Fermilab-TM-2437-AD

Recycler Short Kicker Beam Impedance

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Introduction

Measured longitudinal and calculated transverse beam impedance is presented for the short kicker magnets being installed in the Fermilab Recycler. Fermi drawing number ME-457159. The longitudinal impedance was measured with a stretched wire and the Panofsky equation was used to estimate the transverse impedance. The impedance of 3319 meters (the Recycler circumference) of stainless vacuum pipe is provided for comparison. Although measurements where done to 3GHz, impedance was negligible above 30MHz. The beam power lost to the kicker impedance is shown for a range of bunch lengths.

The measurements are for one kicker assuming a rotation frequency of 90KHz. Seven of these kickers are being installed.

Longitudinal and Transverse Impedance

The longitudinal impedance is measured with a wire stretched along the beam path. The wire forms a coaxial, or TEM, transmission line. Attenuation is measured with a network analyzer and used to calculate the longitudinal impedance. The characteristic impedance of the 0.010" tin plated copper wire is about 277Ω. Resistive L-pads are used to match the wire to 50Ω allowing measurement with a network analyzer. Corrections for the L-pad and the skin effect losses on the wire are calculated as shown in the appendix. Longitudinal impedance is extracted from the attenuation (S_{21}) measured through the device. The rotation frequency is assumed to be 90KHz for the Recycler.

$$Z_L = 2Z_0\left(\frac{1}{S_{21}} - 1\right) \qquad \frac{Z_L}{n} = Z_L\frac{\omega_0}{\omega} \qquad \omega_0 = 2\pi\ 90KHz$$

The kicker has a 38" long ceramic beam tube 2"x4" OD with 0.23" wall. Thin copper strips 0.25" wide are adhered at the center of the top and bottom outside surfaces. Resistors can be attached at both ends to allow beam image current to travel on the strips in order to reduce beam impedance. Both 50 and 200 ohm resistors at all four ends of the two strips where measured. The amplitude of the kicker induced currents in the strips may require higher values.

The kicker plate is about 30.25" long with 50 ohm coaxial connections at each end. The input, or downstream end, is driven through a 50 ohm cable from a high impedance source located in the service building. The upstream end will be terminated in 50 ohms. Measurements where made with the upstream end terminated and the downstream end open. The open ended cable to the power supply will reduce the impedance at frequencies where it is an odd number of quarter wavelengths long.

The Main Injector beam pipe is 4.84" wide, 2.09" tall, and the resistivity is 74 μΩ-m. Using a machine circumference of 3319m and pipe radius of 1.05" the impedance becomes 10.2Ω at 90KHz.

For a circular beam pipe with radius b, and resistivity ρ:

$$\frac{Z_L}{m} = \frac{\rho}{\delta 2\pi b} \qquad \delta = skin\ depth = \sqrt{\frac{2\rho}{\omega\mu}}$$

$$Z_L \approx 10.2\Omega\ at\ 90KHz$$

The transverse impedance can be calculated from the longitudinal impedance. The Panofsky equation was derived for a round pipe but is often used to estimate transverse impedance for more complex shapes.

$$Z_T \approx \frac{2c}{\omega b^2} Z_L \qquad Z_L\ measured\ at\ the\ center\ of\ radius\ b$$

$$= \frac{2c}{\omega_0 b^2} \frac{Z_L}{n}$$

$$for\ b = 1.05"\ and\ \omega_o = 2\pi 90KHz$$

$$Z_T \approx 1.49 \frac{Z_L}{n} \left[\frac{M\Omega}{m}\right]$$

longitudinal impedance (1 kicker)

