Calculation of Magnetic Field Attenuation by Metalized Coating and Core Material for Pulsed Magnet

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Abstract

The magnetic field inside a thin metalized coating was calculated by solving simultaneous differential equations numerically. Its sheeet resistance which assures a 2 µs flat top during a 6 µs pulse width is about 1 Ω/□ for a storage ring chamber of SPring-8. And we measured the high frequency characteristics of several materials(steel core, ferrite, dust core, amorphous alloy) for the bump magnet. The characteristics at high frequency is much improved by introducing a gap in a magnetic circuit. It might possibly be realized to improve the saturation flux density by replacing the ferrite by each among thin steel, amorphous and dust core when the pulse width is the order of several µs.

1. Introduction

A ceramic chamber is used where an applied magnetic field changes fast. Thus the inside surface of ceramic chamber is covered with metalized coating. If the conductive coating is thicker, the magnetic field inside the chamber is too weak and the heating power is large. While the wall current is hard to flow and electro magnetic wave leaks, if the coating is too thin. A precise calculation is useful for assuring a longer flat top in a short pulse width. It is not easy to calculate analytically the field inside the elliptical chamber in core gap of some distance. In this report we show the attenuation of the magnetic field by easy calculation without using the large code.

In order to make the strong magnetic field during the short time, a kicker and/or a bump magnet are used. Ferrite is used because its high frequency characteristics is good. However the saturation flux density of ferrite is about 0.4T, while that of steel or amorphous alloy is higher than 1T. Though the high frequency characteristics of steel and amorphous is worse than that of ferrite because of eddy current etc., the gap in the magnet improves these characteristics. In order to determine the core material for bump magnets, the permeability and phase shift at high frequency are measured in several material (thin steel, ferrite, amorphous, and dust core). Though many problem are remained to make up the pulse magnet made of amorphous alloy, it was possible by using amorphous or dust core that the magnetic flux density raises up to 0.5 T in 2 µs.

2. Calculation of Attenuated Magnetic Flux

2.1 Method

As illustrated in Fig.1, the following are assumed: 1) the shape of the coating is elliptical; 2) the magnetic pole face is wide so that the effect of edze part is negligible; 3) eddy current can be divided into symmetrical current loops Ii (i=1,2.....).

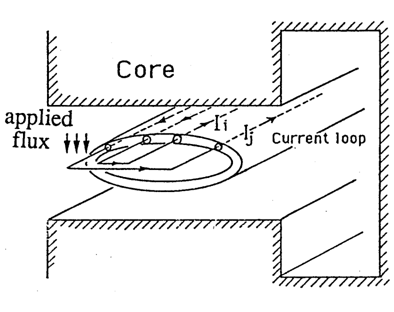

Fig.1. Eddy current loops on a elliptical coating caused by applied magnetic field between the core.

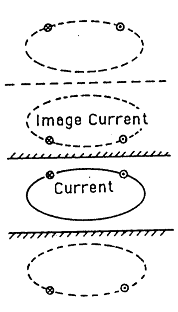

Fig.2. Image currents accounting for the influence of the core.

The interaction between the current loop Ii and Ij is not only direct one but also includes ones through the influence of core. These interactions expressed in terms of mutual inductance Mji are calculated by using image currents, which accounts for the effect of core as shown in Fig.2.

Those flux Φji surrounded in the loop Ii which made by the current loop Ij is written

$$\Phi ji = \Phi(\text{by real } Ij) + \Phi(\text{by image } Ij) \equiv Mji\ Ij \qquad (1)$$

Then, using Faraday's law the following equation are given,

$$-\frac{d\,\Phi(t)ext,i}{dt} = IiRi + Li\frac{dIi}{dt} + \sum_{j\neq i} Mji\frac{dIj}{dt} \quad (i=1,2.....) \qquad (2)$$

where Φ(t)ext,i represents the applied flux by the magnet, Ri is the resistance of the circumference of the loop i, and Li is its self inductance. Eq.(2) is transformed as

$$\frac{dIi}{dt} = \frac{1}{Li}\left(-\frac{d\,\Phi(t)ext,i}{dt} - IiRi - \sum_{j\neq i} Mji\frac{dIj}{dt}\right). \qquad (3)$$

