FERMILAB-PUB-11-686-AD

Tevatron Resistive Wall Current Monitor*

J. Crisp[b], **B. Fellenz** [a†]

[a]*Fermi National Accelerator Laboratory,*
Batavia, IL, U.S.A.
E-mail: fellenz@fnal.gov

[b]*Michigan State University,*
East Lansing, MI, U.S.A.
E-mail: crisp@frib.msu.edu

ABSTACT: Resistive Wall Current Monitors (RWCM) were designed and built for the Fermilab Tevatron (Tev) project. These devices measure longitudinal beam current from 3 KHz to 6 GHz with 1.34 ohm gap impedance. There are two RWCM's installed a few feet apart in the Tevatron, upstream RWCM is used for general purpose use, downstream RWCM is dedicated for longitudinal parameters of coalesced beam bunches and bunch intensities. The design provides a calibration or test port for injecting test signals. Microwave absorber material is used to reduce interference from spurious electromagnetic waves traveling inside the beam pipe. This paper will do an overview how the RWCM was designed and its test results.

KEYWORDS: Beam-line instrumentation (profile monitors; beam-intensity monitors; bunch length monitors; resistive wall current monitor: RWCM)

* Work supported by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.
† Corresponding author.

Contents

1. Introduction

Resistive wall monitors have been built and installed in all of the accelerators at Fermilab [1-3]. They are used to measure longitudinal bunch shapes, calculate emittance, bunch intensities and diagnose instabilities. In the Tevatron, the signal is used by the Sampled Bunch Display [4-7] as well as the Fast Bunch Integrator [8-10] systems to measure and track the intensity of individual bunches. Recently, they have been used to monitor luminosity for colliding beams operation.

2. How a Resistive Wall Current Monitor works

A resistive wall current monitor, basically consist of a resistive gap along a conducting pipe. Charged particles traveling inside the vacuum pipe, produces an image current along the inside surface that has equal magnitude but opposite sign (Figure 1). When this image current passes through the resistive gap, a voltage signal is produced.

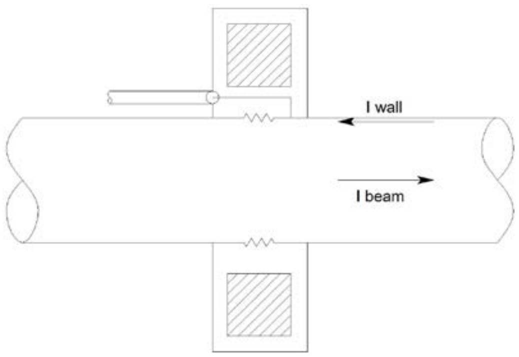

Figure 1. Basic resistive wall current monitor.

In order to measure the image current, the beam pipe is cut and a resistive gap is inserted. 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 form a high pass filter with a corner frequency of R/2πL, 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 absorber are used to maximize the impedance and minimize resonances within the desired bandwidth. The shielded case has a impedance greater than 20 ohms with the ferrite cores in parallel with the 1.34 ohm gap impedance.

2.1 Ceramic gap

A ceramic vacuum break was used at the gap to isolate the ferrite and other materials from the vacuum. The ceramic break is made of three ceramic rings, the center ring isolates the vacuum and the outside rings are metalized for making a connection for the circuit board around the gap, plus it helps the ceramic break be much more mechanically stable (Figure 2). The image current produces a voltage across the inside surface of the gap that propagates radially out to the resistors on the surface. Looking from inside of the pipe radially outward the ceramic gap forms a parallel plate transmission line with a plate separation equal to the gap width and plate width equal to 2π times the radius of the ceramic gap. The impedance of the gap is

$$Z = 377 \frac{h}{2\pi r} \frac{1}{\sqrt{\varepsilon_r}}$$

where ε_r is the dielectric constant of the ceramic, h is the distance between the plates and r is the average radius of the gap ceramic. For the gap, r = 1.78 inches, h = 0.125 inches and ε_r = 9.1 making a radial line impedance of 1.4 ohms.