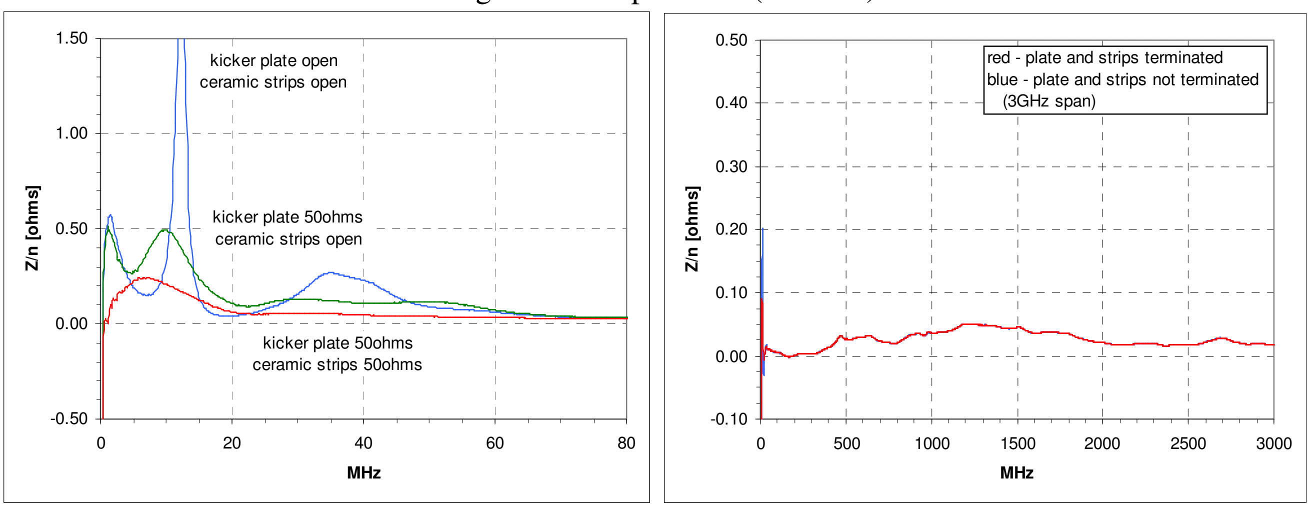


Figure 1. The peak impedance (Z/n) is 0.5 ohms with one end of the kicker plate terminated in 50 ohms. The impedance can be reduced further by terminating the copper strips on the ceramic beam tube, 50 ohms was used here.

longitudinal and transverse impedance (1 kicker)

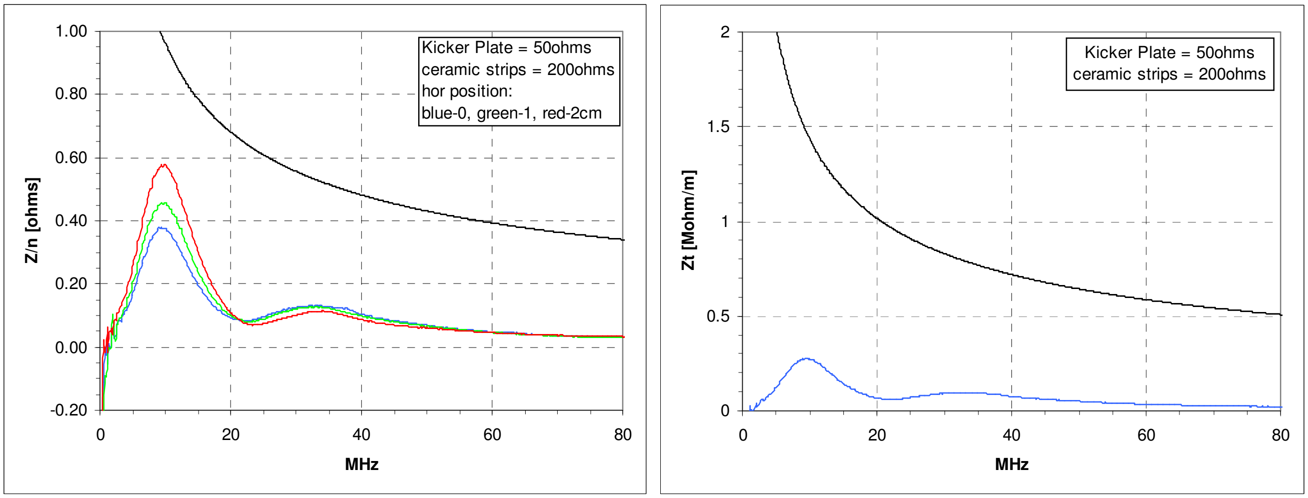


Figure 2. For this measurement, 200 ohm resistors were used at both ends of the two copper strips and the kicker plate was terminated in 50 ohms at one end. The wire was moved horizontally to reveal some position sensitivity. Estimated transverse impedance of one kicker is shown on the right. The black trace indicates the impedance of 3319m of 1.05" radius round stainless pipe in both plots.

