An Improved Resistive Wall Monitor

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Abstract. Resistive wall monitors were designed and built for the Fermilab Main Injector project. These devices measure longitudinal beam current from 3 KHz to 4 GHz with a 1 ohm gap impedance. The new design provides a larger aperture and a calibration port to improve the accuracy of single-bunch intensity measurements. Microwave absorber material is used to reduce interference from spurious electromagnetic waves traveling inside the beam pipe. Several types of ferrite materials were evaluated for the absorber. Inexpensive ferrite rods were selected and assembled in an array forming the desired geometry without machining.

INTRODUCTION

Resistive wall monitors have been built and installed in each of the accelerators at Fermilab. They are used to measure longitudinal bunch shapes, calculate emittance, and diagnose instabilities. In the Tevatron, the signal is used by the Sampled Bunch Display as well as the Fast Bunch Integrator systems to measure and track the intensity of individual bunches. Recently, they have been used to monitor luminosity for colliding beams operation. Along with monitoring bunch manipulations such as cogging and coalescing, all of these functions will be useful in the new Main Injector.

An explanation of how a resistive wall monitor works along with a description of new features incorporated into the Main Injector design are described below.

HOW A RESISTIVE WALL MONITOR WORKS

A resistive wall monitor measures the image charge that flows along the vacuum chamber following the beam. The image charge has equal magnitude but opposite sign. Depending on the beam velocity, the image charge will lag behind and be spread out along its path. The ultimate bandwidth of such a detector is limited by this spreading of the electric field lines between the beam and the inside walls of the beam pipe. The spreading angle is approximately $1/\gamma$ for relativistic beams (γ is the ratio of total energy to rest energy). The estimated bandwidth limit from spreading is 47 GHz at injection to the Main Injector for a 3 cm radius pipe and 8 GeV proton energy. In practice, the detector response is difficult to maintain above the microwave cutoff frequency of the beam pipe, measured to be 1.5 GHz for the elliptical beam pipe used in the Main Injector. Above cutoff, the characteristic impedance of the beam pipe and the impedance of nearby structures such as bellows or changes in geometry can effect accuracy.

