiring errors. However, we still manage to get the polarity wrong on a regular basis.

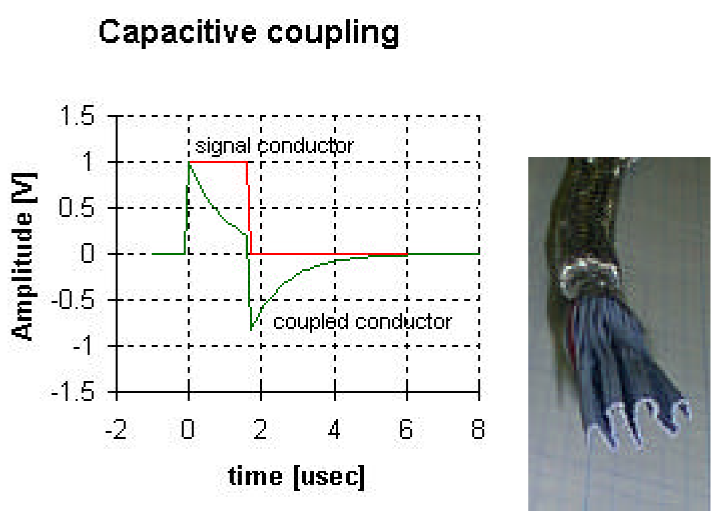


FIGURE 8. Effect of capacitive coupling between signal conductors in Multiwire cable.

The multiwire scanner simultaneously integrates all 96 channels. One feature of the firmware running the scanner is that if any one channel exceeds a limit, integration is stopped for all channels. Unfortunately, capacitive coupling between conductors in the “flat to round” cable can cause ghost profiles or satellites. Figure 8 suggests what a capacitively induced signal might look like on a single conductor. If the integration window is closed before the capacitively coupled signal integrates to zero, then a net signal will be measured and a ghost profile will appear as shown in Figure 9. The normal integrate window is sufficiently long to make capacitive coupling insignificant. The advantages of “flat to round” cable outweigh this undesirable feature.

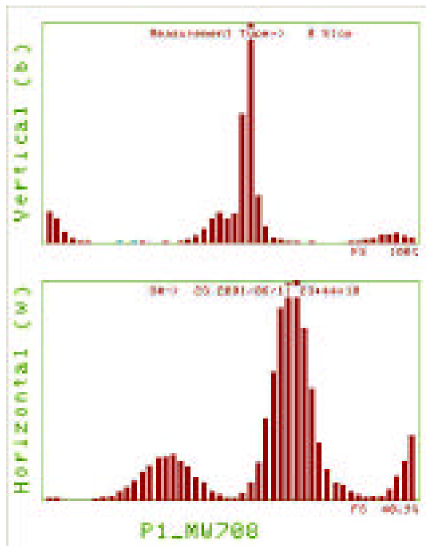


FIGURE 9. If the integration window is closed before the capacitivly coupled signal averages out, satellite profiles are left in the profile.

BPM’s

Resonant BPM’s

The Fermilab Recycler uses a split tube BPM. An 11 inch section of elliptical beam tube is sliced at an angle to form the two BPM electrodes. The electrodes are held inside of a concentric vacuum chamber. The system is configured to measure the 3^{rd} harmonic of the bunch spacing at 7.5MHz. To improve the signal to noise ratio, a resonator is formed with the plate to ground capacitance and an inductor. A preamplifier is located near the BPM and connected to it through a two foot cable. The plate impedance at resonance is 1.5 K_ and is determined by the preamp input impedance as shown in Figures 10 and 11.

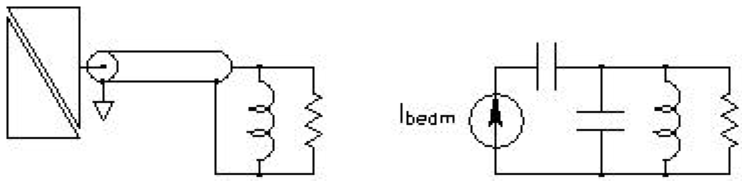


FIGURE 10. Beam Position Monitors used in the Fermilab Recycler are made to resonate at 7.5MHz by connecting the capacitive plate in parallel to an inductor through a short cable.

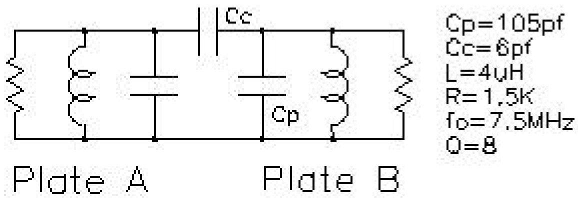
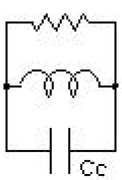


FIGURE 11. The beam position monitor plates are coupled through the small capacitance between them. Coupling will be significant if the plate to ground impedance is comparable to the coupling impedance.

