Induction Acceleration for Beam-Orbit Control

誘導加速による電子ビーム軌道の位置制御

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Abstract

The electric field $\vec{E}$ induced by a varying magnetic filed can be used for acceleration. Suppose, an electron makes a circular orbit surrounding a magnetic flux Φ which is changing with time. According to Maxwell equations, $\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi}{dt}$, where the line integral is along the electron orbit, i.e. the acceleration voltage per turn is expressed by the flux change. A well-known example of application of this scheme is the betatron.

In this paper, application of this acceleration scheme to a 150 MeV electron ring at Hiroshima University is studied.

The electron beam injected by microtron loses its energy by 59.7 eV per turn due to synchrotron radiation. As the ring has not any accelerations instruments, the beam orbit moves toward the inner wall of the vacuum pipe. It is about 3 ms from the time of injection to the dumping against the beam pipe. If the loss energy of the beam is compensated by induction acceleration, the beam can keep circulating for longer time.

To induce the accelerating electric field, a troidal coil wound on an iron core is placed across the electron beam line. It is necessary that $d\Phi/dt$ is constant during the operation. The maximum value of Φ is determined by the saturation and the cross section of the core material. The iron core saturates at about 2 Tesla. In order to keep the constant acceleration voltage for 6 ms, the cross section of the iron core should be more than 0.12 m^2. It is very big size and heavy; total core weight is about 2 ton.

The inductance L of the troidal coil is not constant as the magnetic permeability μ of the electromagnetic steel sheet depends on the *B-H* hysteresis curve. To make the constant alteration of the magnetic field, we need to shape the current pulse form in accordance with the variation of the μ. A variable current supply that can make a rapid pulse with an arbitrary is necessary. We made a software which can program the current form on general Windows OS for a Yokogawa DAC module. We also designed a small-sized model of an induction magnet, which has 1/8 cross section of the iron core to be installed. Combining the software and the small-sized model, the magnetic permeability of the core material is measured to determine the most suitable form.

Contents

Chapter 1

Introduction

New types of induction accelerators are recently attracting interest: A novel induction acceleration in a fixed-field alternating-gradient magnet was proposed by T. Ohkawa et al. It was the first application of this scheme to a circular accelerator [1][2]. Another example is a 3.6 MeV induction LINAC constructed in collaboration of High Energy Accelerator Research Institute (KEK) and Japan Atomic Energy Research Institute (JAERI). Now, the induction synchrotron for KEK 12 GeV Proton Synchrotron is being constructed [3][4][5]. To accelerate protons up to 12 GeV is a hard task and we need to develop many big induction magnets and switching systems for high frequency current.

On the other hand, with this scheme we can easily give a small amount of energy enough to compensate the synchrotron radiation loss at a small-scale circular storage ring. We can also control the position of the beam orbit by adjusting the accelerating voltage.

We examine the applicability of such an acceleration scheme to a 150 MeV small-scale electron ring at Hiroshima University which is called REFER, Relativistic Electron Facility for Education and Research.

In Chapter 2, we discuss about the actual situation of the REFER ring and the significance of application of induction acceleration. In Chapter 3, we discuss about the possible difficulties to be overcome. In Chapter 4, we discuss about the measurement using the small-sized model of an induction magnet.

Chapter 2

Possible application of induction acceleration to REFER

2.1 The 150MeV electron ring REFER

REFER is an electron beam ring at Hiroshima University in which an electron beam goes along the circular orbit of circumference of 13.5 m. This ring has neither an acceleration structure nor an electron gun. It accepts a 150 MeV electron beam from a microtron that belongs to Hiroshima Synchrotron Radiation Center, Hiroshima University (HiSOR).

The injection beam parameters depend on those of microtron as shown Table1-1 [6], while Table1-2 shows the REFER basic parameters [7].

Output Beam Energy	150 MeV
Input Beam Energy	80 keV
Peak Beam Current	2-10 mA
Beam Pulse Width	0.2-2 μsec
Repetition	0.2-100Hz
Beam Emmitance	0.5π mm-mr (1σ)
Energy Dispersion	±0.1% (1σ)
Mag. Field of Bending Mag.	1.23 T
Magnetic Field Gradient	0.14 T/m
Pole Gap of Bending Mag.	10 mm
Number of Turns	25
Energy Gain per Turn	6 MeV
Accelerator Structure	8 Cell Side-Coupled Cavity
Accelerator Bore	10 mm
RF Frequency	2856 MHz
RF Field Gradient	15 MV/m
RF Wall Loss	1.5 MW (Max.)
Beam Loading	2.0 MW (Max.)

Table1-1 The microtron parameters

Electron Energy	150 MeV
Length of Beam Orbit	13.5 m
Long Straight Section	2.5 m
Short Straight Section	0.7 m
Field of Bending Mag.	0.67 T
Radius of Curvature	0.75 m
Frequency	10-100 Hz
Horizontal Tune	1.39
Vertical Tune	1.65
Number of Bending Mag.	8
Value n of Bending Mag.	0.55

Table1-2 The REFER basic parameters

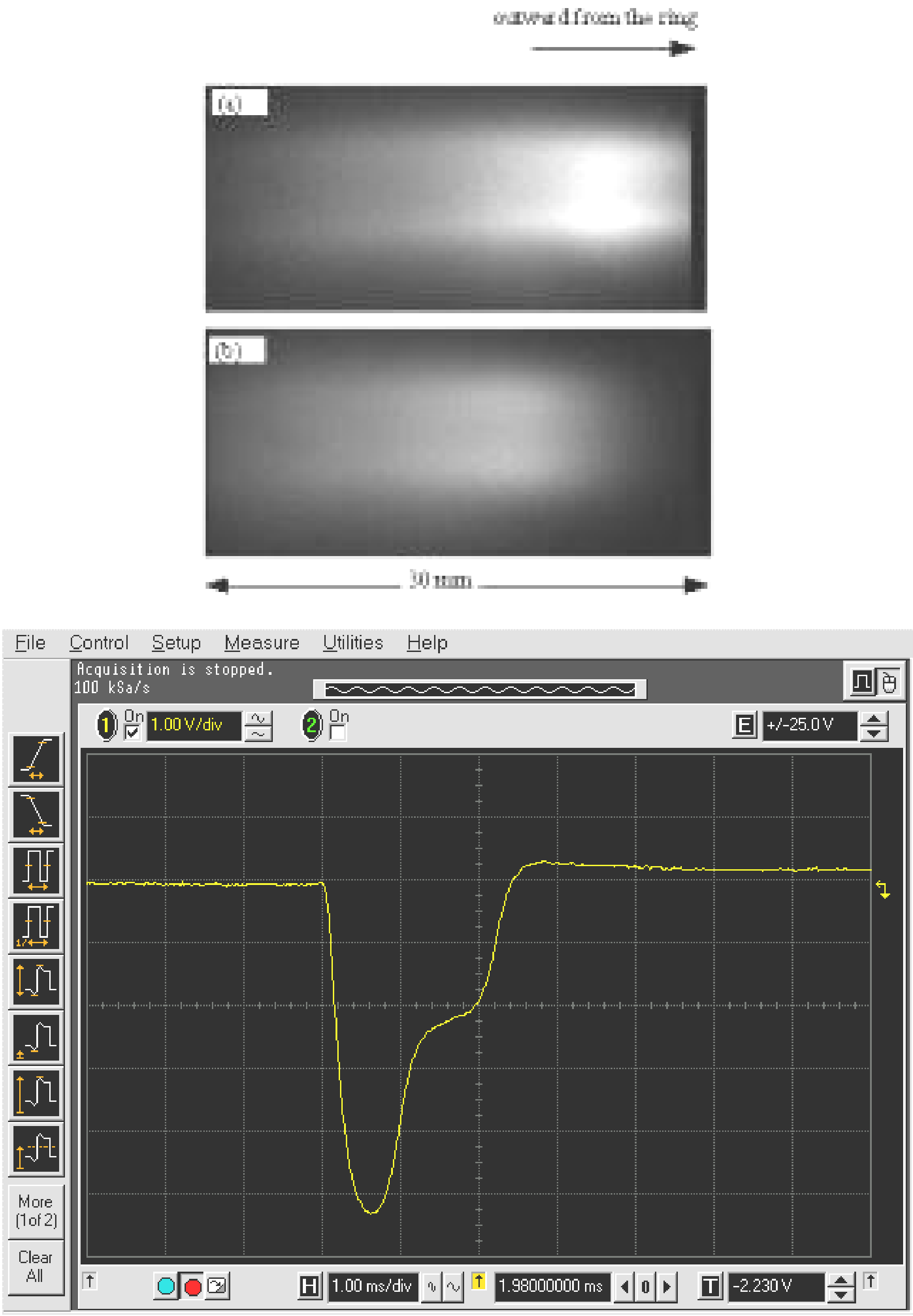
This ring is used to study parametric x-rays, laser compton scattering, and the development of a x-ray source based on new mechanism. The ring has an inner target set in a vacuum chamber placed on the beam orbit.

