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The paper describes an experimental study of a kicker magnet for the extraction system of a synchrotron. The magnet which uses ferrite as the return yoke, has a gap of 2 in., and a pole tip area of 12 in.^{2}. The maximum field is 2.5 kG, which is established with a rise time of about 100 nsec. The pulse length for the magnetic field is 4.8 μsec, and the repetition rate is 60 pulses/sec. The magnet is excited from a coaxial, lumped-constant, pulse line. Construction techniques employed and theoretical limitations of this type of system are discussed.

Introduction

A number of high-speed switching magnets are needed for a new accelerator under study at the Lawrence Radiation Laboratory in Berkeley. It is necessary to be able to establish magnetic fields of the order of a few kilogauss in times of the order of 100 nsec. These requirements suggest ferrite-core magnets, now in use at CERN, Brookhaven, Princeton-Pennsylvania, and Stanford. However, the 60-cycle repetition rate of the accelerator under study plus the large number of magnets required makes the problems of cost, power, and reliability much more severe than in previous applications. Novel features of the present design include coaxial construction to minimize and control stray fields, and the use of recently commercially available ceramic capacitors of suitable voltage and capacitance range.

The first high-speed ferrite-core magnet was proposed by O'Neil and Korenman.[1] This magnet was built in a lumped-constant transmission-line configuration as a convenient way of matching the required magnet voltage and current to a power supply--which consisted of a pulse line. Kuiper and Plass extended O'Neil's analysis and made important contributions to construction techniques of this type of magnet.[2] Forsythe showed that the lumped capacitors used in the previous ferrite-core magnets contributed little if anything to the speed of the magnets and added a severe complication to the manufacturing process.[3,4] He developed the "picture frame" type of ferrite-core magnets which are used at Brookhaven.

We are engaged in an experimental study of picture-frame-type ferrite-core magnets and their power supplies. A variety of magnets can be built having different pole-tip configurations and peak magnetic fields while exhibiting the same electrical characteristics to the power supply. The first magnet studied had a gap of 2 in. and a pole tip area of 12 in.^{2}. The design objective for this magnet is to produce a field of 2.5 kG with a rise time of 100 nsecs and a pulse length of 4.8 μsec with a repetition rate of 60 pulses/sec. The magnet is excited from a coaxial pulse line. A phase-II radar-type hydrogen thyratron is used as the high-speed switch.

The basic problem in a system of this sort is to transform the energy contained in the electric field of the pulse-line capacitors into energy contained in the magnetic field of the magnet. This transformation should be carried out in a controlled, predictable manner, with as little disturbance as possible to adjacent equipment. It seems to us that basically we are dealing with a very-high-powered radiofrequency system. During the pulse the power is about 200 MW and the 100-nsec rise time suggests an upper frequency limit of about 1.5 Mc for the power spectrum. This combination of power and bandwidth is probably best handled in a coaxial system. It confines the fields well in a precise way and minimizes the amount of stray field.

We consider the lumped-constant-line type of ferrite-core magnet as the general case. The "picture-frame" magnet is simply the limiting case, where the number of sections of the line is unity (i.e., n = 1). A distributed magnet would be the other limit--an infinite number of sections (i.e., n = ∞).

Derivation of the Design Equations of Ferrite-Core Magnets

Consider the lumped-constant-line magnet shown in Fig. 1. Assume that it is divided into n sections. The total magnetic flux per section in webers is

$$\Phi = B\, w\ell / 10\, n\, (39.37)^2. \qquad 1(a)$$

The current in the exciting winding necessary to establish this field is

$$I = 2.02 \times 10^3\ Bg. \qquad 1(b)$$

In Eqs. (1), B is in kilogauss, and w, ℓ, and g are in inches.

The inductance per section in henries is

$$L = \Phi/I = 3.2 \times 10^{-8}\ w\ell/g\,n. \qquad (2)$$

For a matching termination, the filling time, τ, of the magnet in seconds is determined by the velocity of propagation, v, of the line and the number of sections, n:

$$\tau = n/v = n(LC)^{1/2} = nL/Z_0, \qquad (3)$$

where $Z_0 = (L/C)^{1/2}$ and $v = (LC)^{-1/2}$. Eliminating L and Z_0 in (3) we find that the required magnet voltage depends only upon the total magnetic flux and the filling time:

$$V = 6.45 \times 10^{-5}\ B\ w\ \ell/\tau. \qquad (4)$$

Equation (4) says that the filling time of the magnet is proportional to the total amount of magnetic field and inversely proportional to the applied voltage and is independent of the number of sections in the magnet. The capacitance in farads per section can be obtained from Eq. (3) by eliminating the inductance L:

$$C = \tau Z_0/n \qquad \text{or} \qquad C_T = nC = \tau Z_0. \qquad (5)$$

The total capacitance of the magnet is independent of the number of sections. Equations 1(b), (4), and (5) form a complete set of design equations for the lumped-constant-line type of ferrite-core magnet. These design equations say that once the amount of magnetic field and the filling time are determined, the required voltage is determined. Once the magnetic field intensity and the magnet gap is chosen, the required current is established. With these quantities selected, the total required capacitance in the magnet is fixed, but the number of sections into which the magnet is divided is completely arbitrary.