Beam Power Loss

The beam power lost to the real part of the kicker impedance for a Gaussian bunch can be calculated as shown below.

$$I(t) = \frac{Ne}{\sigma_t \sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t}{\sigma_t}\right)}$$

$$I(f) = Ne\ e^{-\frac{1}{2}\left(\frac{f}{\sigma_f}\right)} \qquad \sigma_f = \frac{1}{2\pi\sigma_t}$$

$$P(f) = \mathrm{Re}(f)\ I^2(f)$$

$$\frac{E}{bunch} = 2\Delta f \sum_{f=0}^{\infty} \mathrm{Re}(f)\ I^2(f)$$

$$Power = \frac{E}{bunch}\ x\ \frac{bunches}{second}$$

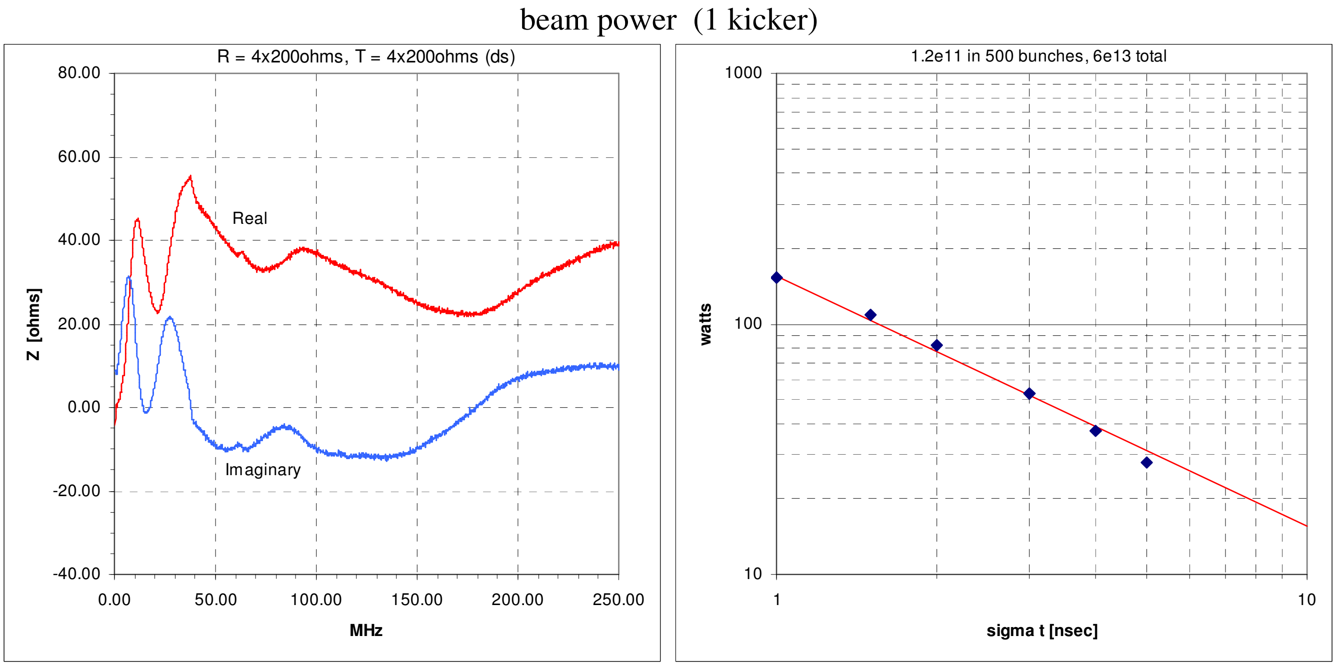


Figure 3. Separate real and imaginary components of the longitudinal beam impedance for one kicker is shown on the left. Only the real part contributes to beam power loss. The power loss is 153 watts for 6e13, 1nsec sigma, in 500 bunches per turn.