Plate to plate capacitance causes problems. An impulse or swept sine wave applied to one plate is coupled to the other plate, changing measured position. At 7.5 MHz, the coupling impedance (1/jwC = 3.5K_) is comparable to the 3K_ preamplifier input impedance (1.5K_ each side). The coupling impedance can be reduced by shunting it with an inductor between the two electrodes, Equation 7. Coupling will be reduced by a factor of Q for the resonant circuit. Figure 11 shows the coupling with and without the inductor for an impulse and a swept sine wave applied to one electrode.



$$Q = 2\pi \frac{pk\ Energy\ Stored}{Energy\ Lost \big/ Cycle} = 2\pi \frac{\frac{1}{2} C V^2}{\frac{1}{2}\frac{V^2}{R}\frac{1}{f}} = \omega_o RC \tag{8}$$

$$R = Q\left(\frac{1}{\omega_o C}\right)$$

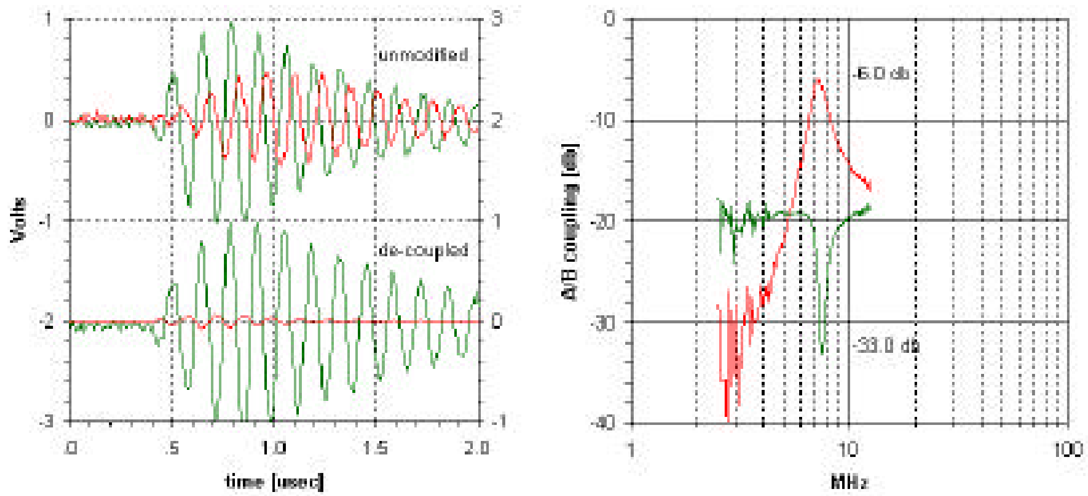


FIGURE 12. Measurements of coupling before and after adding the de-coupling inductor in time and frequency. On the left, the signal on both the driven and coupled electrodes are shown for both the coupled and de-coupled condition. On the right, only the coupled plate is shown for both the coupled and de-coupled condition. Coupling was reduced by 27db at 7.5MHz.

BPM Cables

The Main Injector at Fermilab has 208 bpm's that use 262000 feet of RG8/U cable (49.6 miles)! The longest cable length is 1400 feet and the shortest is 120 feet. The cable was pulled as pairs to obtain similar length and facilitate phase matching. The spread in propagation velocity required pulling an extra 2% or 30 feet to each bpm. A number of bpm's were outside of the specification and required adding cable to one side to obtain matched delay through the pair. Figure 13 indicates the percent difference between cables in a pair as they were pulled in. The cable did not meet the manufacturers specification ±2% variation in velocity.

Figure 13 also shows the measured characteristic impedance for one pair of cables. Only a half dozen were measured with similar results. Again, the cables did not meet the manufacturer's specification of ±2_.