To simplify construction of the magnet, one should choose a minimum value of n. This would appear to be n = 1, which physically becomes the picture-frame type of ferrite-core magnet. This type of magnet is simply a limiting case of the lumped-constant-line type of magnet.

One is tempted to conclude from this analysis that the filling time of the two types of magnets is the same. However, the equations taken from transmission-line theory imply an infinite number of sections, so one can only assume the analysis to be approximate for finite and small values of n. It is not surprising that Forsythe, in studying the picture-frame magnet rigorously, found that there was very little difference in filling time between it and the many-sectioned lumped-constant-line magnet.[3,4]

The Ferrite-Core Magnet

The magnet and its pulse line are shown in Fig. 2. In our first application, the ferrite-core magnet (Fig. 3) must produce 2.5 kG over 12 in.^{2} in 100 nsec. According to Eq. (4), the magnet voltage in kV must be

$$V = 6.45 \times 10^{-5} \times (2.5 \times 12)/10^{-7} = 19.4.$$

From Eq. (1b), we have

$$I = 2.02 \times 10^3 \times 2.5 \times 2 = 10.1\ \text{kA},$$

and therefore

$$Z_0 = V/I = 19.4/10.1 = 1.93\,\Omega \approx 2\,\Omega.$$

Total capacitance of the magnet section should be

$$C_T = \tau Z_0 = 10^{-7} \times 2\,F = 0.2\,\mu F.$$

Half of this value (i.e., 0.1 μF) should be connected on either side of the magnet.

The Pulse Line

Characteristics of the pulse line are given in Table I.

Table I. Pulse-line characteristics

Characteristic impedance	2 Ω
Capacitance per section	0.15 μF
Inductance per section	0.6 μH
Propagation time	0.3 μsec per section
Number of sections	8 sections
Total pulse length	4.8 μsec
Peak voltage	40 kV
Peak current	10 kA
Charging frequency	360 Hz
Repetition rate	60 Hz

At maximum voltage the pulse line stores 1.08 kJ. Since essentially all of this energy is dissipated in the terminating resistor during each pulse, the average power is 65 kW. To minimize charging losses, resonant charging is used.

Construction details of the pulse line are given in Figs. 4 and 5. Sixty 2500-pF, 40-kV ceramic (Sprague type 710C7) capacitors are used per section. The inductances are wound from 1/4-in. copper tubing. The terminating resistors are (Carborundum Co. 889SF) 25Ω, 200 W water-cooled carbon-composition type. The hydrogen thyratron is a General Electric type ZT7005-A with water cooling.

Experimental Results

Results of the first tests of the ferrite-core magnet system are shown in Figs. 6 and 7. At the time of these tests we had received only about half of the capacitors for the pulse line, so we assembled only the first four sections of the line. The capacitors that we did receive measured low in value--averaging about 1700 rather than 2500 pF, so that each section of the pulse line measured only 0.1 instead of 0.15 μF. To make Z_0 2Ω, we reduced the pulse-line inductances from 0.6 to 0.4 μH. Thus we should produce a 2-μsec pulse. From Fig. 6 it is apparent that the pulse length is almost exactly 2 μsec. The ringing apparent in Fig. 6 can no doubt be corrected through the use of a Gibbs suppressor. With the oscilloscope sweep speed expanded to 100 nsec/cm, Fig. 7 shows the rise time of the magnetic field. The field rises from about 5% to 90% of full field in

100 nsec. We decided to postpone the full field tests until after the pulse line has been properly trimmed and the individual components completely checked out. It appears that the experimental results agree well with the predictions of the design equations for ferrite-core magnets.

Footnotes and References

*This work was done under the auspices of the U. S. Atomic Energy Commission.

[1] G. K. O'Neill and V. Korenman, The Delay Line Inflector, Princeton-Pennsylvania Accelerator Project Internal Report GKO'N-10, VK13, December 18, 1957.