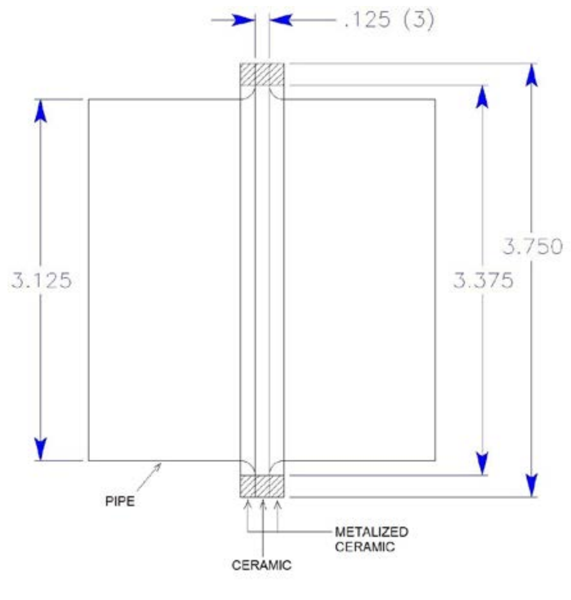

Figure 2. Ceramic gap.

2.2 Circuit board

The resistive gap is formed with 80 equally spaced 120 ohm 1% ceramic chip resistors soldered across two metal bands that are then soldered to a flexible circuit board wrapped around the outside of a ceramic gap (Figure 3). 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 make electrical contact with the pipe. The voltage across the gap is measured at 4 equally spaced positions 90° apart 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. The combined signal is then brought out with a 0.065 inch semi-rigid coax from a launch on the combiner board. A calibration port is incorporated on the board similar to the combiner, microstrip transmission lines and series resistive splitters inject a calibration signal at the 4 points evenly spaced between the monitor points. Resistive "L" pads are used to terminate the microstrip lines into the 1.34 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 2 of the series resistors with a small compensating capacitor. The calibration port is also brought out using a similar semi-rigid coax.

The calibration port allows you to inject a test signal into the monitor to test the monitor when installed or allow automatic calibration between beam pulses to correct for component and cable changes.

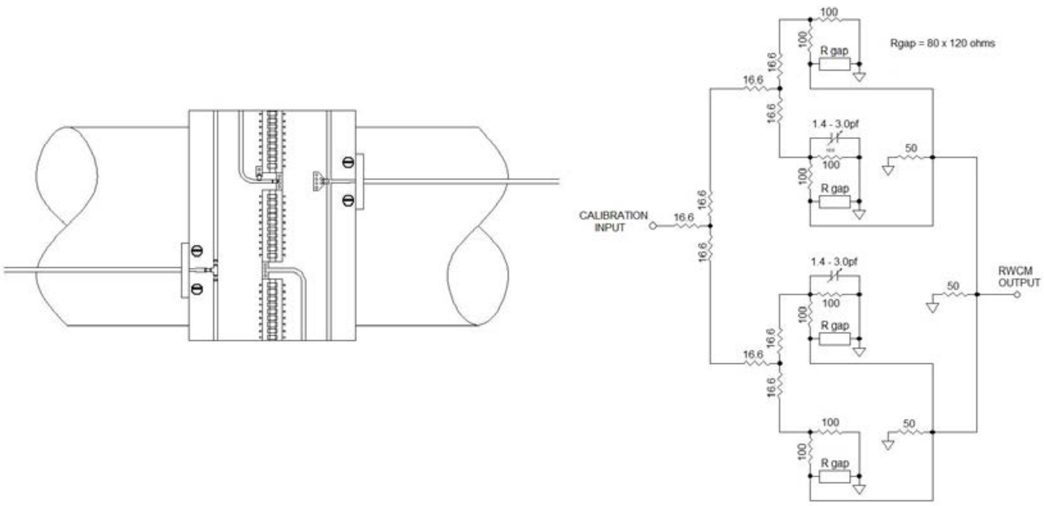

Figure 3. Resistive wall current monitor printed circuit board wrapped around ceramic gap, and associated electrical diagram.