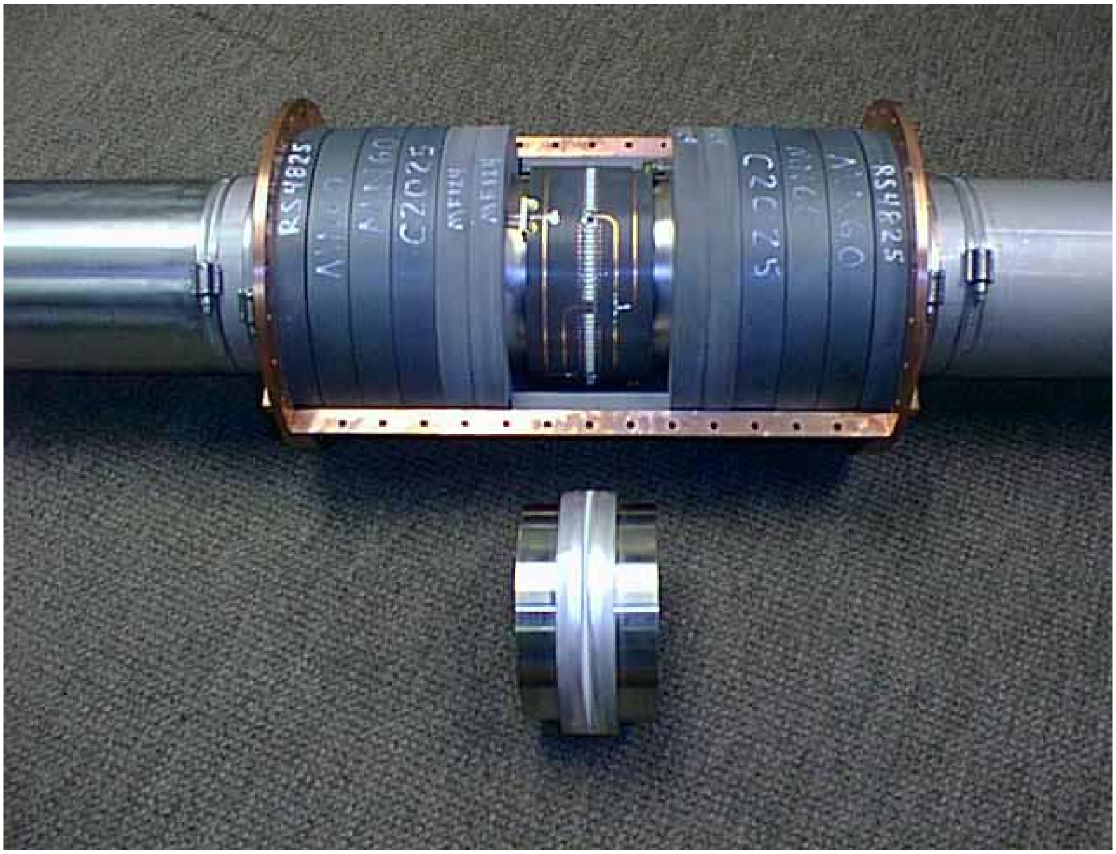

FIGURE 1. Resistive wall monitor showing circuit board and ferrite.

In order to measure the image current, the beam pipe is cut and a resistive gap is inserted (Figure 1). Various ferrite cores are used to force the image current through the resistive gap rather than allowing it to flow through other conducting paths. In addition to image current, other currents are often found flowing along the beam pipe. The gap and cores are placed inside a metal can to shunt these “noise” currents around rather than through the resistive gap. The inductance of the cores and the resistance of the gap forms a high pass filter with a corner frequency of $R/2\pi L$, typically a few kilohertz. Above this frequency, cores act to minimize the net current through their center by inducing a current through the resistive gap that just cancels the beam current.

The gap impedance is chosen to be well below the impedance of the cores inside the shielding can. Several types of ferrite and microwave absorbers are used to maximize the impedance and minimize resonances within the desired bandwidth. The Main Injector shielding can has an impedance greater than 30 ohms with the ferrite cores. In parallel with the 1 ohm gap impedance, 30 ohms can cause frequency dependent errors of $\pm 1.5\%$ or 0.15 db.

If the charge density around the circumference of the gap is not uniform, the voltage across the gap will vary around the circumference. The gap will act as an azimuthal transmission line transporting charge until the voltage equalizes. The time domain response of the detector would be distorted during this time. Position detectors have been made by exploiting this effect. The elliptical shape of the Main Injector pipe aggravates this problem (Figure 2). To overcome this problem, a round geometry is used for the gap and the signals from several monitor points equally spaced around the circumference are combined to form a single output.

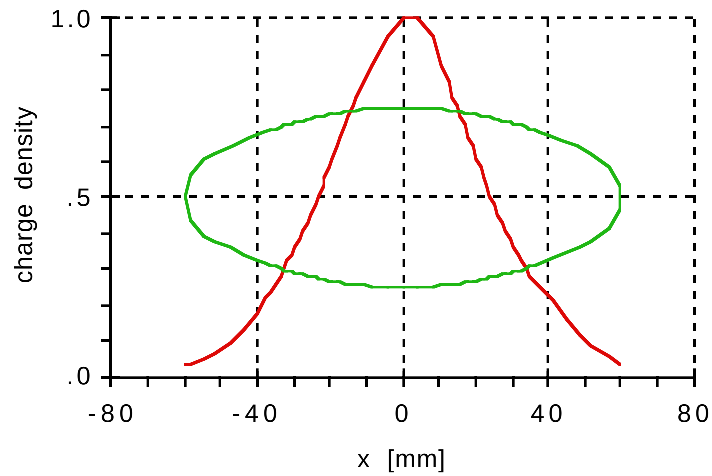

FIGURE 2. Cross section of Main Injector beam tube and charge density versus horizontal position induced by a line charge at the center.