2.2 The present situation of REFER

The electron beam injected by the microtron loses its energy by 59.7 eV per turn due to synchrotron radiation. As the ring has not any acceleration instruments, the beam orbit moves toward the inner wall of the vacuum pipe.

The upper photographs in Fig.2-1 show typical examples of images recorded by a synchrotron monitoring camera. The bottom shows the oscilloscope output of the ring current monitor. The horizontal axis is the time in 1.00 ms/div. The vertical axis is the output voltage of the current monitor in 1 V/div. It can be converted to the circulating current using a conversion factor measured in a previous experiment [8]; 5 V on the current monitor corresponds to 100 mA.

The time indicated as (a) in Fig.2-1 is the beam injection time. From the injection time to 0.5 ms voltage changes from 0 V to about 5.5 V. This part of the curve is governed by the rise time of the electronic circuit and does not necessarily reflect the pulse shape of the beam current. According to Fig.2-1 at the point (b), about 1.5 ms after the injection, voltage is about the half of the maximum. The photograph (b) of the upper part of Fig.2-1 is the beam orbit observed at the time (b). The right side of the photograph is outward side of the ring and the width of the photograph corresponds to 30 mm in the actual space. Comparing (a) with (b), the beam intensity is high and the beam orbit is in the right side at the time (a), and at the (b) the beam intensity is lower and the beam orbit has moved toward the inner side of the vacuum pipe by about 15 mm. It is about 3 ms from the time of injection to the dumping against the beam pipe.



(a)　　　(b)

Fig.2-1　The photographs of the synchrotron monitor and the current monitor

2.3 The improvement plan

We want to improve the REFER ring, at least in the following 2 points.

(1) To increase the beam life time

(2) To make the orbit radius constant without depending on time

In our plan the loss energy 59.7 eV per turn due to synchrotron radiation of the beam is compensated using the scheme of the induction acceleration. If the loss energy of the beam is properly compensated by induction acceleration, the beam can keep circulating for longer time. Furthermore, we will be able to control the beam orbit by adjusting the rate of the flux change in the induction coil.

Another point is that we may possibly reduce the unwanted radiation caused by the collision of the low energy electrons with the vacuum pipe by properly controlling the beam dumping time.

Chapter 3

The application of induction acceleration scheme to REFER

3.1 The principle of induction acceleration

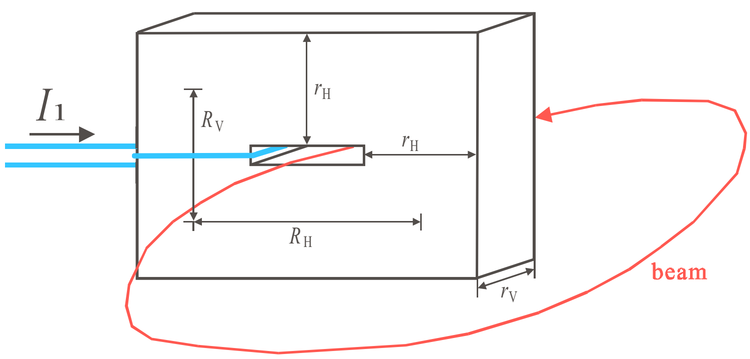
The principle of induction acceleration is derived from the Maxwell equations. The electric field $\vec{E}$ induced by a varying magnetic filed flux is related to the electromotive force V_0 in the following way;

$$\oint \vec{E} \cdot d\vec{l} = (-)\frac{d\Phi}{dt} = V_0 \quad . \qquad (3\text{-}1)$$

This means that an electron is accelerated by e$V_{0,}$ if it makes a circular orbit, following the integration path in (3-1), surrounding a magnetic flux Φ that is changing with time. For applying to REFER we require the voltage V_0 to be 59.7 V.

3.2 Saturation of the core material

To induce the accelerating electron field, a troidal coil wound on an iron core is placed across the electron beam, as schematically illustrated in Fig.3-1.



$R_H = 0.45$ m
$R_V = 0.35$ m
$r_H = 0.3$ m
$r_V = 0.4$ m

Fig.3-1 The troidal coil for REFER

The iron core size is determined the maximum value of the magnetic flux density *B*. As described in Chapter 2 it is necessary that $\frac{d\Phi}{dt}$ is constant during at least 3 ms. The maximum value of Φ is determined by the saturation and the cross section *S* of the core material.

According to $\Phi = BS$, $S = r_H r_V = 0.12\ \mathrm{m}^2$,

$$V_0 = \frac{d\Phi}{dt} = \frac{SdB}{dt} = 59.7 \qquad \frac{dB}{dt} \approx 497 \tag{3-2}$$

With the knowledge that the iron core saturates at about 2 Tesla, we have;

$$\Delta B = 497\,\Delta t < 2\ \text{Tesla} \qquad \Delta t < 4.02\times10^{-3}\ \text{s} \tag{3-3}$$

Thus, the iron core saturate after about 4 ms.

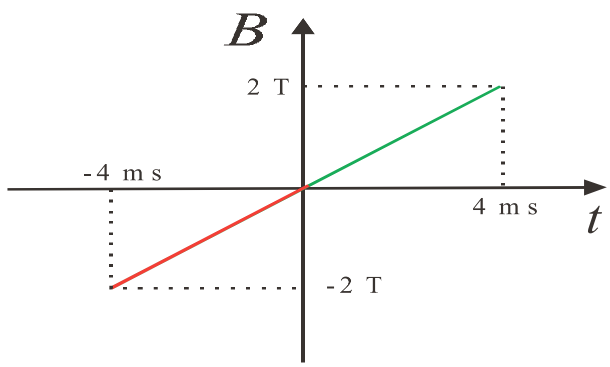


Fig.3-2 During 8ms the beam can accelerate

If the initial value of *B* starts from –2 Tesla, during total 8ms the beam can be accelerated in the same electric field strength. (Fig.3-2)

The iron core, which has the cross section 0.12 m^2, is very big size and its weight is about 2 ton.

According to the Ampere's law,

$$\oint \vec{H}\cdot d\vec{l} = HI_1 \qquad lH = NI_1 \qquad H = \frac{N}{l}I_1 \tag{3-4}$$

where *H* is the magnetic field, *N* is the turn number of the troidal coil, and the line integral is along the magnetic flux i.e. l is the average length of the core.

The magnetic flux Φ that goes through the coil is expressed by

$$\Phi = BS = \mu HS = \mu \frac{NS}{l} I_1 \tag{3-5}$$

where μ is the magnetic permeability of the core material.

The inductance L of the coil is

$$L = \mu \frac{S}{l} N^2 . \tag{3-6}$$

If L does not depend on time, a constant electron field 59.7 V to accelerate the electron beam per turn might be achieved by satisfying the relations

$$\begin{gathered} V_0 = (-)\frac{d\Phi}{dt} = L\frac{1}{N}\frac{dI_1}{dt} = 59.7 \\ \therefore \frac{dI_1}{dt} = 59.7 \times \frac{N}{L} \quad \text{A/s} \end{gathered} \quad . \tag{3-7}$$

Obviously, the above considerations are not enough to determine the rate of change of the magnet current I_1 because the inductance is time dependent due to the nonlinear *B-H* relation as discussed in the next section.

3.3 The *B-H* curve

In this section, we study the dependence of the *B-H* hysteresis of the core material.

The inductance L of the troidal coil is not constant as the magnetic permeability μ of the electromagnetic steel sheet depends on H. In the induction acceleration we must supply a rapidly varying current pulse to the troidal magnet. Ordinary iron cores suffer from the effect of the eddy current. We need the iron core that has a less effect of the eddy current and we chose the electromagnetic steel sheet of silicon steel is KAWATETSU 30RG120. We make a core by stacking the 0.3 mm thick sheets with varnished insulator on the surface.

Fig.3-3 is a model hysteresis curve approximated by an arc-tangent function imitating the data of 30RG120 in the catalog [9]. The horizontal axis is H in A/m and vertical is B in Tesla. This function is

$$B = a\tan^{-1}\left(\frac{H-b}{c}\right).$$

$$\begin{cases} a = 1.114 \\ b = 6.2 \\ c = 2.232 \end{cases} \qquad (3\text{-}8)$$

In this consideration the current goes up only and the value of the core saturation is 1.75 Tesla. When the current goes down the *B-H* curve is different from (3-8).

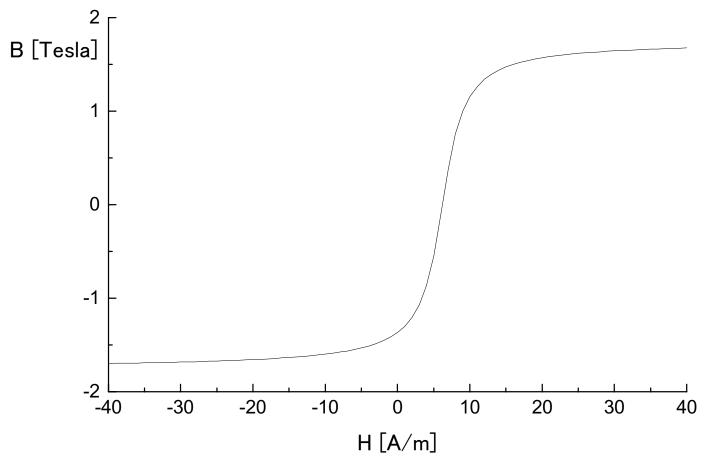


Fig.3-3 A model hysteresis curve of 30RG120 when the current goes up only

3.4 Determination of magnetic permeability

The coil turn number to be installed beam line is 2. (N = 2) From Ampere law the relationship between H and I_1 is

$$H = \frac{N}{l} I_1 = 1.25 I_1 \ . \qquad (3\text{-}9)$$

As the magnetic permeability μ is the inclination of the *B-H* curve,

$$\mu = \frac{\partial B}{\partial H} = \frac{a}{1+\left(\frac{H-b}{c}\right)^2} \ . \qquad (3\text{-}10)$$

According to Fig.3-3, we see that μ is almost constant at the neighborhood of the point of B = 0. Thus, $\mu\big|_{B=0} = \frac{\partial B}{\partial H}\Big|_{B=0} = a = 1.114$, we regard as the inclination is constant. To make the induction acceleration voltage 59.7 V, $\frac{dI_1}{dt}$ is

$$\frac{dI_1}{dt} = 59.7 \times \frac{N}{L} = 59.7 \times \frac{l}{\mu NS} = 357.2 \text{ A/s} \quad . \tag{3-11}$$

Combining the model *B-H* curve and $\frac{dI_1}{dt} = 357.2$ A/s, $\frac{d\Phi}{dt}$ alteration plots is shown in Fig.3-4. The left vertical axis is $\frac{d\Phi}{dt}$ V (red line plotted), the right vertical axis is I_1 A (blue line plotted), horizontal axis is time. The numerical result shows the territory of $\frac{d\Phi}{dt}$ = const is few, thus the dependence of μ appears $\frac{d\Phi}{dt}$ alteration directly. In the experiments we measure directly $\frac{d\Phi}{dt}$ value alteration. So, we can determine μ by getting the $\frac{d\Phi}{dt}$ alteration when $\frac{dI_1}{dt}$ is constant.

$$\frac{d\Phi}{dt} = \mu \frac{NS}{l} \frac{dI_1}{dt}$$

$$\mu = \frac{l}{NS} \frac{1}{\left(\frac{dI_1}{dt}\right)} \frac{d\Phi}{dt} \quad . \tag{3-12}$$

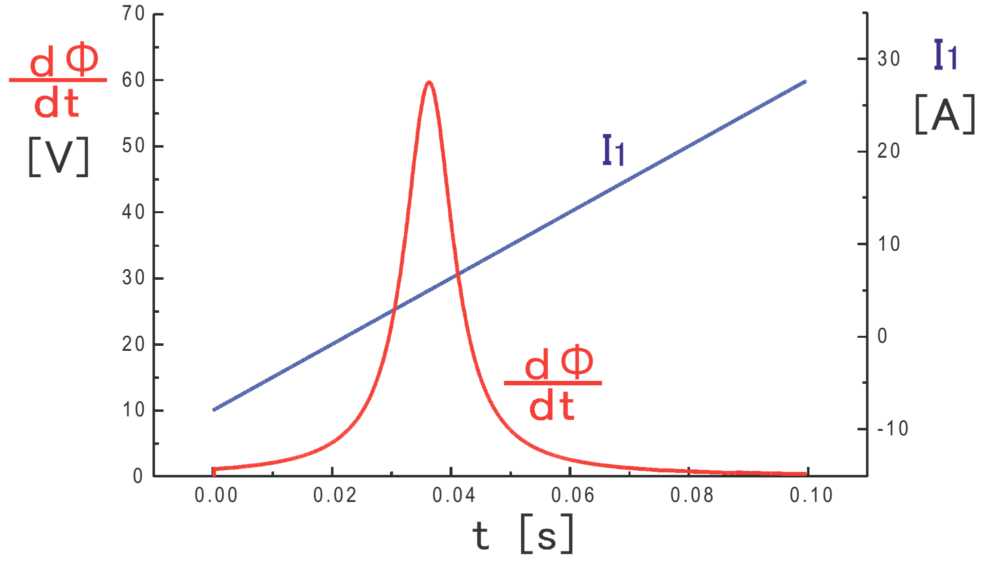


Fig.3-4 $\frac{d\Phi}{dt}$ alteration plots in $\frac{dI_1}{dt} = 357.2$ A/s

3.5 The energy conservation

In section 3.4, $\frac{dI_1}{dt}$ and V_1 are determined independently from the beam current I_2 to accelerate. The beam-energy loss by the synchrotron radiation is directly proportional to the value of the beam current, on the other hand the providing power V_1I_1 is not concerned with I_2 at all. We wonder about the energy relationship between revenue and expenditure. In this section we discuss about the energy conservation. We use a simplified model which is shown as an equivalent circuit in Fig.3-5.

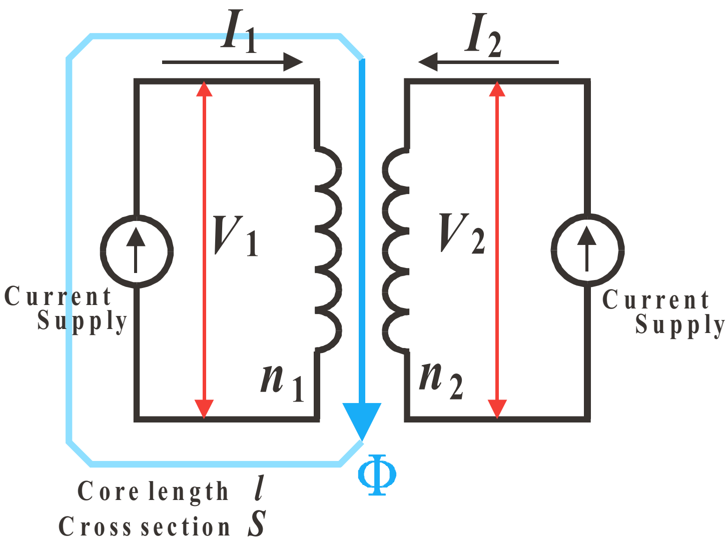


Fig.3-5 The simple model to estimate the energy conservation

The left hand side shows the current supply and a troidal coil which has a core cross-section S and a core average length l. The core is made of ideal magnetic material with constant magnetic permeability μ and can store limitless magnetic energy. The current supply is the ideal current supply element. I_1 is the current value and V_1 is the voltage across the coil whose turn number is n_1. Φ is the magnetic flux through the core magnet cross-section. The right hand side of Fig.3-5 represents the electron beam. The current supply makes the current form shown in Fig.3-6 (c), the current value I_2 corresponds to the beam current. n_2 is the turn number of the coil, in this case $n_2 = 1$. V_2 is the induction acceleration voltage $V_2 = 59.7$ eV.

The magnetic flux Φ is

$$\Phi = BS = \mu HS = \frac{\mu S}{l}\left(n_1 I_1 + n_2 I_2\right) \ . \tag{3-13}$$

The voltage produced by the time variation of Φ is

$$V_1 = n_1 \frac{d\Phi}{dt} = \frac{n_1 \mu S}{l}\left(n_1 \frac{dI_1}{dt} + n_2 \frac{dI_2}{dt} \right) . \tag{3-14}$$

$$V_2 = n_2 \frac{d\Phi}{dt} = \frac{n_2 \mu S}{l}\left(n_1 \frac{dI_1}{dt} + n_2 \frac{dI_2}{dt} \right) . \tag{3-15}$$

From V_1 and V_2,

$$V_2 = \frac{n_2}{n_1} V_1 . \tag{3-16}$$

Suppose we give the one period triangle current form I_1,

$$I_1 = \begin{cases} at - b & \left(0 \le t \le \frac{2b}{a} \right) \\ -at + 3b & \left(\frac{2b}{a} \le t \le \frac{4b}{a} \right) \end{cases} . \tag{3-17}$$

I_1 current form is shown in Fig.3-6 (a). The derivative of I_1 is shown in (b). During the period $0 \le t \le \frac{2b}{a}$ the beam current is constant $I_2 = I_2$ and during $\frac{2b}{a} \le t \le \frac{4b}{a}$ the beam current is 0. I_2 current form is shown in Fig.3-6 (c) and $\frac{dI_2}{dt}$ is shown in (d). In Fig.3-6 (d), spikes due to the derivative of step functions, i.e. delta functions, show up.

V_1 and V_2 are derived from I_1 and I_2 current forms, which are shown in Fig.3-6 (e) and (f), respectively. The power at the instance is shown in (g) and (h).

The energy conservation at the moment is

$$V_1 I_1 + V_2 I_2 = \frac{dE_{\text{mag}}}{dt} \tag{3-18}$$

where, E_{mag} is the stored magnetic energy in the core iron magnet.

The time integration from 0 to $\frac{4b}{a}$ (one cycle) is

$$\int V_1 I_1 dt + \int V_2 I_2 dt = \int \frac{dE_{\text{mag}}}{dt} dt . \tag{3-19}$$

In the integrated power of $V_1 I_1$, contributions from two spikes of the delta function, (shown on Fig.3-6 (g)), add ups to be

$$\int V_1 I_1 dt = 2 \times \left(-\frac{n_1 \mu S}{l} b n_2 \times \int I_2 \delta(t) dt \right) = -\frac{2 n_1 n_2 b \mu S I_2}{l} . \tag{3-20}$$

The integrating power of $V_2 I_2$ remains the area of the rectangular. (shown on Fig.3-6 (h))

$$\int V_2 I_2 dt = \frac{n_1 n_2 \mu Sa}{l} \times I_2 \times \frac{2b}{a} = \frac{2n_1 n_2 b\mu SI_2}{l} \quad . \tag{3-21}$$

The equation (3-19) is

$$\int (V_1 I_1 + V_2 I_2) dt = \int \frac{dE_{\mathrm{mag}}}{dt} dt = 0 \quad . \tag{3-22}$$

After the one cycle the magnetic energy E_{mag} is reset.

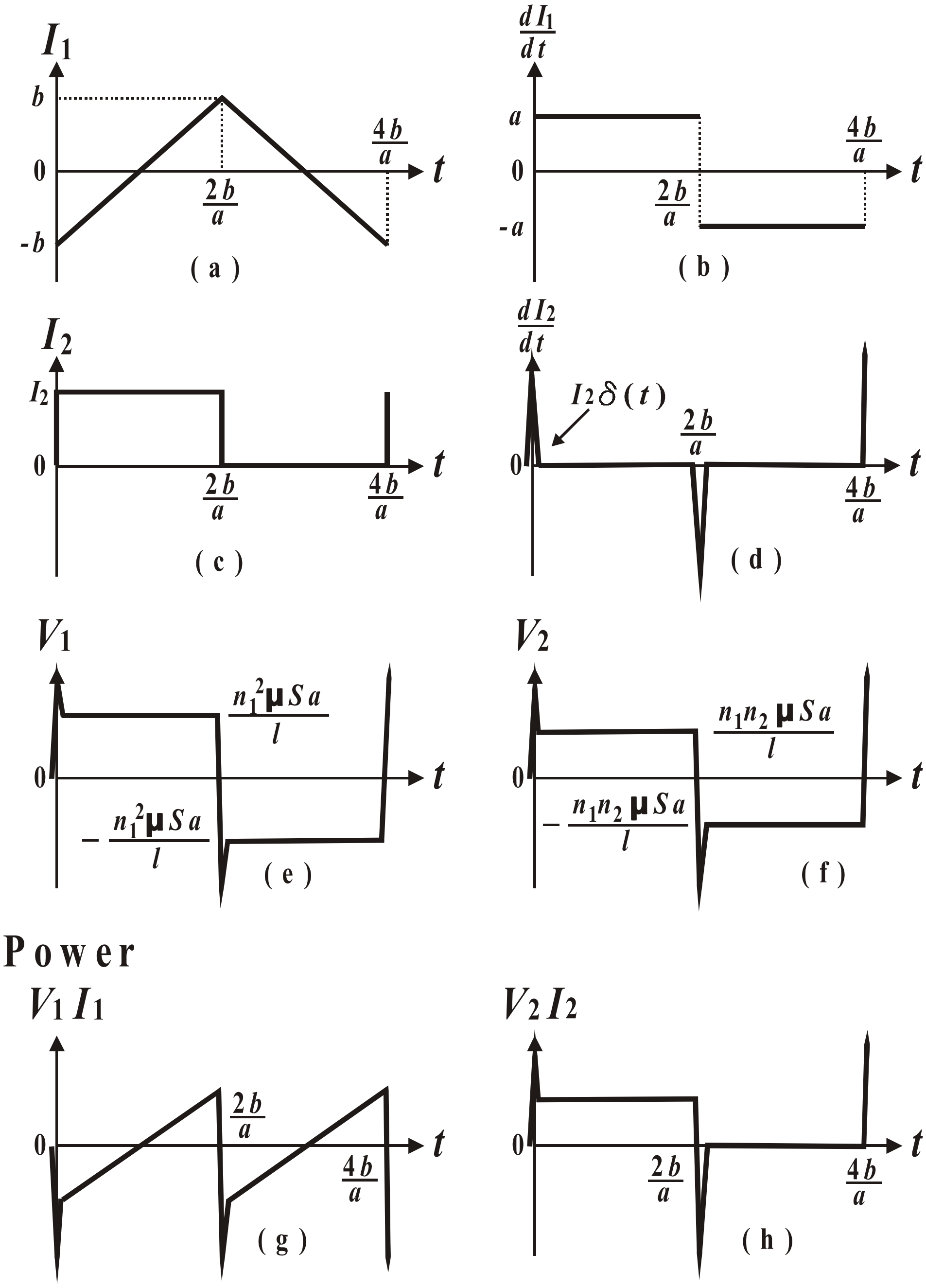


Fig.3-6 The supplement figures to estimate the energy conservation

3.6 A current form generator

To make the constant growth of the magnetic field, we need to shape the current pulse form in accordance with the variation of μ. As we control the current supply using a DAC module, we make software for the Yokogawa DAC module (WE7000 series). We made it on the general OS Microsoft Windows Operating System so that everyone can easily use it..

Basic operation of the software is such that at a specified time the corresponding current value is sent to the DAC module. The program was coded in Borland C++ Builder 4, using Windows DLLs of Yokogawa module control. DLL, Dynamic Link Library, is made from functions that can be used in various programming languages. We can use the functions including the DLLs by making declarations in the first section of the program.

More detail of the usage of DLLs is described in Appendix. In Fig.3-7 shown is the control window of the first version. Through this window, it is possible to send a control command to the module, to get the value of the current voltage of the module, and to set an arbitrary value used in a manual operation.

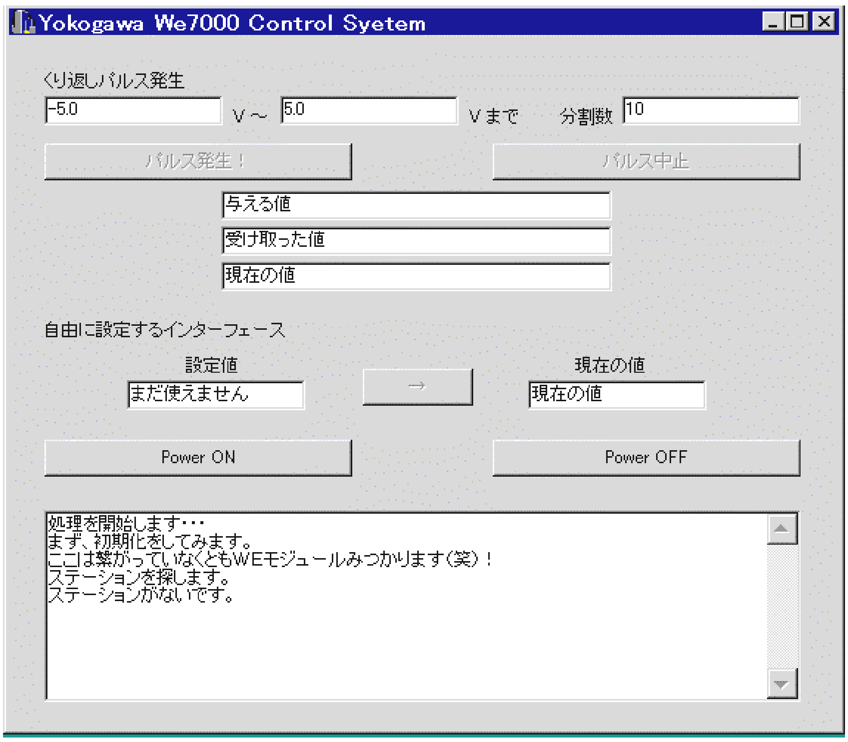


Fig.3-7 A software of controlling the DAC module

Chapter 4

Experiments, Results, and Discussions

4.1 The magnet cores

We observed the voltage produced by the induction acceleration using two small model-magnet cores. The first one is made from ordinary steel sheet of 10 mm thickness. The shape and the size are shown in Fig.4-1. The left hand is the drawing and the right is the photograph.

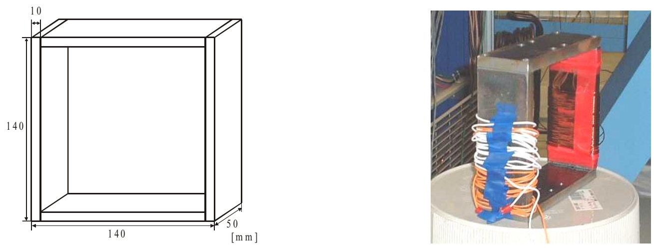


Fig.4-1 The small magnet core made from ordinary steel

The second one is the 1/8 model that has 1/8 cross section of the magnet to be installed, which is proposed in Chapter 3. It is made from the same material as the one used for the magnet core to be installed; 30RG120 electromagnetic steel sheet. This could be installed to the REFER beam line because its height is the same as that of the beam line and the central hole allows the beam pipe to go through. Theoretically if this 1/8 model were installed to the beam line, the electron would be accelerated by 7.46 V per turn during about 8 ms. The 1/8 model is shown in Fig.4-2.

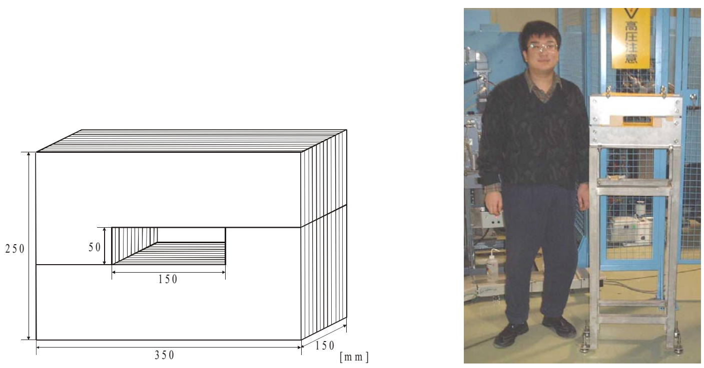


Fig.4-2 The 1/8 model magnet made from 30RG120

The right hand is the photograph of the 1/8 model. The author of this work, who is 170 cm tall, is standing near by.

4.2 Setup of the experiments

Setup of the experiments is shown in Fig4-3.

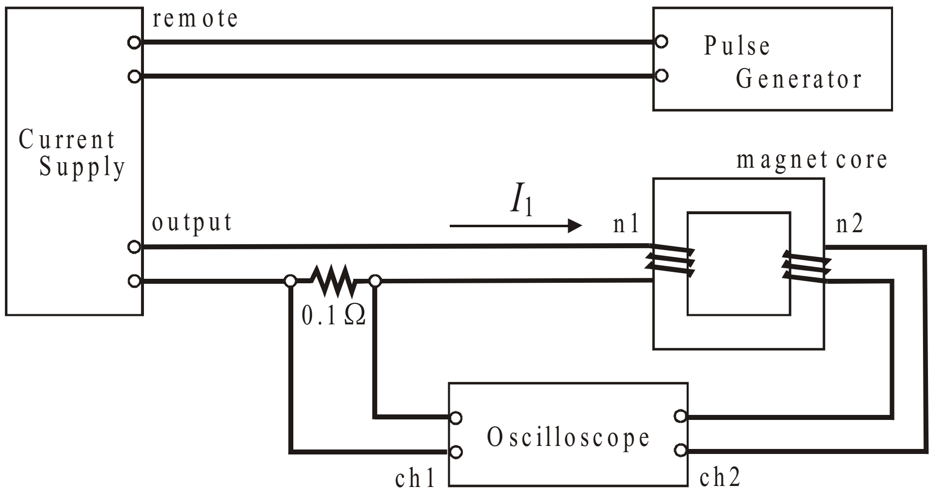


Fig.4-3 The setup of the experiments

We use a current supply and a pulse generator as the high frequency pulse supply. This current supply can be controlled by an analog remote pulse, if we want 1 A output, 1 V receives the remote terminal of the current supply. In this experiments, we require that $\frac{dI_1}{dt}$ is constant during a pulse width, the pulse shape for the remote controlling input is taken to be triangular.

This current supply output range is –5 A to 5 A, –35 V to 35 V. On the oscilloscope, ch1 is the coil ampere monitor measured by the voltage across a resister of nominal resistance 0.1 Ω . It turned out, however, that its resistance is 0.14 Ω by the measurement with a resistance meter.

In the output of the digital oscilloscope the yellow line is the ch1 input, the green line is the ch2 input. In Fig.4-4 ch1 is the output of the pulse generator voltage which indicates the output ampere of the current supply. Ch2 is the voltage across the resister shown in Fig.4-3. From theses outputs, we see that the resistor voltage 700 mV corresponds to 5 A.

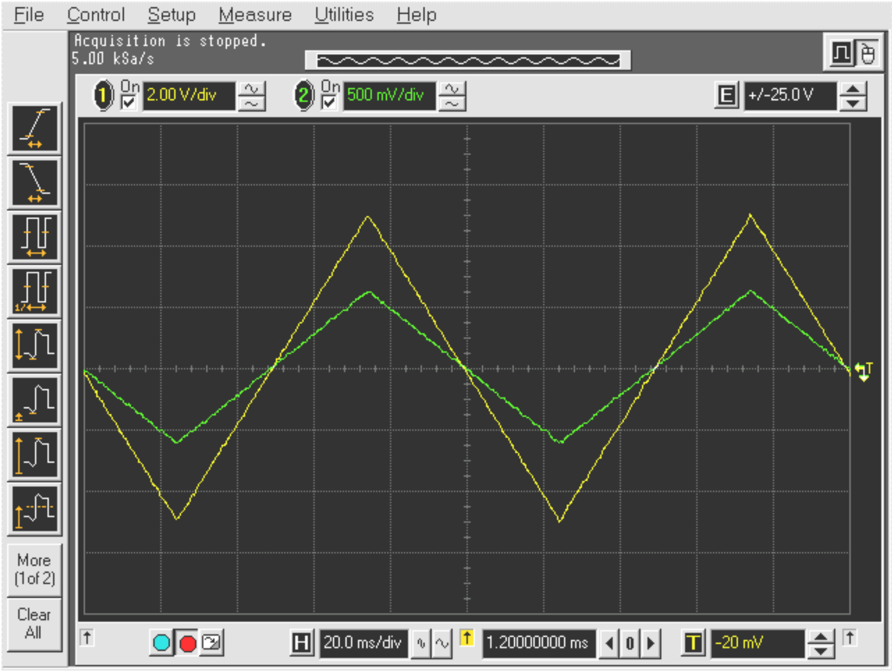


Fig.4-4　The coil ampere monitor from the voltage

In Fig.4-3 n1 and n2 of the magnetic core are turn numbers of the coil, respectively. The coil current through the n1 turn coil is I_1. The small ordinary steel core has 40 turns for n1 and 35 turns for n2. The 1/8 model has 2 turns for n1 and 10 turns for n2. The purposes of this experiment are (i) the measurement of the magnetic permeability μ of the material used for the core, and (ii) the measurement of the acceleration voltage produced by the $\frac{dI_1}{dt}$ alteration.

4.3　Results and Discussions

Using the small general steel core, we supplied triangular wave current obtained from the pulse generator. Fig.4-5 (1) is 10 Hz pulse, Fig.4-5 (2) is 50 Hz pulse. Fig.4-5 (3) is μ calculated with the formula (3-12) using the 50 Hz data.

The μ curve shows unexpected results. Especially, μ should be only plus or minus value, while the results show μ takes both plus and minus values. Furthermore the maximum value of μ shows about 2×10^{-7}. Comparing general steel magnetic permeability is $4\pi\times10^{-4}$, the result is unreasonably small. And the result is smaller than a vacuum magnetic permeability $4\pi \times 10^{-7}$. The measurement of μ shows under the field strength –385 < H < 385 A/m. In this region the core material is not saturated.

The behavior of induced voltage from the ordinary iron core could not be explained by an expected *B-H* curve. This suggests that some other effect, such as the eddy current. One of the way to research other effects is that we should measure the magnetic flux behaviors of within the core material.

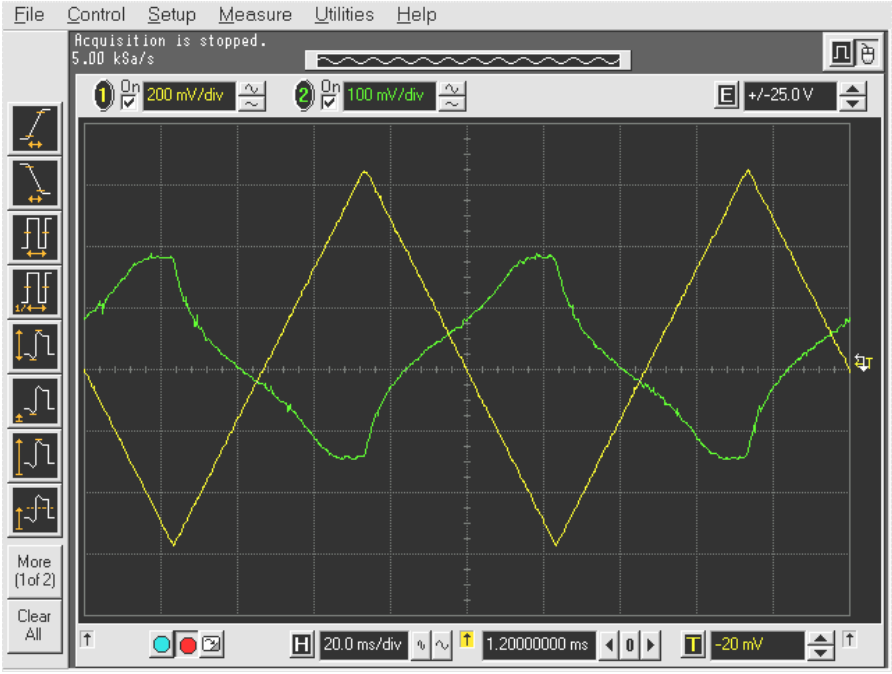
The results of the experiments with the 1/8 model magnetic core are shown in Fig.4-6. Fig.4-6 (1) is the result with the 100 Hz triangle pulse, Fig.4-6 (2) is 500 Hz pulse. Fig.4-6 (3) is μ alteration plotted for 100 Hz.

According to Fig.4-6 (3) the μ is the constant value about 0.1 H/m. This result is reasonable judging from the *B-H* curve shown in Fig.3-3. At this ampere range, the electromagnetic steel sheet is not saturated under the field strength –12.5 < H< 12.5 A/m. The maximum value 1.114 of μ given in the data sheet of the steel supplier is not observed.

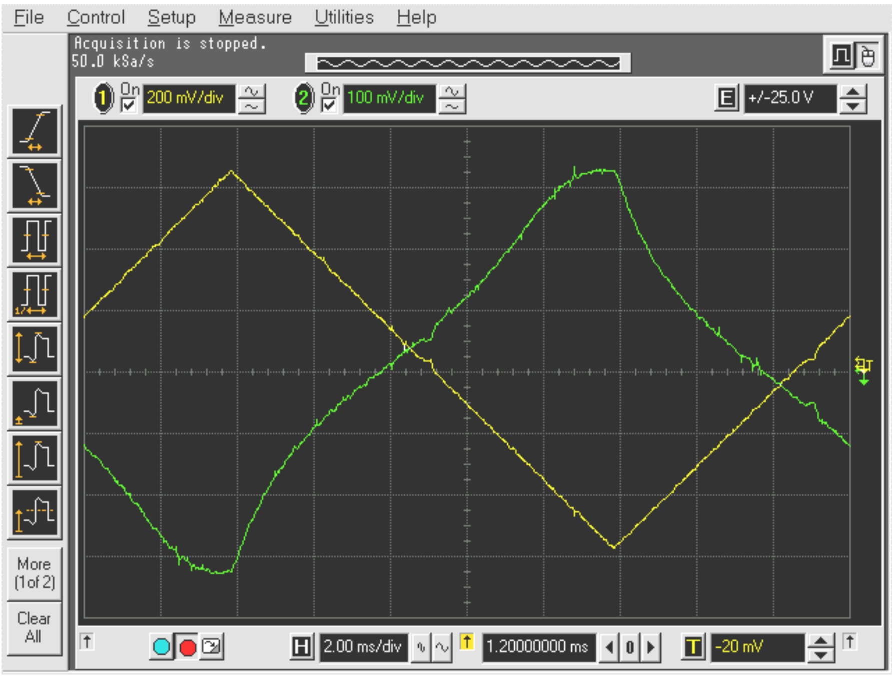
On the other hand, the μ alteration, derived from the 30RG120 fitting curve of Fig.3-3 under the field strength –12.5 < H < 12.5 H/m, is shown in Fig.4-7. The part of Fig.4-6 (3) fall under the same field is shown in Fig.4-8. In Fig.4-7 μ is changing with H but in Fig.4-8 μ is almost constant. These results do not look like on the shape.

One of the reasons of inconsistency is the *B-H* curve mismatch. The *B-H* curve of the catalog derived from a sheet testing, the saturation value of the B is 1.75 Tesla. In this case the core does not arrive at the saturation point, while we do not know the initial situation of the *B-H* curve clearly in the experiment. To avoid them we should make the initial state of the define *B-H* curve, and to saturate the material we need the current supply which has a wide range: –20 to 20 A, or n1 and n2 turn number should be much changed. However, the value of the μ with the 1/8 model is reasonable. The 1/8 model may be able to be used for induction acceleration.

This current supply has the characteristic that the flat part appears during any time when ampere crosses the point of 0 A. This effect appears conspicuously in Fig.4-6.



(1) 10 Hz triangle pulse output



(2) 50 Hz triangle pulse output

Fig.4-5 Using general steel small core

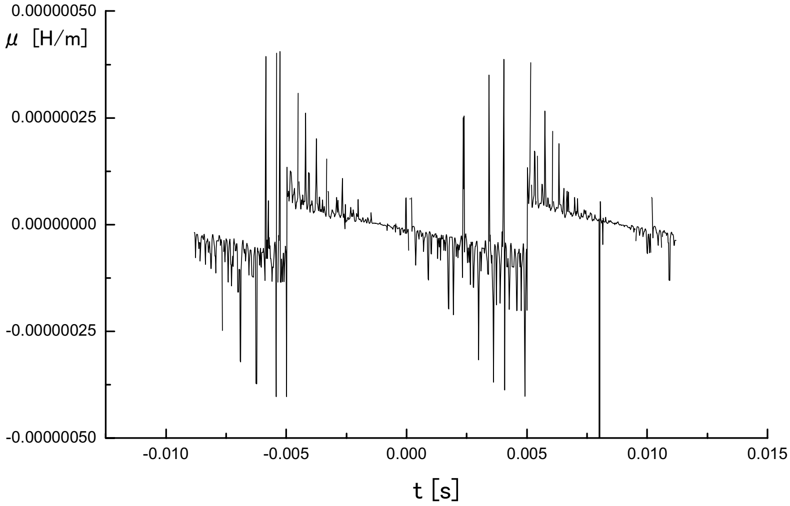
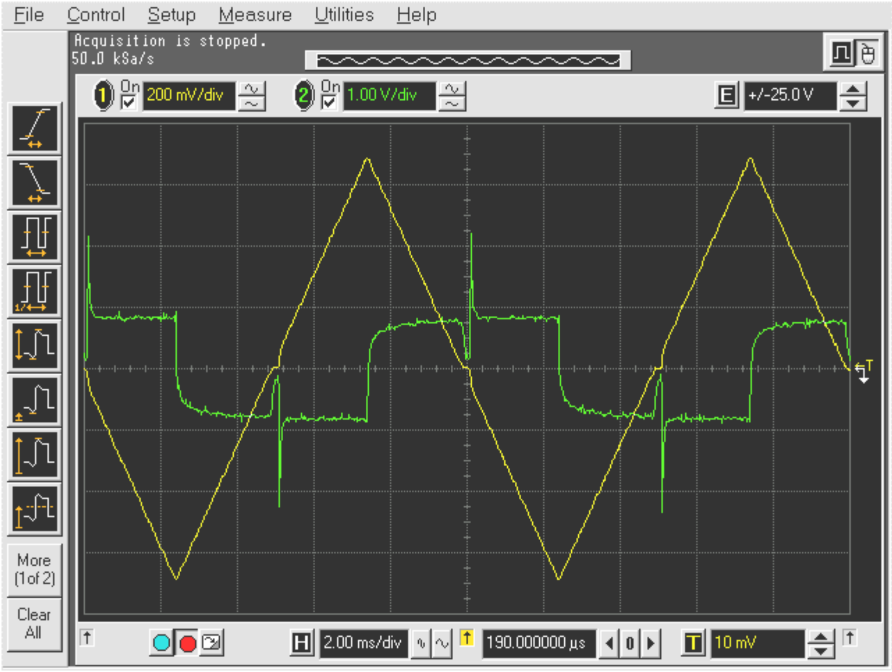


Fig.4-5 (3) μ in 50 Hz pulse



(1) 10 Hz triangle pulse output

(2) 500 Hz triangle pulse output

Fig.4-6 Using 1/8 model magnetic core

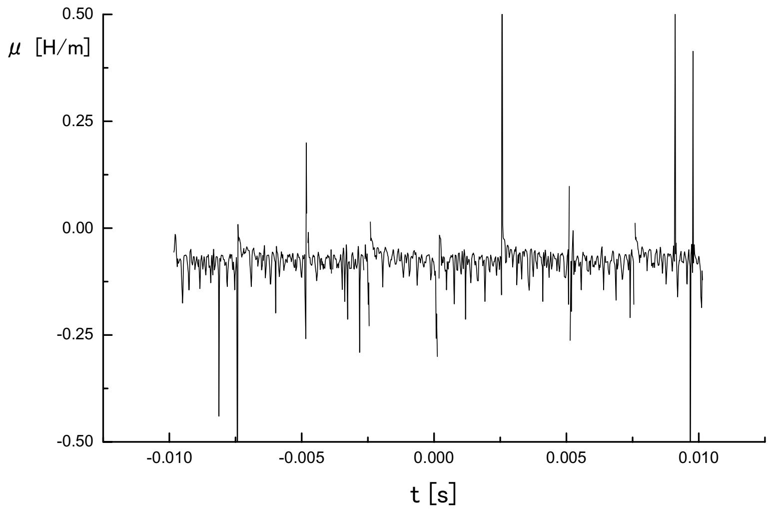


Fig.4-6 (3) μ in 100 Hz pulse

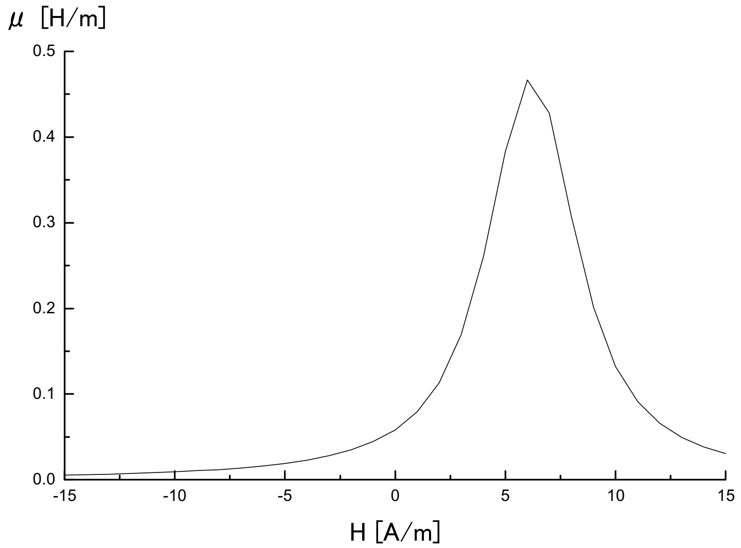


Fig.4-7 The μ alteration under the field strength $-12.5 < H < 12.5$ H/m

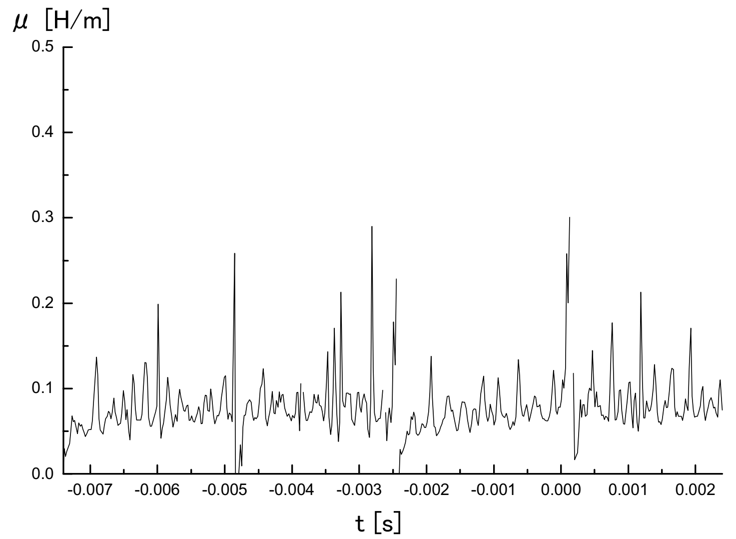


Fig.4-8 The μ alteration with the 1/8 model magnet

Chapter 5

Conclusion

We discussed the scheme of induction acceleration to improve the characteristics of REFER at Hiroshima University. We found that the loss energy 59.7 eV per turn due to synchrotron radiation of the electron beam can be compensated by a troidal coil. We estimated the magnetic core size and material together with the effect of the *B*-*H* hysteresis curve.

We made 2 model magnets. The first one is made from ordinary steel that is 10 mm thick. The second one is a 1/8 model that has 1/8 cross section of the magnet to be installed. It is made from a stack of 30RG120 electromagnetic steel sheets of 0.3 mm thickness.

The experiment with the 1/8 model magnet showed that the magnetic permeability can be regarded as a constant $\mu \approx 0.1$ H/m under the field strength $-12.5 < H < 12.5$ A/m. It is a reasonable value for electromagnetic steel sheets.

On the other hand, the behavior of induced voltage from the ordinary iron core could not be explained by an expected *B*-*H* curve. This suggests that some other effect, such as the eddy current, should be taken into account.

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Appendix

A Software for Yokogawa DAC module

In Appendix we describe to make a control software of Yokogawa DAC module.

We use Borland C++ Builder 4 of the programming language.

As we use DLLs of Yokogawa control API, we send control ASCII command to module. The kinds of ASCII command refer to module manuals.

In this chapter the using way of DLLs and the converting way of Yokogawa giving header file for Microsoft Visual C++ is shown.

We need to define the functions of the DLLs to use control command. For example the command “WeInit” can be used by following programming.

Unit1.cpp

```
//------------------------------------------------------------------------------------------
  #include "WeAscii.h"
  #include "Unit1.h"
//------------------------------------------------------------------------------------------
  // Import DLL
  hWeAscii = LoadLibrary("WeAscii10.dll");
  // Initialize DLL
  WeInit = (ProcWeInit)GetProcAddress(hWeAscii,"WeInit");
//------------------------------------------------------------------------------------------
  WeInit(NULL,"ethernet",WE_CONTROLLER);
//------------------------------------------------------------------------------------------
```

WeAscii.h (This is default setting file gave by Yokogawa)

```
//------------------------------------------------------------------------------------------
  unsigned short WINAPI WeInit( HWND hWnd, char* comm,
                                             unsigned short type );
//------------------------------------------------------------------------------------------
```

Unit1.h

```
//--------------------------------------------------------------------------------------------
 #include "WeAscii.h"
//--------------------------------------------------------------------------------------------
 typedef unsigned short __stdcall (*ProcWeInit)( HWND hWnd,
                                char* comm, unsigned short type ) ;
 // Define DLL
 ProcWeInit WeInit;
//--------------------------------------------------------------------------------------------
```

To use other command we define each command as same “WeInit”.

Above is all of program core part. Next we describe the important attentions which is not written on the API manuals.

1. All functions to send the ASCII commands include “WeAscii10.dll”. So, we import it only.
2. All functions are defined by the unsigned short type. In the manuals gave by Yokoawa, functions are defined by int type. The latter is only visual BASIC. Be careful !
3. On C++ Builder Variant type is very complex. “WeSetControl”, and “WeGetControl” use the Variant type.

Example using Variant type;

Unit1.cpp

```
//--------------------------------------------------------------------------------------------
 #include "WeAscii.h"
 #include "Unit1.h"
//--------------------------------------------------------------------------------------------
 // Import DLL
 hWeAscii = LoadLibrary("WeAscii10.dll");
 // Initialize DLL
 WeSetControl = (ProcWeSetControl)GetProcAddress(hWeAscii,
                                                 "WeSetControl");
 WeGetControl = (ProcWeGetControl)GetProcAddress(hWeAscii,
                                                 "WeGetControl");
```

```
//-----------------------------------------------------------------------------------------
  AnsiString Setting = Edit1->Text;
  WeSetControl(hMo75121,"CH1:Output",Variant((LPCTSTR)Setting.c_str()));
  WeGetControl(hMo75121,"CH1:Output",&value);
  Memo1->Lines->Add("CH1:Output の値 "+ AnsiString(value));
//-----------------------------------------------------------------------------------------
```

WeAscii.h (This is default setting file gave by Yokogawa)

```
//-----------------------------------------------------------------------------------------
  unsigned short WINAPI WeSetControl( HANDLE hMo,
                                      char* command, VARIANT var ) ;
  unsigned short WINAPI WeGetControl( HANDLE hMo,
                                      char* command, VARIANT* var ) ;
//-----------------------------------------------------------------------------------------
```

Unit1.h (This is **important** part)

```
//-----------------------------------------------------------------------------------------
  #include "WeAscii.h"
//-----------------------------------------------------------------------------------------
  typedef unsigned short __stdcall (*ProcWeSetControl)( HANDLE hMo,
                                              char* command, OleVariant var ) ;
  typedef unsigned short __stdcall (*ProcWeGetControl)( HANDLE hMo,
                                                char* command, Variant* var ) ;
  // Define DLL
  ProcWeSetControl WeSetControl;
  ProcWeGetControl WeGetControl;
//-----------------------------------------------------------------------------------------
```

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