2.3 Magnetic Materials

The outer shell of the montor is cylindrical and made of copper. The inside of the cycindrical cavity is partially filled with magnetic material which presents shunt impedance across the resistive gap. This impedance is large relative to the gap resistance at all frequencies of interest. At low frequencies the impedance is simply the single turn winding inductance which sets the L/R time constant. At higher frequencies the impedance is determined by the magnetic materials. To cover all the frequencies of interest and to maintain high shunt impedance, a graded approach was chosen for the design, filling the volume with several different materials as shown in figure 4.

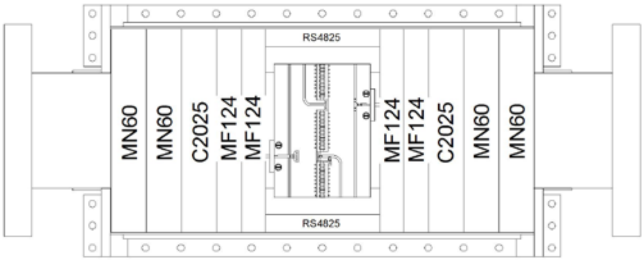

Figure 4. Resistive wall current monitor assembly showing circuit board and ferrite.

Farthest from the gap are Ceramic Magnetic, Inc., MN60, manganese-zinc ferrite cores with $\mu \approx 6000$. Four of these cores 4 inch I.D., 6 inch O.D. and 1 inch high provides low frequency inductance of $\approx 40\mu$H and a broadband impedance of $\approx$ 20 ohms in the ten to hundreds of MHz range. Closer to the gap is two Ceramic Magnetics ferrite cores C2025, $\mu \approx 175$, provides loss at higher frquency signals. Closer yet to the gap is four epoxy cores loaded with microwave absorbing material. The remaining volume near the gap is filled with microwave absorber epoxy sheets wrapped around the gap. The inner wall of the cavity was painted with microwave absorbering material to dampen any resentances inside the cavity. The design results in a broadband impedance between 10 and 20 ohms over a multi-gigahertz frequency range.

3. 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 current monitor cannot differentiate between currents induced by beam and those induced by electromagnetic energy traveling along the beam pipe. In the Fermilab Tevatron, this spurious signal was as large as 10% of the beam signal. To reduce these signals, microwave absorber is placed inside the beam pipe at both ends of the of the resistive wall current monitor.

The absorber material was selected for its vacuum properties as well as its microwave absorbing characteristics. The material that was chosen was Trans-Tech, TT2-111R, 3.125 inch I.D., 3.8 inch O.D. with a variety of different lengths. The material was custom made to fit into a 4 inch O.D. vacuum beam pipe 12 inches long (Figure 5). This allowed the absorber to be inside the vacuum to give maximum attenuation of microwave signals traveling through the beam pipe without aperture restriction.

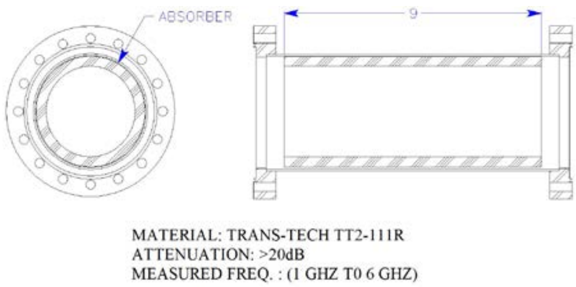

Figure 5. Tevatron microwave absorber.

4. Measurements and results for RWCM

To test the resistive wall current monitor a test fixer was made with a center conductor placed through the monitor to form a 50 ohm coaxial transmission line system (Figure 6). Tapered cones were used at the ends of the structure to match down to standard coaxial connectors and cables. An identical setup with just the pipe was used as a reference point to which the measurements were normalized. The mechanical design of the test fixture allowed for a repeatable measurement each time the fixture was taken apart and reassembled.

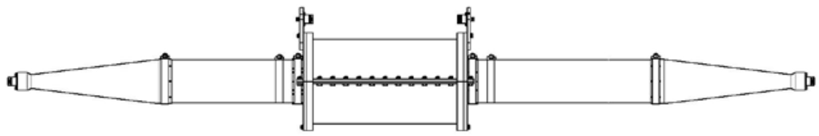

Figure 6. Test fixture with monitor.

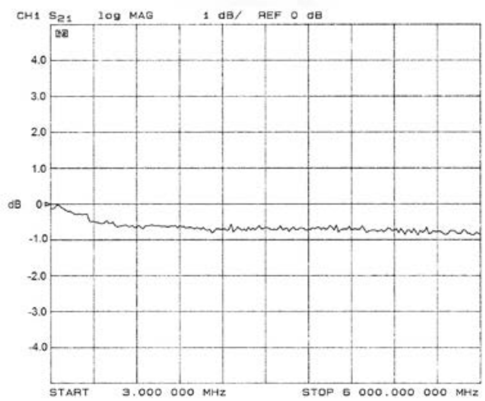

Figure 7. Through response of the reference pipe.

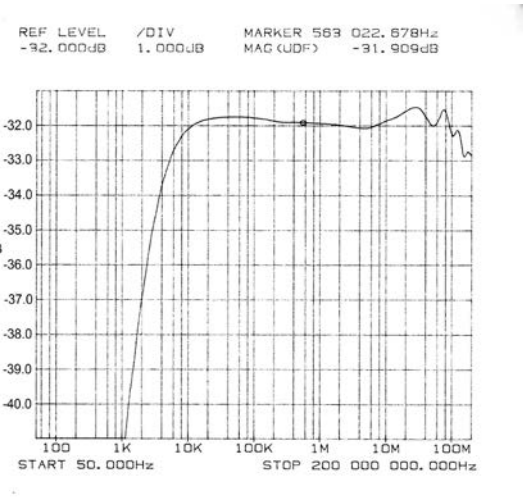

Figure 8. Output low frequency response of the RWCM.

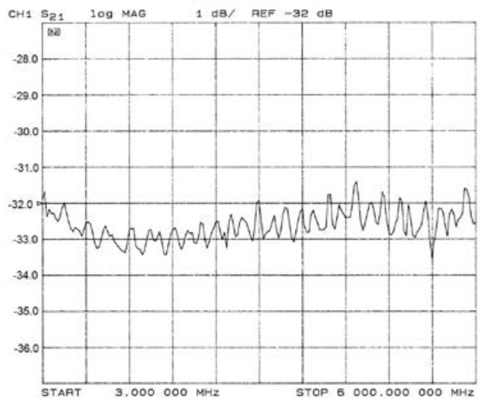

Figure 9. Output of RWCM normalized to the reference signal. The output is the ratio of the 1.34 ohm gap impedance to the 50 ohm test pipe, or -32 db.

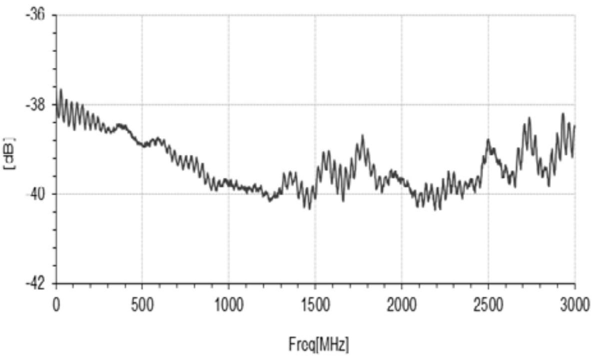

Figure 10. Response between the calibration port and the output port. The nominal response is given by the ratio of the 1.34 ohm gap impedance to the 100 ohm series resistor, or -38db.

5. Measurement and results for microwave absorber

The microwave absorber was measured by placing the absorber pipe in between two beam size pipes with coupling loops in each pipe. Cone terminations where placed on the ends of these pipes to cancel out any standing waves in the test pipe (figure 11).

The measurement was done by comparing the coupling between the loops at each side of the absorber pipe with and without the microwave absorbing material. The test indicated that the absorber would provide greater then 20db of attenuation (figure12).