[2] B. Kuiper and G. Plass, On the Fast Extraction of Particles from a 25-GeV Synchrotron, CERN Internal Report CERN-59-30, August 24, 1959.

[3] E. B. Forsyth, Comparison of Lumped and Distributed Inflector Magnets, Brookhaven Internal Report (AGS) E. B. F-2, March 18, 1963.

[4] E. B. Forsyth, The Fast Kicker of the AGS External Beam System, Brookhaven Internal Report (AGS) E. B. F-3, October 27, 1964.

FIGURE LEGENDS

Fig. 1. (a) Lump-constant-line type of ferrite-core deflecting magnet, (b) typical ferrite and ceramic capacitor construction. and (c) equivalent circuit.

Fig. 2. Simplified schematic diagram of the magnet and its pulse line.

Fig. 3. Ferrite magnet designed for 2.5 kG over an area of 12 in.^{2} with a 2-in. gap.

Fig. 4. Cross section of the pulse line.

Fig. 5. The pulse-line.

Fig. 6. Magnetic field vs time. The vertical scale is 250 G per division; the horizontal, 0.5 μsec per division. For this test, only four sections of the pulse line were installed. The ringing with a period of 1 μsec is caused by the pulse line which has not yet had a suppressor installed.

Fig. 7. Magnetic field vs time. The horizontal scale is expanded from that of Fig. 7 to 100 nsec cm^{-1} so that the rise time of the magnetic field can be observed. The rise time, 100 nsec, agrees exactly with the ferrite-magnet design equation.

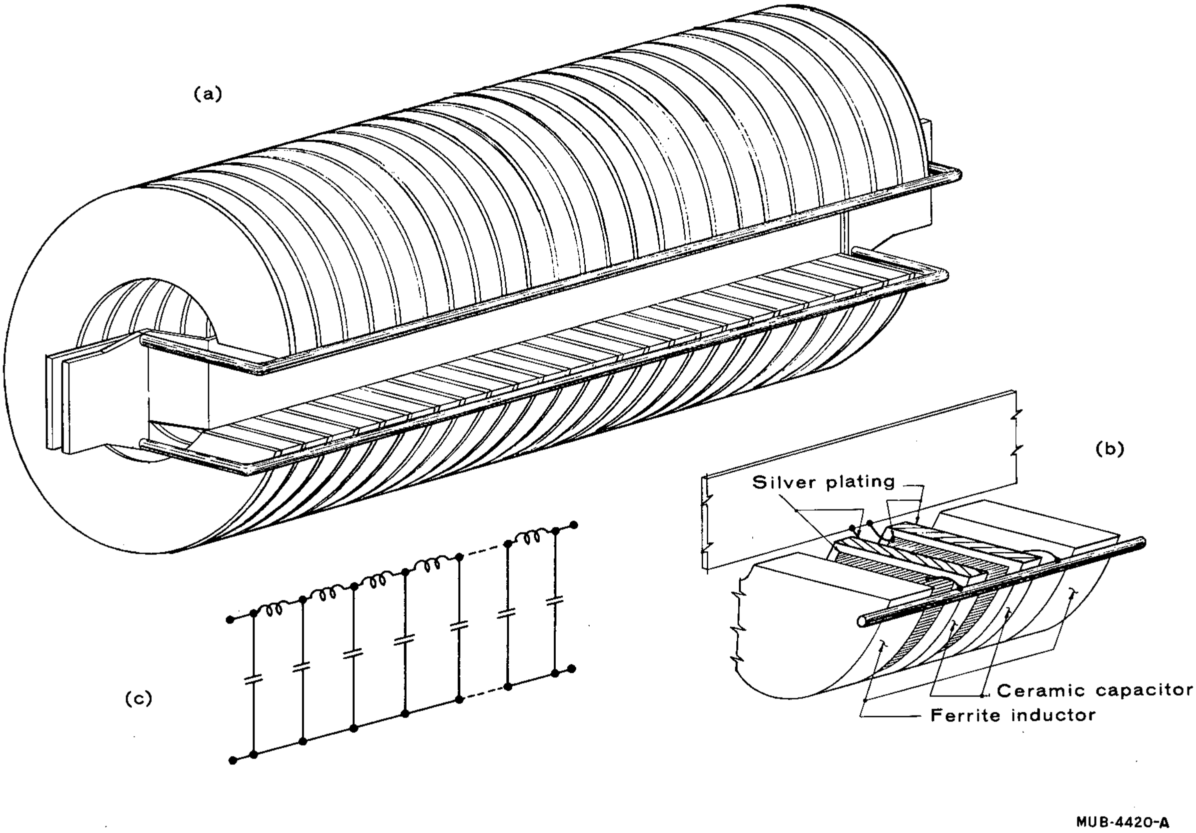
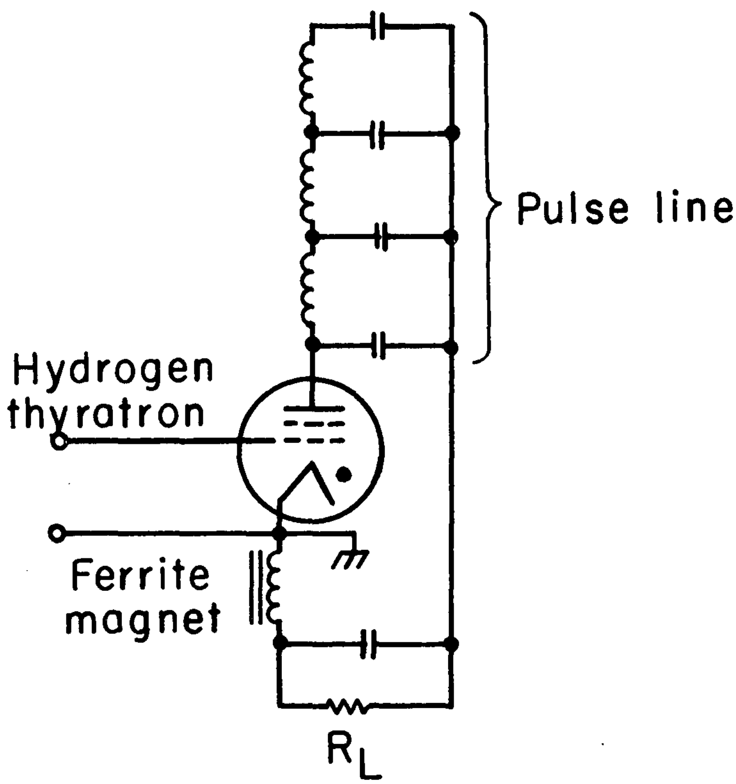