Discussion

The kicker plate forms a 50ohm transmission line with roughly 48nsec delay. The beam current enters one end and exits the other separated by the beam time of flight. At frequencies where the plate electrical delay minus the beam time of flight is 180 degrees, the voltage at the ends combine constructively resulting in an impedance peak. The 48nsec kicker plate delay and 2.6nsec beam time of flight produce an impedance peak at 11MHz. At higher frequency, losses in the ferrite conceal this effect. The electrical delay of the kicker plate likely changes with frequency. Other reactive impedance could shift the peak contributing to the perceived electrical delay.

As mentioned, the drive cable will reduce the impedance when it is an odd number of quarter wavelengths long. A 364nsec cable could be exploited to reduce the peak at 11Mhz.

The 0.0625” wall thickness of the stainless vacuum tube is one skin depth at 100KHz. Below this frequency, impedance can be affected by things outside of the vacuum. Thus, the first few tune lines are exploring impedance of things like magnet laminations.

The amount of beam power, 153 watts for 6e13 in 500 bunches with 1nsec sigma, is not significant for the kicker. However, it is not known how much of that will be dissipated in the 200ohm resistors terminating the copper strips on the ceramic tube. When the spare kicker becomes available this could be measured. One feature of the design is that the strip terminating resistor can be changed without moving the kicker or opening vacuum.

Measurements provided here are for one kicker. The total impedance for the seven kickers being installed is shown in Figure 4 below.

longitudinal impedance for all seven kickers

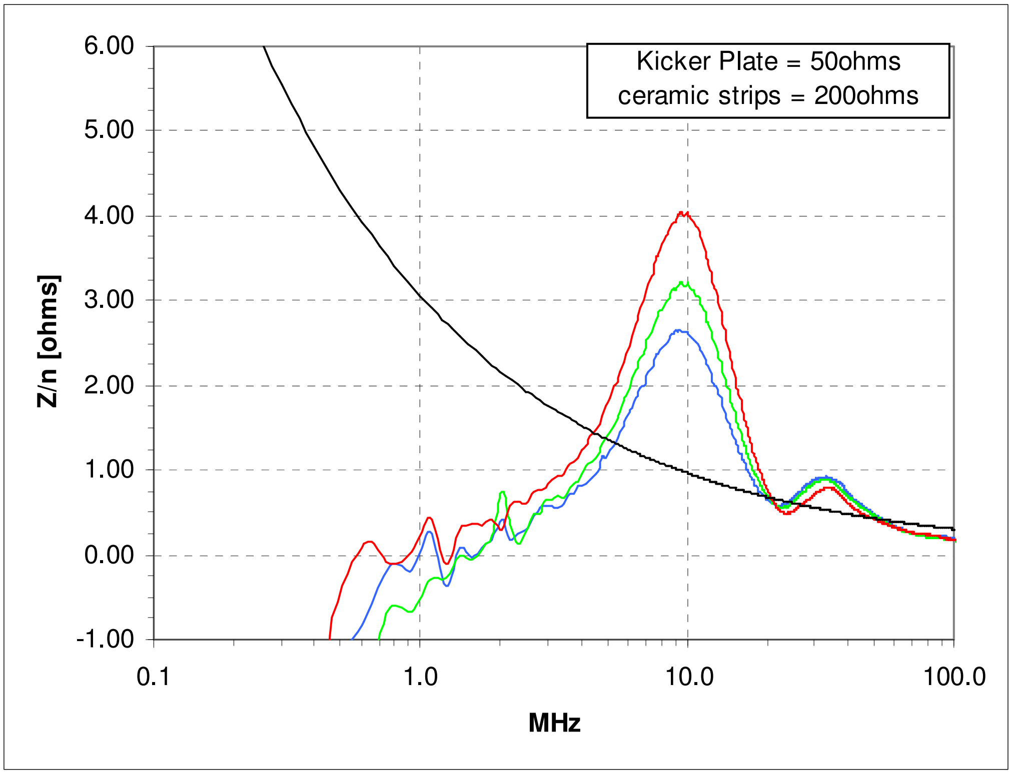


Figure 4. Longitudinal impedance of seven kickers for horizontal beam positions 0, 1, and 2cm from center. The black trace indicates the impedance of 3319m of 1.05" radius round stainless pipe.

