ANALYSIS AND MEASUREMENTS OF EDDY CURRENT EFFECTS OF A BEAM TUBE IN A PULSED MAGNET

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Abstract

The power supply design of the γ_t - jump system in FNAL Main Injector uses a resonant circuit[1]. A critical design parameter is the ac losses of the beam tube in a pulsed quadrupole. This paper gives an analysis to this problem. An equivalent circuit model based on the impedance measurement was established. The measured and calculated losses are in agreement. Another effect of the eddy current is the distortion of the magnetic field inside the beam tube. A Morgan coil was used for field measurements up to 10 KHz. These results are presented in this paper.

I INTRODUCTION

The power supply of FNAL Main Injector γ_t - jump system requires a pulsed magnet string as part of its resonant circuit. The total ac losses of magnet string is critical on designing the power supply. The ac losses come from coil winding resistance, laminations and beam tube due to eddy current effects. The transfer function of magnetic field and magnet current is no longer a constant. Magnetic field attenuation inside of the beam tube and the time delay between the field and current increase as frequency increases. The ac losses of the beam tube and the associated effects on magnetic field are the focus of this paper.

II BEAM TUBE AC LOSSES

In order to study the AC losses of a beam tube in a pulsed magnet, an air core quadrupole magnet called QXR with a circular stainless steel beam tube was used for analysis and measurements. The core losses from this air core quadrupole magnet are very small and can be neglected. The sources of the ac losses come from the beam tube due to eddy current effect and winding dc resistance.

The first approach for estimating the ac losses of a beam tube is the electrical equivalent circuit based on impedance measurement.

Figure 1 shows a circuit basic model for a magnet with a beam tube. The degree of the circuit complexity is dependent on the impedance measurement data. The values of the frequency independent circuit elements are selected such that the basic model matches the impedance measurement data both in magnitude and phase. The resulting basic circuit model can be converted and simplified to the circuit model shown in figure 4. The R_w represents the winding dc resistance of the magnet. $L(f)$ is the equivalent inductance of the magnet and $R(f)$ represents the beam tube ac losses due to eddy current. The $L(f)$ and $R(f)$ are frequency dependent variables and they are determined by the impedance of the magnet.

$$L(f) = \frac{4\pi^2 f^2 L_{eq}{}^2 + R_{eq}{}^2}{4\pi^2 f^2 L_{eq}} \tag{1}$$

$$R(f) = \frac{4\pi^2 f^2 L^2{}_{eq} + R_{eq}{}^2}{R_{eq}} \tag{2}$$

where $R_{eq} = \mathrm{Re}(Z) - R_w$, $L_{eq} = \mathrm{Im}(Z)/2\pi f$. Perform simple circuit analysis on the circuit in figure 4, the power dissipated in *R(f)*, which represents the beam tube ac losses, is obtained by

$$P_{BeamTube} = \frac{4\pi^2 f^2 L(f)^2}{R(f)} I_{mag}{}^2 \tag{3}$$

and the power dissipated in R_w is

$$P_{Winding} = [1 + \frac{2\pi f L(f)}{R(f)}]^2 R_w I_{mag}{}^2 \tag{4}$$

where I_{mag} is the magnet inductance current and it is directly related to the magnetic field inside the beam tube.

The impedance data taken from the measurement for the QXR magnet are shown in figure 2. The measured R_w is $140\,m\Omega$. The frequency independent circuit elements in figure 1 were selected such that the basic circuit model matches the data (R1=8 Ω, R2=400 Ω, R3=20 Ω, L1=420 μH, L2=230 μH, L3=230 μH). The

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basic circuit model is then converted to the simplified model as shown in figure 4. The $L(f)$ is plotted in figure 5 by using equation (1). Figure 5 shows the QXR inductance decreases as frequency increases. This is because the flux is reduced by the eddy current induced B field. The ac losses of the beam tube is generated by equation (3) in figure 3 with beam tube ac losses in watts per ampere squared as function of frequency. As seen in figure 3, the beam tube ac losses rise linearly as a function of f^2 below 2 KHz. There is a fall off from this linear relationship above 2 KHz. This is partly due to the decrease of $L(f)$ as frequency increases as explained above.

The second approach for estimating the ac losses of the beam tube is theoretical calculation based on the quadrupole field and the properties of the beam tube. When a circular beam tube is placed in a varying quadrupole field, the eddy current induced field is

$$B'_{ed} = \frac{1}{2} \mu_o \frac{dB'}{dt} \sigma \; t \; r \quad (5)$$

The ac losses due to the eddy current is

$$P_{ed} = \frac{1}{4} \pi (\frac{dB'}{dt})^2 \sigma \; t \; r^5 l_{tube} \quad (6)$$

where μ_o is the permeability of air, B' is quadrupole field gradient, σ is the conductivity of tube material, t is the thickness of the tube, and l_{tube} is the length of the tube. The field gradient of an air core quadrupole is:

$$B' = \frac{1}{2} \frac{\mu_o N I_{mag}}{A^2} \quad (7)$$

where N is number of turns per gap which is twice the number of turns per pole, A is the radius of inscribed circle of the magnet poles. The inductance is

$$L = \frac{1}{4} \pi \mu_o N^2 l_{mag} \quad (8)$$

where l_{mag} is the length of the magnet. From equation (6), (7), and (8), one gets the beam tube ac losses due to eddy current:

$$P_{ed} = \pi^2 f^2 \mu_o L \sigma t r \frac{l_{tube}}{l_{mag}} I_{mag}{}^2 \quad (9)$$

Equation (9) uses the fact that A is about the same as r in the measurement. For a given set of beam tube data and the measured magnet inductance, the calculated ac losses of the beam tube is obtained by equation (9) and the result is plotted in figure 3. It is seen that the results from the two different approaches agree with each other up to 2 KHz.

III MAGNETIC FIELD DISTORTION

In order to understand the possible associated distortion of the quadrupole field, a Morgan coil is placed inside the stainless steel beam tube of the QXR magnet. The coil has a set of pickups that can probe various multiple components of a varying field, including dipole, normal quadrupole, skew quadrupole, sextupole, octupole, decapole,12-pole and 20-pole.

The coil is positioned manually at the center of the beam tube such that the normal quad signal reaches maximum while the dipole and skew quad signals minimum with a sinusoidal excitation current at 130 Hz. The measurement was carried out in the frequency range from 130 Hz to 10 KHz. The results are shown in figure 6. In an ideal situation, the normalized ratio of magnetic field and current B/I, which is proportional to the ratio of pickup signal to time derivative of magnetic field, should be a constant as frequency increases. The actual decline of B/I is believed to be the result of the eddy current in the beam tube.

Almost all the error field signals remain to be small (< 3%) in this frequency ranges shown in figure 7. These error fields are probably mainly due to the position error of the coil rather than from the eddy current effect. One exception is the 12-pole. This is the first allowed (by symmetry) error field. It reaches about 12% of the normal quad field at 10 KHz.

IV CONCLUSION

The ac losses of the beam tube due to eddy current has been analyzed by using impedance measurements and theoretical calculations. The agreement between these two approaches below 2 KHz gives us confident on estimating beam tube ac losses as functions of current and frequency for the γ_t - jump system design. The magnetic field distortion due to eddy current effect on a stainless steel beam tube is small.

V ACKNOWLEDGEMENTS

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REFERENCES

[1] W. Chou et al., ‘The Design of a γ_t-Jump System for the FNAL Main Injector’, This conference.

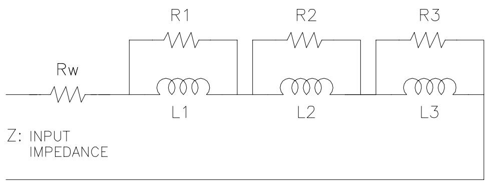

Fig 1 Magnet Equivalent Circuit General Model

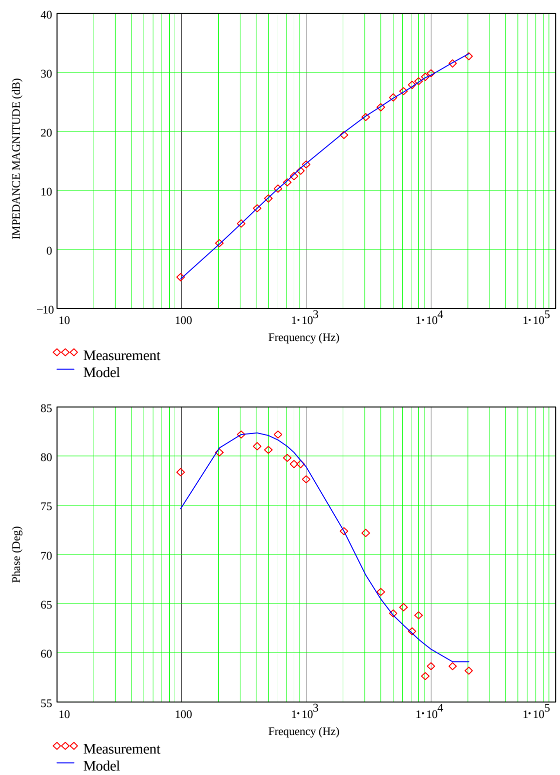

Fig 2 Impedance Plot

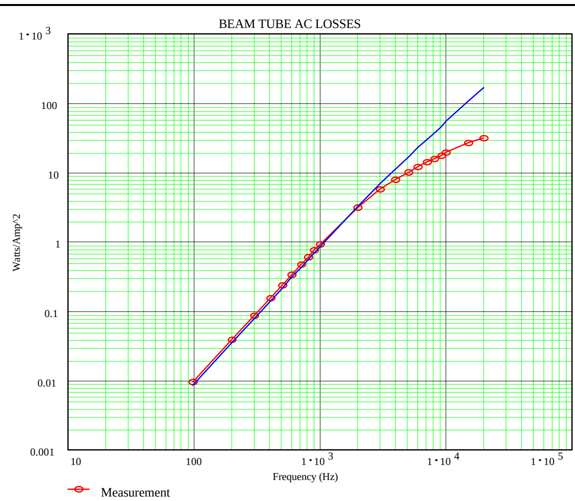

Fig 3 Beam Tube AC Power Losses Plot

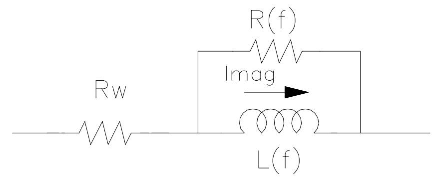

Fig 4 Magnet Circuit Model

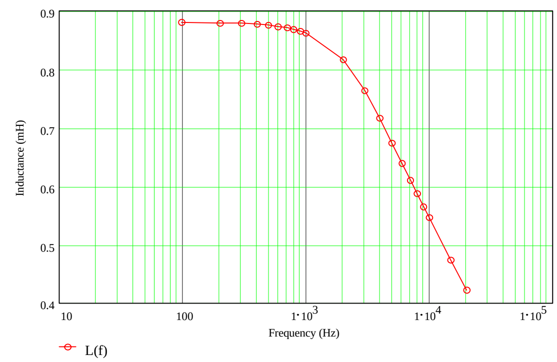

Fig 5 Inductance Plot

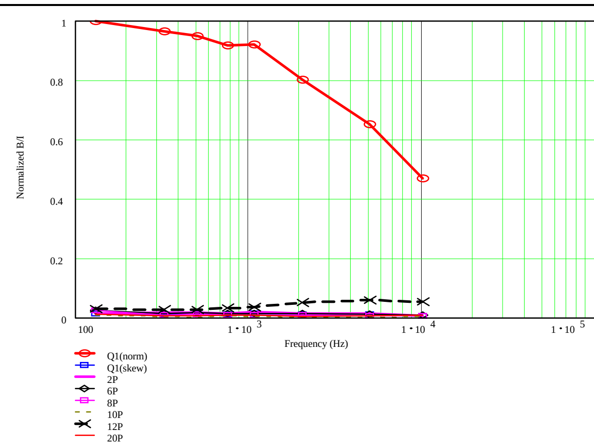

Fig 6 Magnetic Field and Current Transfer Function

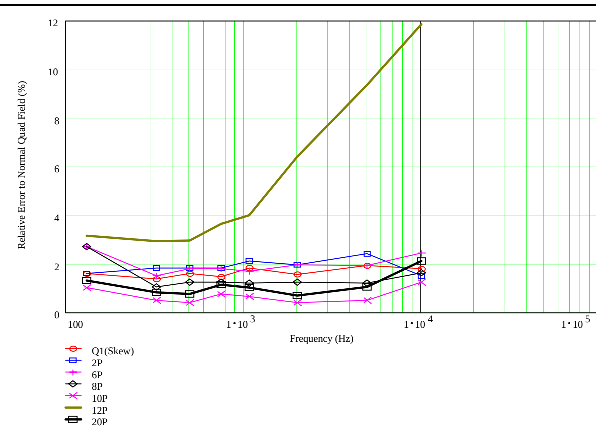

Fig 7 Multiple Field Relative Error