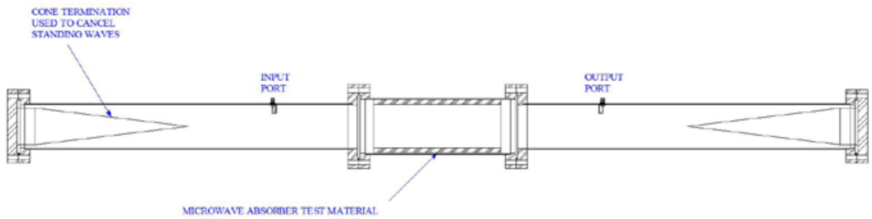

Figure 11. Test fixture for testing the microwave absorber material.

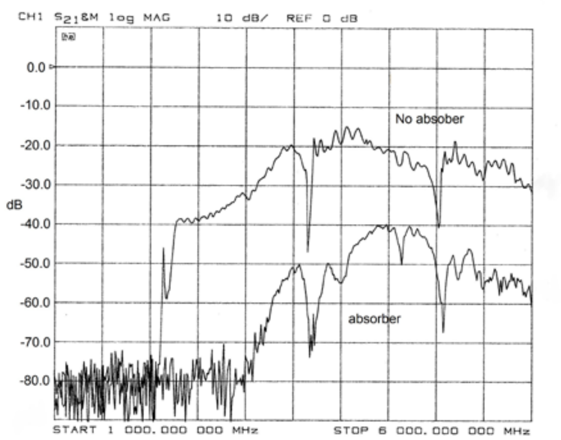

Figure 12. Transmission through an absorber with (lower trace) and without (upper trace) absorbing material installed. The cut-off frequency of the test setup is 1.2GHz.

6. Conclusion

The resistive wall current monitor with its wide bandwidth and flat response is an invaluable tool for beam instrumentation in the Tevatron and other beam lines at Fermilab. The device allows for the measurements of longitudinal bunch shape, intensities and emittence measurements.

Acknowledgments

Fermilab is operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.

References

[1] R. Weber, *Longitudinal Emittance: An Introduction to the Concept and Survey of Measurement Techniques Including Design of a Wall Current Monitor*, *AIP Conference Proceedings on Accelerator Instrumentation*, No. 212, pp. 85-126, (1989).

[2] B. Fellenz and J. Crisp, *An Improved Resistive Wall Monitor*, BIW 98, AIP Conference Proceeding 451, pp. 446-453.

[3] J. Crisp and B. Fellenz, *Calibration of the Resistive Wall Monitor for the SBD and FBI Systems*, Fermilab-TM-2208, June 2003.

[4] Craig D. Moore, *Single Bunch Intensity Monitoring System Using an Improved Wall Current Monitor*, in the Proceedings of *IEEE Particle Accelerator Conference*, Chicago, Illinois, 20-23 March 1989, pp 1513. Also in *IEEE Part. Accel.* 1989, pp. 1513-1515.

[5] S. Pordes, J. Crisp, B. Fellenz, R. Flora, A. Para, A.V. Tollestrup, *Signal Processing for Longitudinal Parameters of the Tevatron Beam*, in proceedings of *Particle Accelerator Conference (PAC05)*, pp. 1362-1364, 16-20 May 2005, Knoxville, Tennessee, USA.

[6] S. Pordes, et al., *Measurement of Proton and Anti-proton Intensities in the Tevatron Collider*, in proceedings of *Particle Accelerator Conference (PAC03)*, pp. 2491-2493, 12-16 May 2003, Portland, Oregon, USA.

[7] R. Thurman-Keup et al., *Longitudinal bunch monitoring at the Fermilab Tevatron and Main Injector synchrotrons*, to be submitted to *Journal of Instrumentation.*

[8] G. Vogel et al., *A Multi-Batch Fast Bunch Integrator for the Fermilab Main Ring*, in proceedings of *Beam Instrumentation Workshop (BIW96)*, p. 414, 6-9 May 1996, Argonne, Illinois, USA.

[9] J. Utterback et al., *Fast Bunch Integrator, A system for Measuring Bunch Intensities in Fermilab's Main Ring*, *ICALEPCS 95*, October 29, 1995, Chicago, Illinois, USA.

[10] T. Meyer et al., *Fast Bunch Integrators at Fermilab during Run II*, to be submitted to *Journal of Instrumentation*.