References:

1) Sacherer, F., Nassibian, G.; "Methods for Measuring Transverse Coupling Impedances in Circular Accelerators"; Nuc. Inst. And Meth., Vol. 159, pgs 21-27, 1979.

2) Panofsky, W.K.H., Wenzel, W.A.; "Some Considerations Concerning the Transverse Deflection of Charged Particles in Radio-Frequency Fields", Rev. Sci. Instrum., Vol 27, pg. 967, 1956.

3) Crisp, J., Fellenz, B.; "Measured Longitudinal Beam Impedance of a Tevatron Separator"; Fermilab TM-2194; November 25, 2002.

4) Chao, A., Tigner, M. ; "Handbook of Accelerator Physics and Engineering"; World Scientific Publishing; 1999; pg. 570.

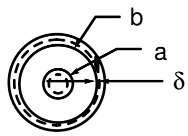
5) "Reference Data for Radio Engineers"; sixth edition; Howard W. Sams; 1984.

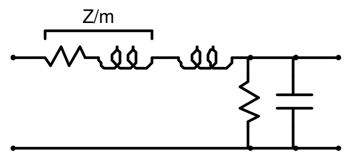
6) M. Harrison, F.N. Rad; "Symmetric and Non-Symmetric Lambertson Magnets"; FN-398; February 1984.

7) Martens, M.A., Ng, K.Y.; "Impedance Budget and Beam Stability Analysis of the Fermilab Main Injector"; 1993 PAC.

Appendix 1:

Skin Effect Losses in Coaxial Cable





$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \qquad \gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$

high frequency approximation $R \ll \omega L$ *and* $G \ll \omega C$

$$Z_0 \approx \sqrt{\frac{L}{C}} \qquad \alpha = \frac{R}{2Z_0} + \frac{G}{2} Z_0 \approx \frac{R}{2Z_0} \qquad \beta = \frac{\omega}{\upsilon_p} \approx \omega\sqrt{LC}$$

The inductive impedance equals the real impedance in a good conductor.

$$Z/m \approx \left(\frac{\rho_a}{a\pi\delta_a} + \frac{\rho_b}{b\pi\delta_b}\right)(1 + j) = R/m\,(1 + j)$$

'a' is the diameter of the outer conductor and 'b' is that of the center conductor. (the impedance is generally dominated by the losses on the small center conductor)

skin depth in good conductor: $\delta = \sqrt{\frac{2\rho}{\mu\omega}}$

or $R/m \approx \alpha 2 Z_0 \sqrt{f/f_0}$ *for* α *measured at* f_0

A good approximation is to calculate the attenuation at 1GHz and assume the actual attenuation is proportional to the square root of the frequency.

$$\frac{Vout}{Vin} = e^{-\gamma d} \qquad mag = e^{-\alpha d} \qquad ang = \left(\frac{\omega}{\upsilon_p} - \beta\right) d$$

It was interesting to see a knee in the attenuation versus frequency using 0.010" (30 gauge) tin plated copper wire. Below 200MHz the attenuation corresponds to the resistivity of copper (1.74e-8Ω-m) at higher frequencies it matches the resistivity of tin (11.4e-8Ω-m). The skin depth at 200MHz in tin is .00047", about the plating thickness.

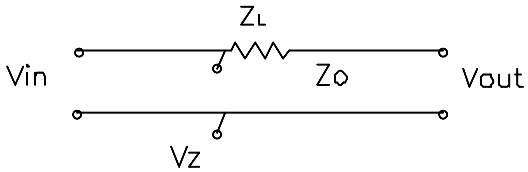
Wire Data:

wire	tin plated copper	(30 gauge)	
wire diameter	0.010"		
wire resistance <200MHz	10.4	'Ω/m@1GHz'	(Cu - 1.74e-8 Ω-m)
wire resistance >200MHz	26.6	'Ω/m@1GHz'	(Sn – 11.4e-8 Ω-m)
skin depth in tin @200MHz	.00047"		