These differential equations can be solved numerically by integrating dIi/dt every very short time using the computer. The hole size of this computer program including graphics is 150 lines in BASIC, and the solver part is only 15 lines. The time step must be chosen so that the oscillation is not generated. This easy method is general and can be used for the calculation of eddy current and the dynamic magnetic field in the dipole magnet. If the coating thickness is much larger than the skin depth, the eddy current must be divided into multi loops on a few layers.

2.2. Results

The geometry of the coating which thickness is uniform and sample of eddy currents distribution are shown in Fig.3. The magnitude of eddy current on wider loop is larger than that of inner loop. It is noted that the current and the electromotive force on several µm coating are very large. Figure 4 shows the behaviour of the magnetic flux density B at the center (x=0) and a shift point (x=1.6 cm) on the median plane, when the coating thickkness (the sheet resistance Rs)is changed. The B at x=0 was almost the same as that at x=1.6 cm. If Rs=0.1 Ω/□, the flat top of 1 µs is impossible. The influence of the current around the edge was neglected in this calculation.

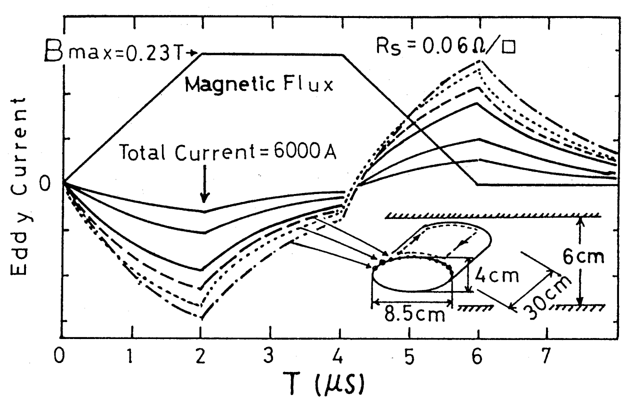

Fig.3. Transition of eddy currents.

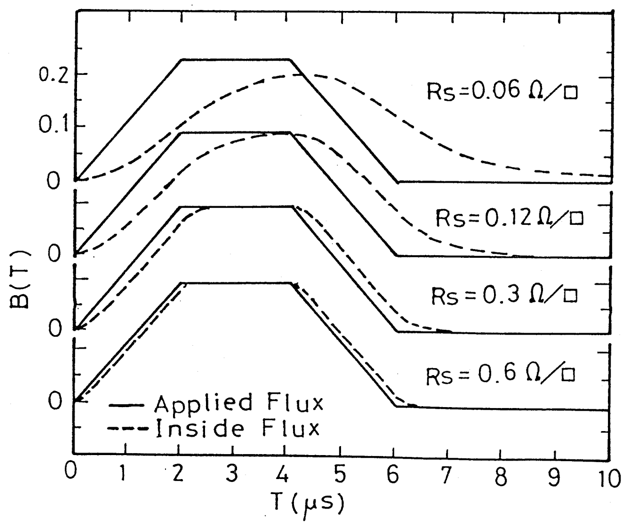

Fig.4. The behaviour of B when Rs is changed.

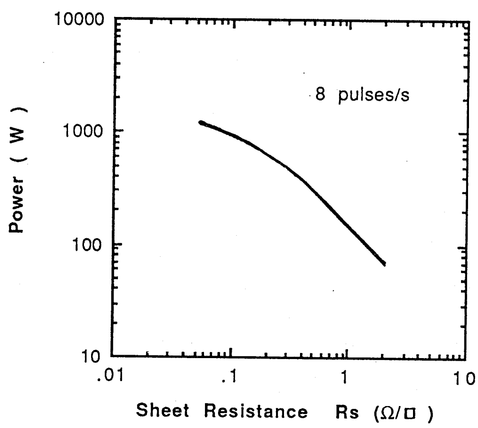

Fig.5. Variation of heat power vs sheet resistance.

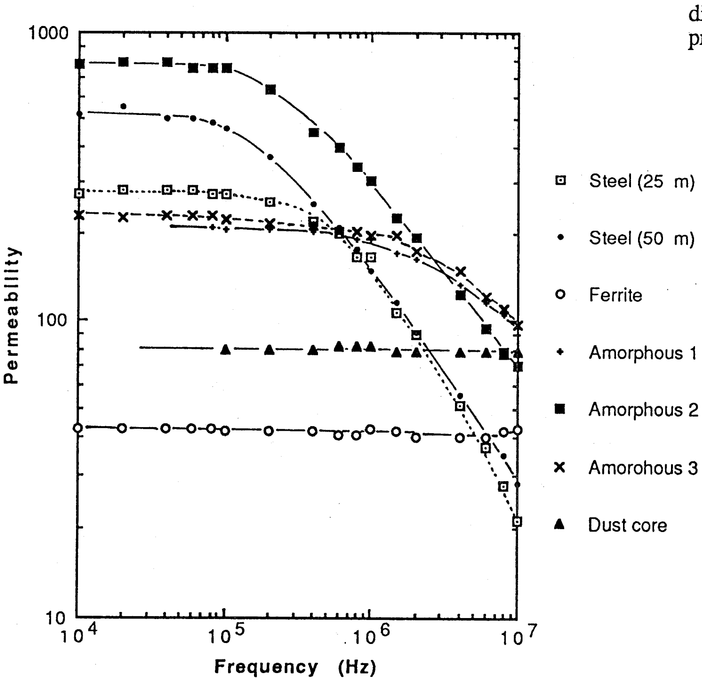

Fig.7. Effective permeability vs frequency.

The averaged heat power including eight pulses during one second, versus Rs is plotted in Fig.5. It is important that the heat power is chosen to be as low as possible because the heat conductivity of ceramic is small. Since the shape of the magnetic flux must be trapezoidal, it is desirable that the sheet resistance is larger than 1 Ω/□.

3. High frequency characteristics of amorphous core etc.

3.1. Permeability and Phase Shift Measurements

The block diagram for measurements is shown in Fig.6. The samples have no gap because the power is limitted up to 100 w at 12 MHz by RF amplifier. The turn numbers are 4 on both primary and secondary coils. The impedance of the resistor 5 Ω for measuring the current at high frequency (~ 10 MHz) is measured by a vector impedance meter and its inductance and capacitance were negligible in this measurement. The diameter of the wire for the coil is 0.2 mm and also stray capacitance of these coils were also negligible. The voltage attenuation by the probe at high frequency (~10 MHz) was neglected. The ring shaped core were excited by the sinusoidal wave of 10 cycles and this excitation was repeated for 1 ~ 10 ms interval for avoiding the temperature rise of the sample.

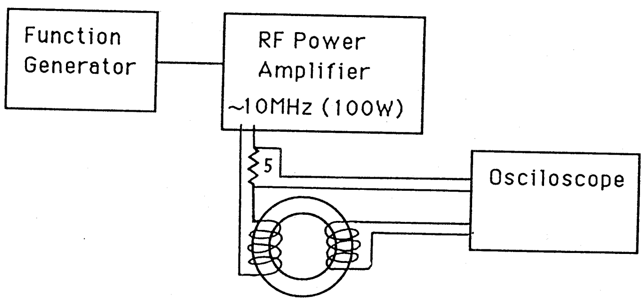

Fig.6.Block diagram for permeability and phase shift measurements.

Figure 7 shows the effective permeabilities vs frequency at B=0.001 T. The core shape made of thin steel (25μm, 50μm) and amorphous 1, 2 are cut core with an about 4 cm x 6 cm frame and that of others is toroidal ones which radius is from 2 cm to 3 cm. Phase shift shown in Fig.8 was obtained by measuring the time difference between two sinusoidal waves, that is, the current of primary coil and dB/dt of secondary coil.

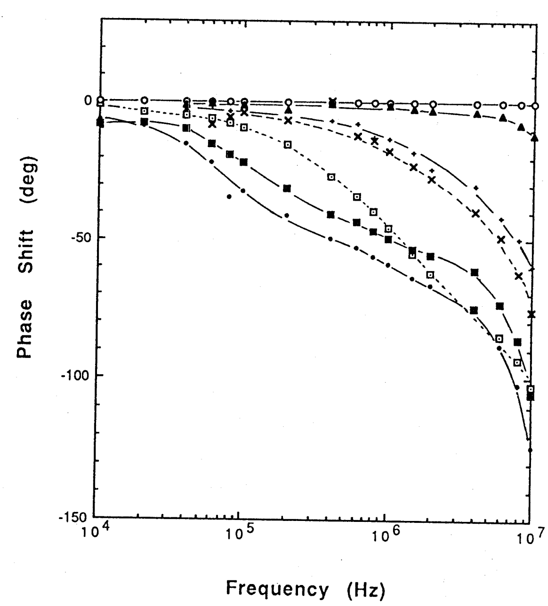

Fig.8. Phase shift vs frequency.

3.2. Calculation of B

As is well known, ac effective permeability consists of real part μ and imaginary one μ'. Thus if no gap, then B is expressed using phase shift θ_o shown in Fig.8 as

$$B=\mu_o(\mu + i\mu')H = \mu_o\sqrt{\mu^2+\mu'^2}\; e^{i\theta_o}H = \mu_o\,\mu_{eff}\, e^{i\theta_o}H. \quad (4)$$

where μ_{eff} represents the effective permeability as,

$$\mu_{eff} = \mu_o\sqrt{\mu^2+\mu'^2} \quad (5)$$

and θ_o is expressed using permeability as

$$\tan(\theta_o) = \frac{\mu'}{\mu}. \quad (6)$$

If there is a gap in the magnetic circuit which length consists of l_g (gap) and l_m (magnet), B is given, using the current I and turn number n

$$B=\frac{nI}{\frac{l_g}{\mu_o}+\frac{l_m}{\mu_o(\mu+i\mu')}} = \frac{\frac{\mu_o(\mu+i\mu')\,n\,I}{l_m}}{(\mu+i\mu')\frac{l_g}{l_m}+1} \quad (7)$$

Therefore it is possible to calculate the B when the circuit has a gap using the effective permeability and the phase shift which are measured without gap. For instance, the relation θ_o (without gap) and θ_g (with gap) is derived from Eq.(7),

$$\tan(\theta_g) = \frac{\tan(\theta_o)}{\frac{\mu_{eff}}{\cos(\theta_o)}\cdot\frac{l_g}{l_m}+1} \quad (8)$$

Though the field in the magnet generally does not obey the superposition principle, in this calculation Fourier integral is used. The shape of exciting current I(t) is assumed to be trapezoidal as shown in Fig.3. This waveform is expressed by Fourier integral. Its coefficients is given by,

$$a(\omega) = \frac{2}{\pi}\int_0^{\infty} I(t)\cos(\omega t)\,dt = \frac{24}{\pi T}\frac{1}{\omega^2}\sin\left(\frac{T}{12}\omega\right)\sin\left(\frac{T}{6}\omega\right) \quad (9)$$

where ω is frequency and T =12 μs. Then, the B(t) of assumed bump magnet is reconstructed as,

$$B(t) = \int_0^{\infty} a(\omega)\, b(\omega)\, \cos(\omega t - \theta_g(\omega))\, d\omega, \quad (10)$$

where $b(\omega)$ is the reduction factor derived from Eq.(7)

$$b(\omega)=\left|\frac{1}{l_g+\frac{l_m}{(\mu+i\mu')}}\right|, \quad (11)$$

and $\theta_g(\omega)$ is calculated from Eq.(8). The μ_{eff} and θ_g are obtained from the data in Figs.7 and 8 using approximate equitions. Figure 9 shows the integrated B in the gap (l_g/l_m = 1/50), this core material is "Steel(50 μm)". The increment during 1.5 μs in the flat top 2μs is 1.0 %. Measured B was obtained by integrating dB/dt, and is shown in Fig.10. The left is in the case l_g/l_m = 2/15, and right l_g=0.

3.3. B-H chracteristics measurement

The calculation in section 3.2 was carried out using the observed values where B is the orded of $10^{-2} \sim 10^{-3}$T. Since actually used B is the order of 0.3 T, the raised B for a short time was examined. The diagram for the measurement was similar to that shown in Fig.6. The primary turn number was determined so that the impedance at 100 kHz is next to the output impedance of power amplifier, i.e, 50 Ω. After the residual magnetization disappeared by exciting the core by fading ac current, a linearly increasing current was applied for 2μs. Then the maximum B was obtained by integrating dB/dt. Only the first pulse was measured by digital storage oscilloscope. Figure 11 shows the maximum B which can be achieved for 2 μs vs H. The B of a ferrite sample saturates at around 0.2 T, while that of steel, amorphous and dust core does not seem to saturate.

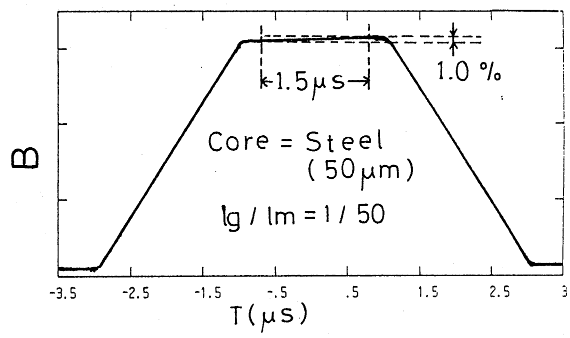

Fig.9 Calculated B using Fourier integral accounting for phase shift.

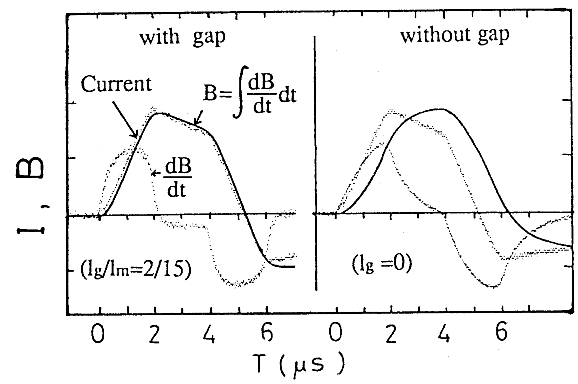

Fig.10. Measured current and dB/dt and integrated B.

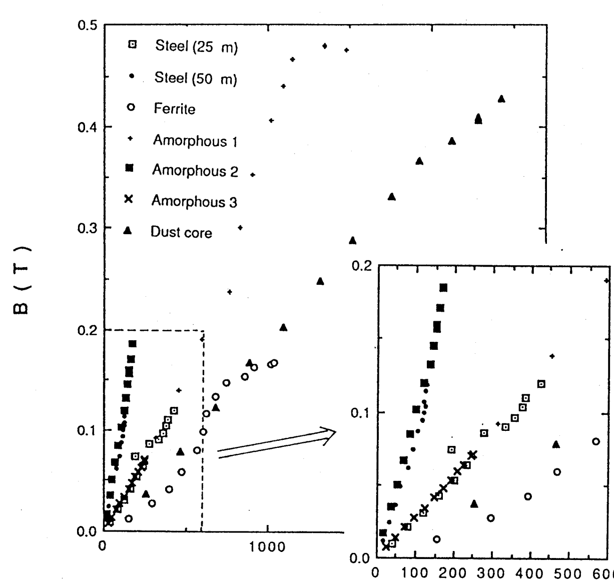

Fig.11. Achieved B against H during 2 μs.

Acknowledgements

We would like to thank the staffs concerned with amorphous alloy in Tokin Corp., Nippon Kinzoku company Ltd., Kawasaki Steel Corp., and Nippon Steel Corp. for preparing the core samples.