DESIGN IMPROVEMENTS

Circuit Board

The resistive gap is formed with 112 equally spaced 122-ohm 1% ceramic resistors mounted on a flexible circuit board wrapped around the outside of a ceramic gap. The board material is Rogers RT/Duroid 5880 and is .020 inches thick with copper clad on both sides. The outside rings on the ceramic gap physically support the circuit board, and are plated with a conducting layer to make electrical contact with the pipe. The voltage across the gap is measured at four equally spaced positions and combined with a shunt resistive combiner using microstrip transmission lines on the board. Keeping the transmission lines as short as possible reduces the effect of small termination errors and insures a flat frequency response.

A calibration port was incorporated on the Main Injector resistive wall monitor. Similar to the combiner, microstrip transmission lines and series resistive splitters inject a calibration signal at four points evenly spaced between the monitor points. Resistive “L” pads are used to terminate the microstrip lines into the 1 ohm gap impedance. These resistors reduce the transmission from the calibration port to the output port by 40 db. The capacitance of the ceramic and the gap impedance limit the calibration bandwidth. This was extended slightly by shunting two of the series resistors with a small compensating capacitor.

On-line calibration is important to maintain accurate bunch intensity measurements. Small errors caused by impedance mismatch or changes in measurement electronics can cause significant errors. Desired accuracy of bunch intensity measurement is better than 1% or 0.09 db. This fidelity is required over large bandwidths to avoid errors caused by changes in bunch length. One hundred feet of 7/8 inch diameter foam dielectric solid jacketed cable is used to transport the signals from the beam enclosure. The cable attenuation at 1 GHz is 1.31 db/100ft and must be accounted for when calibrating the signal. The VSWR of this cable and connectors is specified to be less than 1.2, which can generate frequency dependent errors as large as 20%. The calibration port allows automatic calibration between beam pulses to correct these effects as well as any cable or component changes.

Ceramic Gap

A ceramic vacuum break was used at the gap to isolate the ferrite and other materials from the vacuum. The geometry was carefully designed to avoid resonances. The image current produces a voltage across the inside surface of the gap that propagates radially out to the resistors on the surface. The radial thickness of the ceramic is 1/4 wavelength at 5 GHz. The permitivity of ceramic is about 10, making the characteristic impedance 120 ohms per square. For a 1-ohm impedance, the optimum length of the ceramic gap is 0.14 inches (circumference*gap impedance/ohms per square). Three ceramic rings are used to form the gap to make them easier to manufacture. The center ring isolates the vacuum and the outside rings help balance the forces exerted by differential expansion between ceramic and metal as they are heated and cooled from brazing temperature. A round geometry was chosen to obtain more uniform image current around the circumference and is significantly cheaper to build.

Noise Reduction

Other currents not associated with the image current may flow along the beam pipe and interfere with its measurement. The current divider formed between the shielding can and the 1-ohm resistive gap reduce the amount allowed to flow through the gap by 100 db, the ratio of their impedances. This requires care in making the electrical connection between the shielding can and the beam pipe to insure a very low impedance. The cores inside the shielding can further reduce the noise current allowed to flow through the gap for frequencies above 0.03 hertz. This corner frequency is estimated from the resistance of the shielding can (about 10 μohms) and the inductance of the cores.

Microwave Absorber

When the beam passes a discontinuity, electromagnetic energy is launched into the beam pipe. This energy can travel in either direction but typically travels slower than the beam. The resistive wall monitor cannot differentiate between currents induced by beam and those induced by electromagnetic energy traveling along the beam pipe. In the Fermilab Main Ring, this spurious signal was as large as 10% of the beam signal. To reduce these signals, a microwave absorber is placed inside the beam pipe at both ends of the resistive gap. The transition from the elliptical beam pipe used in the Main Injector to the round gap is done with the microwave absorbers.