Appendix 2: *(useful equations for beam impedance measurements)*

Longitudinal Beam Impedance from stretched wire

<u>lumped impedance:</u>



$$Vz = Vinc + Vref = Vin\left(1 + \frac{(Z_L + Z_0) - Z_0}{(Z_L + Z_0) + Z_0}\right)$$

$$Vout = Vz\frac{Z_0}{Z_L + Z_0} = Vin\frac{Z_0}{Z_L + Z_0}\frac{2(Z_L + Z_0)}{Z_L + 2Z_0}$$

$$\frac{Vout}{Vin} = S_{21} = \frac{2Z_0}{Z_L + 2Z_0}$$

$$Z_L = 2Z_0\left(\frac{1}{S_{21}} - 1\right) = 2Z_0\left\{\left(\frac{\cos(ang(S_{21})}{mag(S_{21})} - 1\right) - j\frac{\sin(ang(S_{21}))}{mag(S_{21})}\right\}$$

$$Z/n = 2Z_0\left(\frac{1}{S_{21}} - 1\right)\frac{f_0}{f}$$

<u>high frequency approximation:</u>

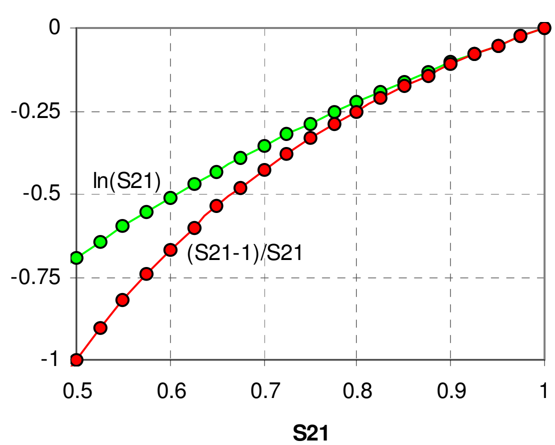
$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \qquad \gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$

$$at\ high\ frequency \quad R \ll \omega L\ and\ G \ll \omega C$$

$$Z_0 \approx \sqrt{\frac{L}{C}} \qquad \alpha = \frac{R}{2Z_0} + \frac{G}{2}Z_0 \approx \frac{R}{2Z_0} \qquad \beta = \frac{\omega}{\upsilon_p} \approx \omega\sqrt{LC}$$

$$\frac{Vout}{Vin} = S_{21} = e^{-\alpha l}$$

$$R = -2Z_0 \ln S_{21} = -2Z_0\frac{S_{21}[db]}{20\log(e)}$$



estimating beam Impedance

Resistive Wall impedance: (from beam pipe resistivity)
For a circular beam pipe with resistivity ρ, radius b, and beam displacement x_o;

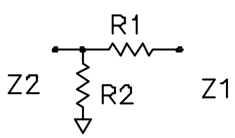
$$\frac{Z_L}{m} = \frac{\rho}{\delta 2\pi b}\left(1 + 2\frac{x_0^2}{b^2}\right) \qquad \delta = skin\ depth = \sqrt{\frac{2\rho}{\omega\mu}}$$

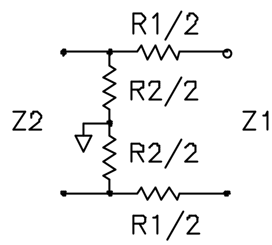
Panofsky equation: (estimate transverse impedance from longitudinal measurement)

$$Z_T = \frac{2c}{\omega b^2} Z_L \qquad \textit{for radius b and } Z_L \textit{ measured at the center}$$

$$\frac{Z_T}{m} = \frac{2c}{\omega b^2}\frac{Z_L}{m} = \frac{2c}{\omega b^2}\frac{\rho}{\delta 2\pi b}\left(1 + 2\frac{x_0^2}{b^2}\right) \qquad \textit{for beam offset } x_0$$

Impedance Matching





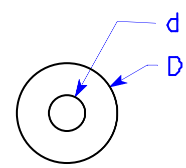
$$R1 = \sqrt{Z1\,(Z1 - Z2)}$$

$$R2 = \frac{Z1\,Z2}{R1}$$

ideal resistor values:

	Z1	Z2	R1	R2	db 0Hz	db/100' 1GHz	d	D
coaxial	277	50	251	55.2	26.07	4.96	.01"	1.0"

coaxial line:



$$Zo = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\ln\frac{D}{d} = 60\ln\frac{D}{d}$$

Zo=277Ω For 0.010" diameter wire in a 1.0" pipe: