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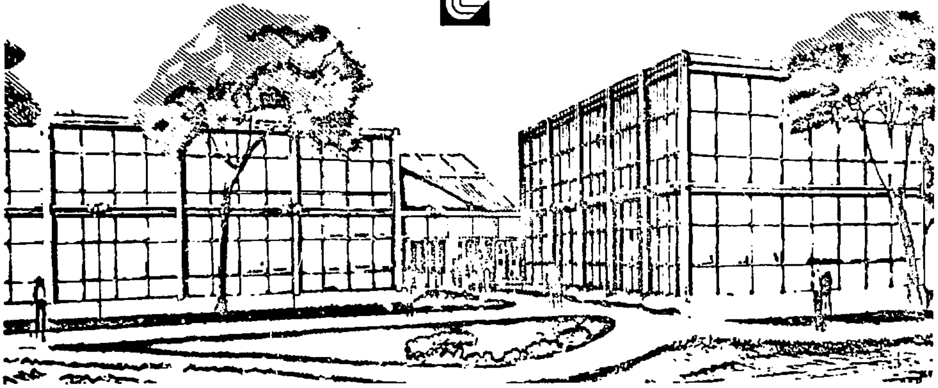

"PULSED FERRITE CORE TESTS FOR 50-ns LINEAR INDUCTION ACCELERATOR"**

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ABSTRACT

The Lawrence Livermore Laboratory undertook an investigation of the properties of ferrite materials to be used in a 5-MeV, 50-ns linear induction accelerator. The investigation, on a part-time basis, lasted about one year and had the cooperation and helpful suggestions of several manufacturers: TDK of Japan, Phillips of Holland, and Stackpole of the U.S.A.

Ferrites have been widely used as tuning cavities for proton synchrotron accelerators at radio frequencies. In such an application, the μQf factor is used in describing the figure of merit for ferrites where a high duty factor requires low loss ferrites. In our linear induction accelerator with an average rep-rate of 5-Hz, the ferrite losses are negligible and the concept of complex permeability in describing the losses will not be introduced, but a large signal $\Delta B/\Delta H$ will be used to describe their properties. The properties of interest in designing the accelerating cavity were: a) flux swing $\Delta B = B_r + B_m > .5T$ b) a residual flux density $B_r < .15T$ with a reset no greater than 2 Oer. c) a relatively high incremental $\mu > 400$ to keep the excitation current small in relation to the load current. d) a high resistivity for the 250-kV voltage hold-off.

I. INTRODUCTION

The principle of magnetic induction has been applied to the acceleration of electrons in betatrons as well as linear accelerators such as the Astron[1] at Livermore and the ERA[2] at Berkeley. The Astron utilized .0025-cm thick Ni-Fe tape wound into cores and the ERA utilized ferrite as magnetic material. The principle can easily be described by referring to Fig. 1a.

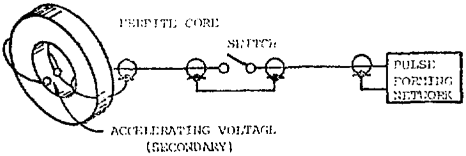

Fig. 1a

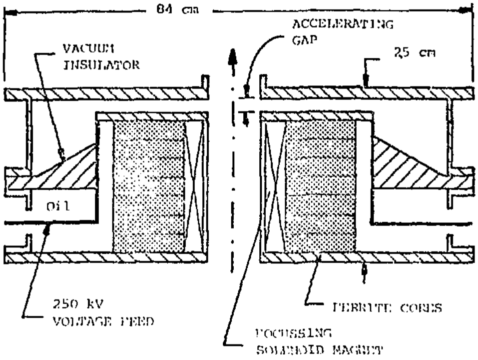

Fig. 1b

A toroidal ring of ferrite material forms essentially a 1:1 transformer, and the change in flux in the magnetic core induces an axial electric field which accelerates the electron beam. The volt-seconds available depend upon the magnetic material and the cross sectional area of the toroidal ring as given by Faraday's law

$$\oint E \cdot d\ell = -\frac{d}{dt} \int_A B \cdot da \qquad (1)$$

or simplified

$$V = -A\frac{dB}{dt} \qquad (2)$$

where A is the ferrite cross sectional area. Fig. 1b shows the actual cross section of an accelerating cavity with symmetric voltage feed points. The cavity contains seven ferrite toroids 2.5-cm thick, 23-cm I.D., and 50-cm O.D. These toroid were manufactured by Stackpole Carbon Co. The accelerating voltage across the 2.5-cm gap is 250-kV for 50-ns. Concentric with the ferrite cores is a solenoidal magnet to provide beam focusing. These accelerating cavities are stacked in series to obtain the desired output beam energy. The electron gun for the accelerator also utilizes the induction principle. Because of restrictions dictated by the gun electron beam dynamics, and ceramic insulator gradients, the ferrite core dimensions were .96-m I.D. and 1.28-m O.D. These cores were manufactured by TDK of Japan to very close tolerances in twelve segments and glued in pairs to form a toroid. The gap at the joint was less than .04-mm.

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II. CORE TESTER

The choice of magnetic material was made after considerable testing to determine the properties which were important for this application. A core-testing device was therefore built to duplicate the drive system of the accelerator. A schematic of the core tester is shown on Fig. 2.

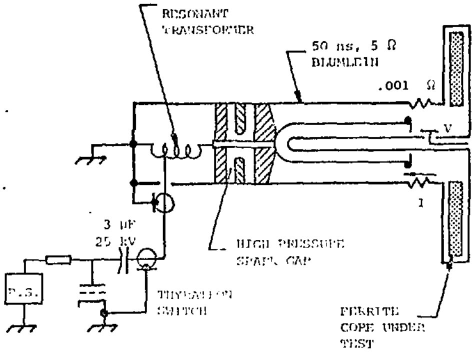

Fig. 2

It consists of a 5-Ω water-filled Blumlein 40-cm in diameter and 80-cm long. The Blumlein energy is delivered to the load by a sparkgap which switches the middle conductor to ground. Output voltage was varied by changing pressure in the sparkgap. The sparkgap used in this apparatus was borrowed from an earlier experiment and a low inductance unit had not yet been developed. This resulted in a pulse with slow rise time and almost sinusoidal shape. Although the full energy of the pulser was never used, it could deliver a 250-kV, 50-ns pulse into a 12.5-Ω load. The Blumlein was charged to full voltage by a resonant transformer with a step-up of ten to one. The primary voltage to the transformer was supplied by discharging a 3-μF 25-kV capacitor with a thyratron. Since the ferrite cores required only a few kiloamps of magnetizing current, to avoid voltage doubling, a 25-Ω dummy load was provided for the Blumlein. The excitation current into the core was monitored by means of a .001-Ω resistor in series with the core; the voltage to the core was derived from capacitive divider concentric with the inner conductor. It was not possible to apply these signals in obtaining B-H loop plots directly so all the information about the cores is in the form voltage and current photographs.

III. EXPERIMENTAL RESULTS

It was observed early in this investigation that there was not always a one-to-one correlation between the properties of small test toroids and the large cores required by the accelerator. Hence, all the tests performed were done on actual full size cores provided by different manufacturers.

The requirement for a ferrite with high resistivity ($\rho > 10^6 \Omega$-cm) stemmed from the fact that 250-kV appears across the seven 2.5-cm toroids and one can avoid elaborate insulation techniques. A high resistivity, however, is no guarantee that a high voltage can be applied across the toroids. A separate test apparatus was used to determine the voltage holding properties of the ferrite. A high voltage was applied by means of two 1-cm balls across the ferrite under oil to see if it would hold the required voltage. All ferrites held at least twice the required minimum of 15-kV/cm. Arc-through typically occurred at 50-kV/cm.

This type of ferrite would ordinarily be considered too lossy for use in synchrotrons. In our application however, this is an advantage since it provides damping for beam induced transients. As the beam traverses the accelerating cavity, a voltage transient is induced which could have frequency components in the low GHz range. Those modes which propagate into the cavity are effectively damped by the terminating resistors and the ferrite. A spectrum analyzer was used to study the absorption properties of the ferrite. A spectrum of the accelerating cavity was taken from the low MHz to a few GHz with and without the ferrite. All ferrites tested were effective in attenuating the Q of higher frequency modes by 20-40 Db.

In designing the induction accelerator, it is desirable to have a high efficiency of energy transfer. That is, the excitation current required to produce a given flux change should be small compared to the load current. It is also desirable that the ferrite behave as nearly as possible to a linear inductor. The requirement of energy uniformity during the beam pulse makes it necessary to apply compensation to the pulsing system to keep a constant voltage pulse. The more nonlinear the ferrite, the more difficult the compensation.

A specification was placed on the permittivity, μ, to be greater than 400. This value of μ is not the initial permeability, but a pulsed or average value from $-B_r$ to B_m. The inductance of the ferrite cavity is given by

$$L = \frac{Z_o}{v} \text{ or } L = 200\,\mu \ln \frac{d_2}{d_1} \qquad (3)$$

L - inductance in nH/m
Z_o - impedance of coaxial ferrite cavity
v - velocity of propagation in ferrite
d_2 - outside diameter of ferrite
d_1 - inside diameter of ferrite

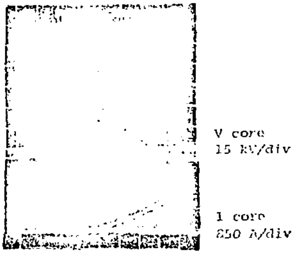

Fig. 3

in nanohenries/m. A μ of 400-1000 results in about one to two kiloamperes of excitation current or 5 to 10% of the total current. Fig. 3 shows a typical plot of current and voltage into a single test toroid. The current waveshape is fairly linear indicating the core to be a linear inductor up to the saturation point.

Calculated inductance

$$L = 200\ (400)\ \left(\ell n \frac{500}{230}\right)\ (.025) \qquad (4)$$

L = 1.5-μH/core for the design voltage-seconds this would result in $\Delta i \sim 1200$-A. One important property of the ferrite, in conjunction with our particular drive system, is its resettability. As can be seen from Fig. 2, during the Blumlein charge cycle, a displacement current flows through the one turn primary to charge the inside coax. For our charging system this resetting current is about 220 amperes. From

$$\oint H \cdot d\ell = i, \text{ it corresponds to a } \Delta H = \frac{\Delta i}{\pi d} \qquad (5)$$

$\Delta H \approx 2$ Oer. If this current resets the core from $+B_r$ to $-B_r$ then the external reset system can be eliminated resulting in considerable cost savings and simplification. Some of the original core samples did not meet this requirement. Before the end of our testing program, however, all manufacturers provided us with samples that met our specifications. The gun cores are about twice the diameter of the accelerator cores and the charging current is not sufficient for reset, therefore, an external pulse must be applied for this purpose.

In a pulsed reset system, to obtain a maximum ΔB, it is important that B_r approach B_m since $\Delta B = B_r + B_m$. The maximum flux swing determines the size of the cavity, hence the length and cost of the accelerator. In our 5-MeV accelerator, it was not too important a factor, but it would be for higher energy machines. Our goal of $\Delta B > .5T$ was achieved by all manufacturers with a reset equivalent to 2 Oer. The table below shows representative data for one accelerator core with the particular pulser waveshape applied to it. This data is obtained by integrating the oscilloscope photograph of the voltage waveform. Where:

B_m - Saturation flux density
B_r - Residual flux density
H - Magnetic field
i - Excitation current
t - Pulse length
d - Diameter of core
A - Cross-sectional area in m^2
V_p - Peak induced voltage

Δt(ns)	ΔB(Tesla)	ΔH(Oersteds)
20	.068	1.96
30	.146	2.83
40	.233	4.7
50	.324	6.1
60	.4	7.8
70	.45	9.4
80	.466	10.2

Because of the almost sinusoidal shape of the applied voltage one could approximate

$$\Delta B \approx \frac{1}{A}\ \left(\frac{2}{\pi}\ V_p\right)\ \left(\Delta t\right) \qquad (6)$$

A typical plot of ΔB vs. ΔH is shown on Fig. 4. It appears that the self resetting current equivalent to two Oer. is sufficient to obtain a total flux swing $\Delta B \approx .5$ Tesla even though a $\Delta H \approx 11$ Oer. are required to drive the ferrite into saturation.

Within the time allotted for testing, several manufacturers had developed a ferrite with the properties desirable for our application. After choosing the appropriate ferrites, a full scale accelerating cavity was built. This module was tested to 500-kV to verify the saturation levels. Fig. 5 is a photograph of the voltage and current just as the cavity begins to saturate where V ~ 320-kV. The full width half max. is 50-ns.

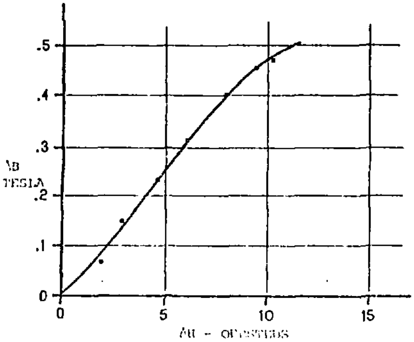

Fig. 4

Fig. 5

IV. CONCLUSION

The appropriate ferrite offers many advantages as a magnetic material for a linear induction accelerator. It is an effective absorber of unwanted higher frequency modes. It is a high voltage insulator, it is a quasi-linear inductor requiring low excitation current, hence is an efficient energy transfer medium and has low coercive force allowing it to self reset during the Blumlein charge cycle. Its primary disadvantage in comparison to steel, is the relatively low flux swing.

Further studies in magnetic materials for accelerating cavities will continue at the Laboratory.

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