In previous resistive wall monitors, the absorber material was selected for its vacuum properties as well as its microwave absorbing characteristics. This application required a size that could not readily be made. Placing inexpensive absorber made from ferrite-loaded epoxy outside a ceramic pipe was tried, but, the required length became excessive because the material had to be placed out in a low-field region.

Several types of ferrite material that could be placed in the vacuum were obtained for testing. The material eventually selected was purchased in .375 inch diameter rods 7.5 inches long. An array of 74 rods held in position at each end with rexolite disks worked well (Figure 3). The inside clearance conformed to the elliptical Main Injector beam pipe. The assembly attenuated microwave signals traveling through a test set-up by 30 db. The amount of power deposited by the beam is estimated to be only 1.2 Watts assuming 10^6 protons in 2 nanosecond long bunches and a continuous 53 MHz bunch rate.

FIGURE 3. Microwave absorber made with an array of ferrite rods.

TESTING AND RESULTS

The most accurate method of measuring the fidelity of the resistive wall monitor was done by forming a 50-ohm transmission line through its center with the appropriate diameter conductor. The ends were gradually tapered to a standard type N connector.

Transmission through this line was flat to ±0.5 db below 4 GHz. Coupling from the transmission line to the output port is proportional to the ratio of the 1 ohm gap impedance to the 50 ohm characteristic impedance of the line, or –34 db. The signal at the output port was flat to ±0.5 db when normalized by the signal passing through it (Figure 4).

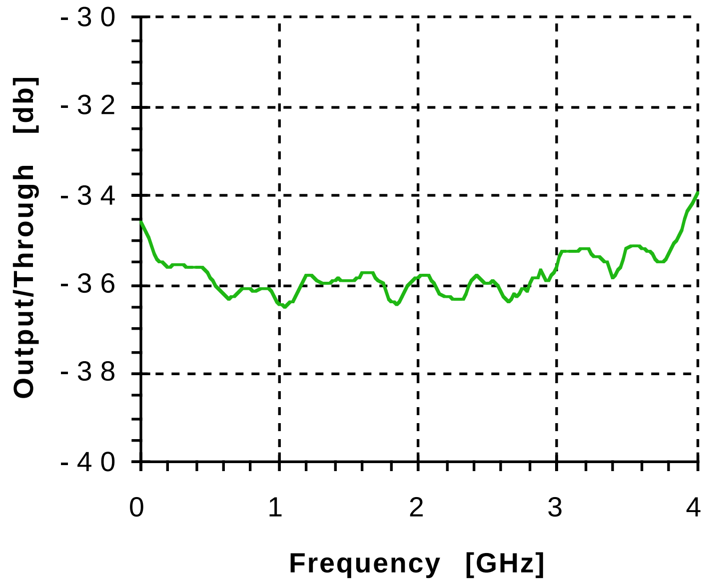

FIGURE 4. Output normalized to the signal passing through the test set-up. The nominal level is given by the ratio of the 1 ohm gap impedance to the 50-ohm test line, or –34 db.