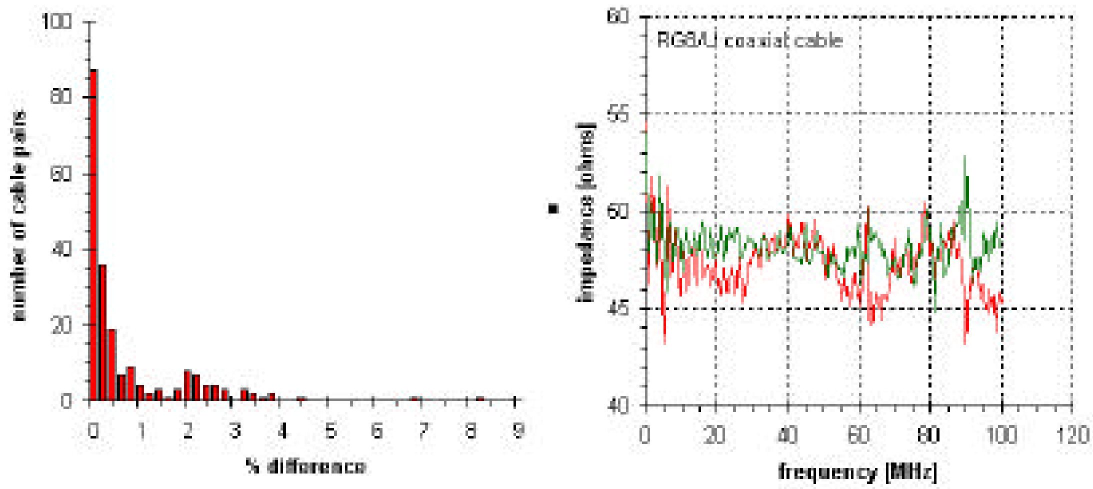


FIGURE 13. Distribution of the percent difference in cable length for the 208 pairs of cables used for the Fermilab Main Injector BPM's. Measured characteristic impedance of one pair of RG8/U BPM cables.

After installing the bpm's in the Booster to Main Injector transfer line we were plagued with complaints of poor accuracy from one particular bpm. Eventually what was found is that one cable of the cable pair had a resonance very near the frequency used by the bpm system. Figure 14 shows the measured characteristic impedance as a function of frequency. The marker is placed at the beam frequency component used by the bpm system, 52.813MHz. The problem was corrected by replacing the pair of cables. The offending cable was closely inspected but no obvious problem could be found. The cable was cut into sections with all sections displaying the same resonance. It is speculated that perhaps the cable reel sat on one side and placed periodic deformations at just the right spacing to make a resonance at exactly the worst possible frequency. A diameter of 2.3 feet corresponds to _ wavelength at 52.813 MHz. This is consistent with the diameter of the reels used. Cables from other nearby bpm's had similar resonance's at higher and lower frequencies as if they were to come from different depths of the reel. A problem in the manufacturing process is also possible.

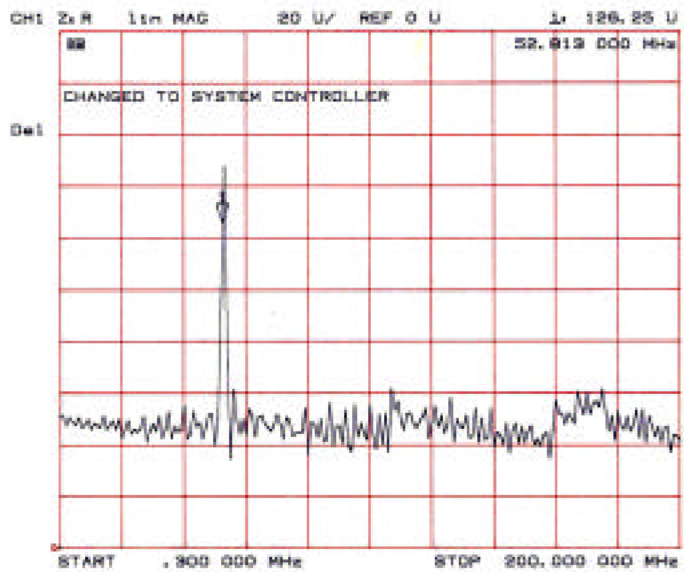


FIGURE 14. Characteristic impedance of a problem BPM cable. The beam bunch frequency being measured (at the marker) was nearly at the peak, making position measurement very sensitive.

Magnetic Interference

DC Current Transformer

A Bergoz Parametric Current Transformer was purchased and installed in the Fermilab Recycler to measure average beam charge. The device worked satisfactory until it was moved. The magnetic field from the now nearby Main Injector bend buss induced a substantial error in the measured beam charge, Figure 15. According to the manual, the transformer has a 100 uAmp/gauss radial sensitivity to magnetic fields. Typical magnetic fields from the buss are a few gauss. The error in Figure 15 is about 1e10 and corresponds to 1 mAmp or 10 gauss. A magnetic shield was constructed with 1/16 inch thick high permeability mu-metal. The shield was 9 inches in diameter and 18 inches long. The shield reduced the magnetic field by 22db, Figure 16.

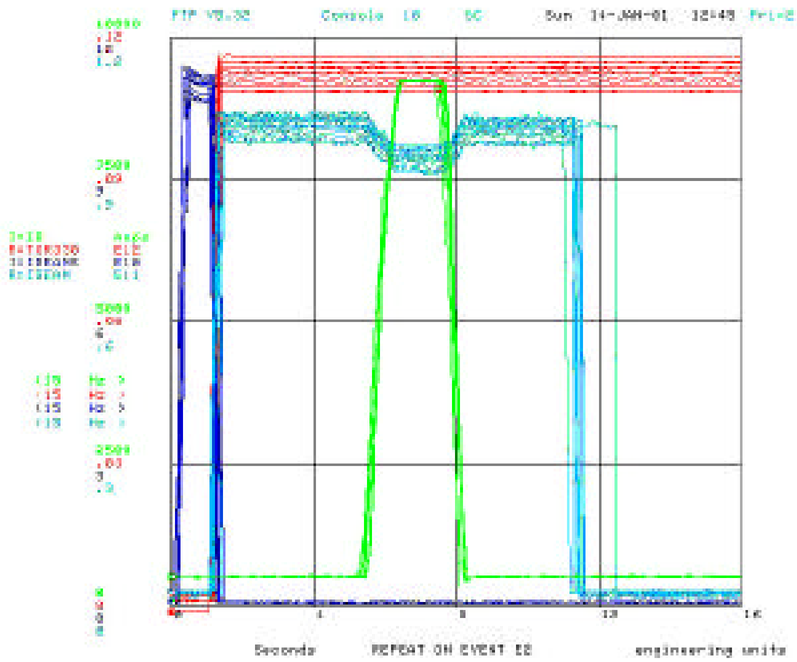


FIGURE 15. Beam charge in Main Injector is transferred into the Recycler at about 1.2 seconds. The Main Injector ramps between 5 and 8 seconds. The measured Recycler beam charge is affected by the current in the Main Injector bend buss.

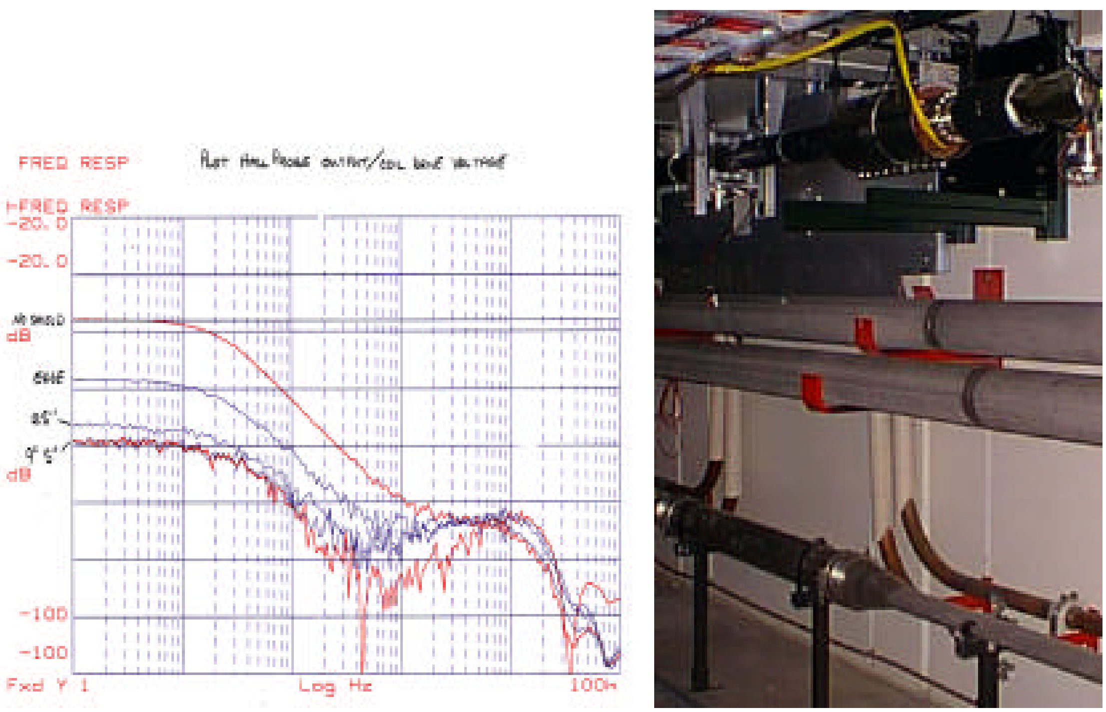


FIGURE 16. A high permeability mu-metal shield was placed around the Bergoz Parametric Current transformer. The Main Injector bend buss is shown in the background attached to the enclosure wall. The plot on the left indicated the measured magnetic field as a function of frequency without the shield, at the edge of the shield, and at 2.5, 5, and 9" from the edge. The shield is 9" in diameter.