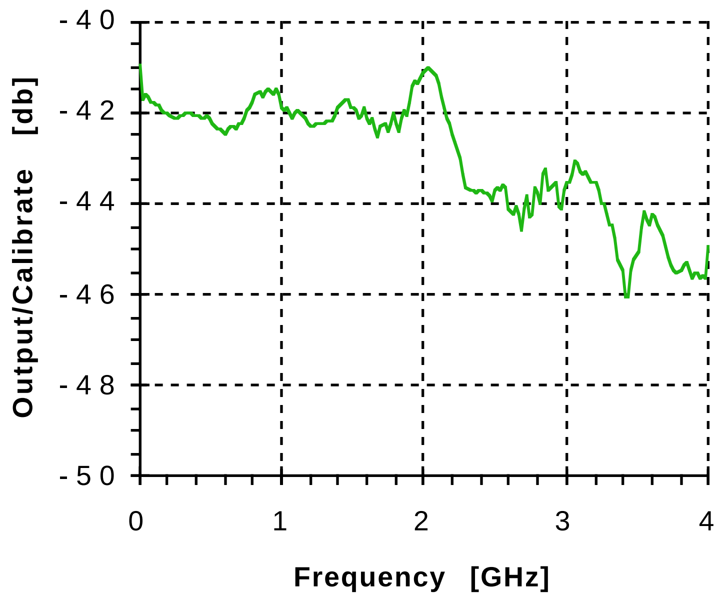

FIGURE 5. Coupling between the calibration port and the output port. Nominal coupling is given by the ratio of the 1 ohm gap impedance to the 100-ohm series resistor, or –40 db.

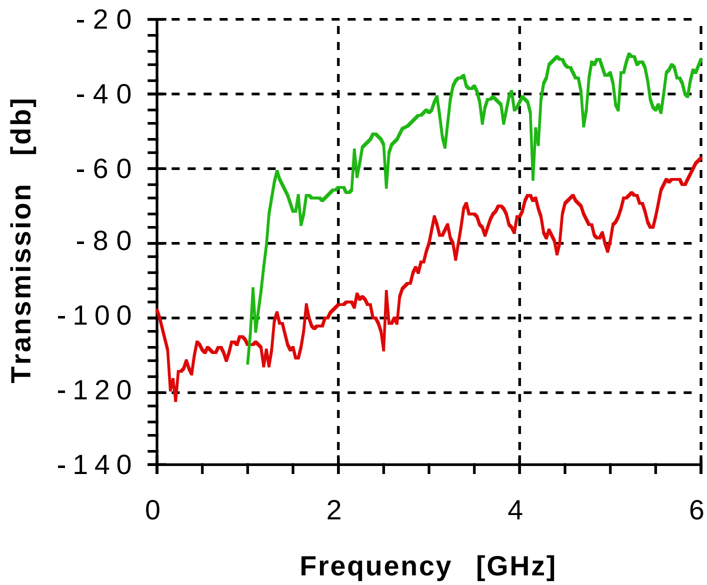

FIGURE 6. Transmission through an absorber with and without ferrite material installed. The cutoff frequency of the test set-up is 1.2 GHz.

The results are somewhat misleading in that the presence of the large center conductor significantly increases the cutoff frequency for microwave modes. The TE_{01} mode has the lowest cutoff frequency and was measured at 1.5 GHz in Main Injector beam pipe. The amount of coupling between the gap and microwave modes is not easily measured. TM modes can induce longitudinal currents that would flow through the resistive gap and thus be strongly coupled. However, the higher order TM modes have an odd symmetry around the circumference and their effect is reduced by combining the four equally spaced pick-off points.

The microwave absorber was measured by comparing the coupling between small loops at each end through the pipe with and without the ferrite absorbing material (Figure 6). Tests indicate that $600 of ferrite provides 30 db of attenuation, better than $7,500 of the previously used microwave absorber material.

CONCLUSION

It is virtually impossible to build a device with sufficient fidelity, accuracy, and stability to measure bunch intensity to 1%. Furthermore, frequency dependent errors would require the calibration to depend on bunch length. The calibration port will allow simple corrections to provide greater accuracy and reliability for measuring bunch intensity as well as easy diagnosis of system errors. The most cost-effective solution is to build a good device and correct measurements with calibration. This approach is commonly used to obtain optimum performance from test equipment.

Stacking up inexpensive ferrite rods allows flexibility in the shape of the absorber without expensive machining. Tests demonstrate $600 of ferrite worked better than $7,500 of microwave absorber used in previous detectors.

REFERENCES

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