(a)
(b)
Silver plating
Ceramic capacitor
Ferrite inductor
(c)
MUB-4420-A

Fig. 1



MUB-7606

Fig. 2

ZN-5127

Fig. 3

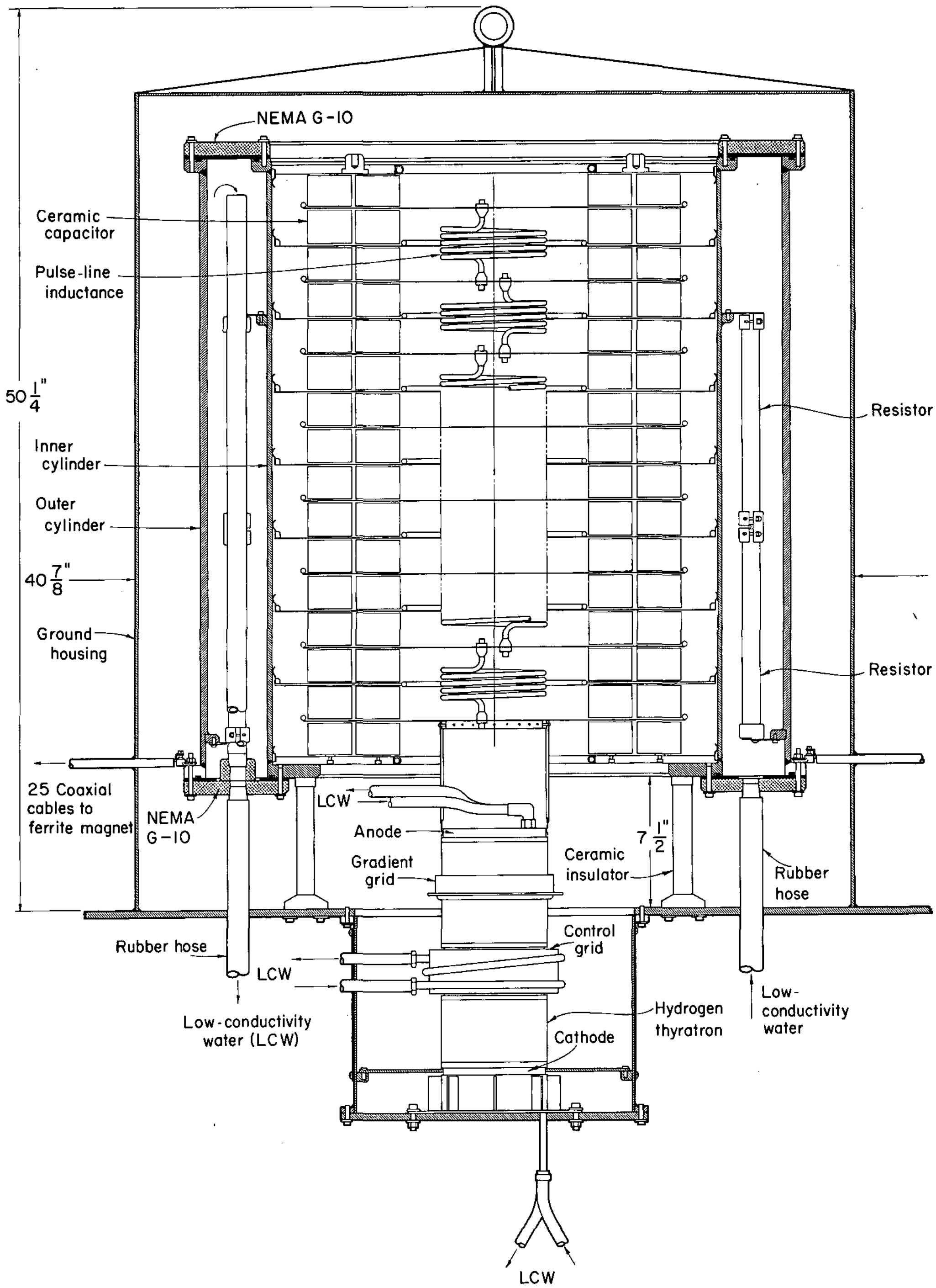
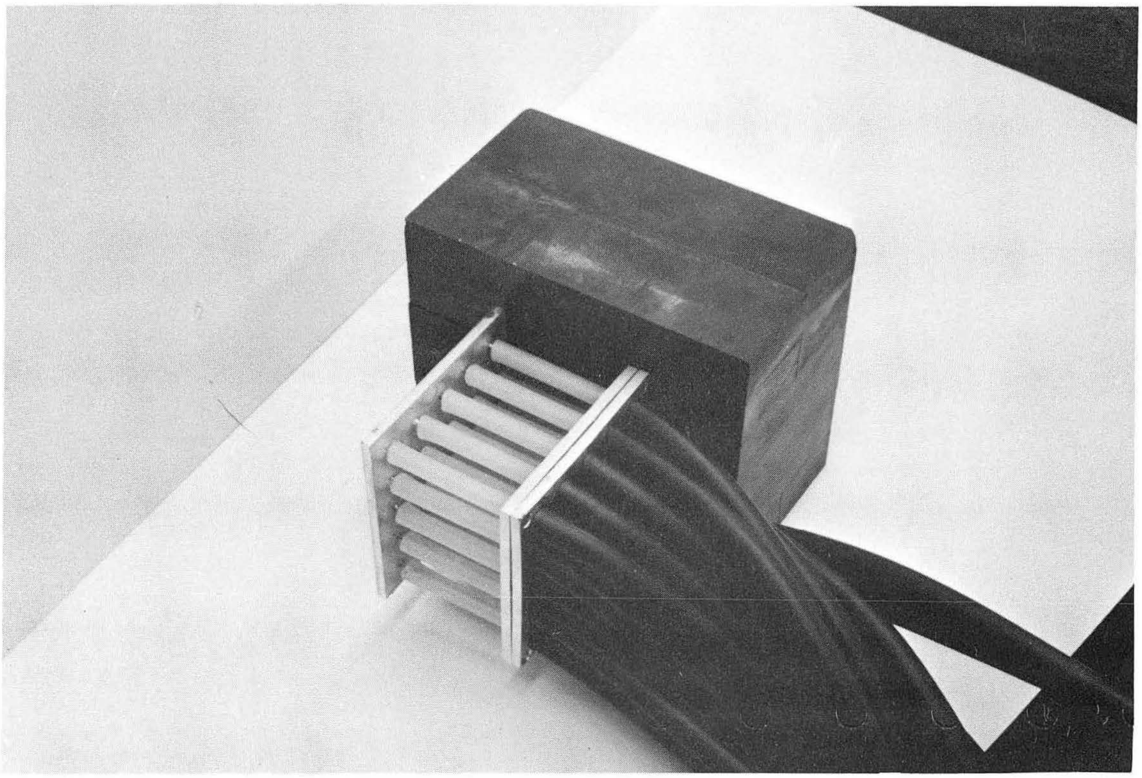
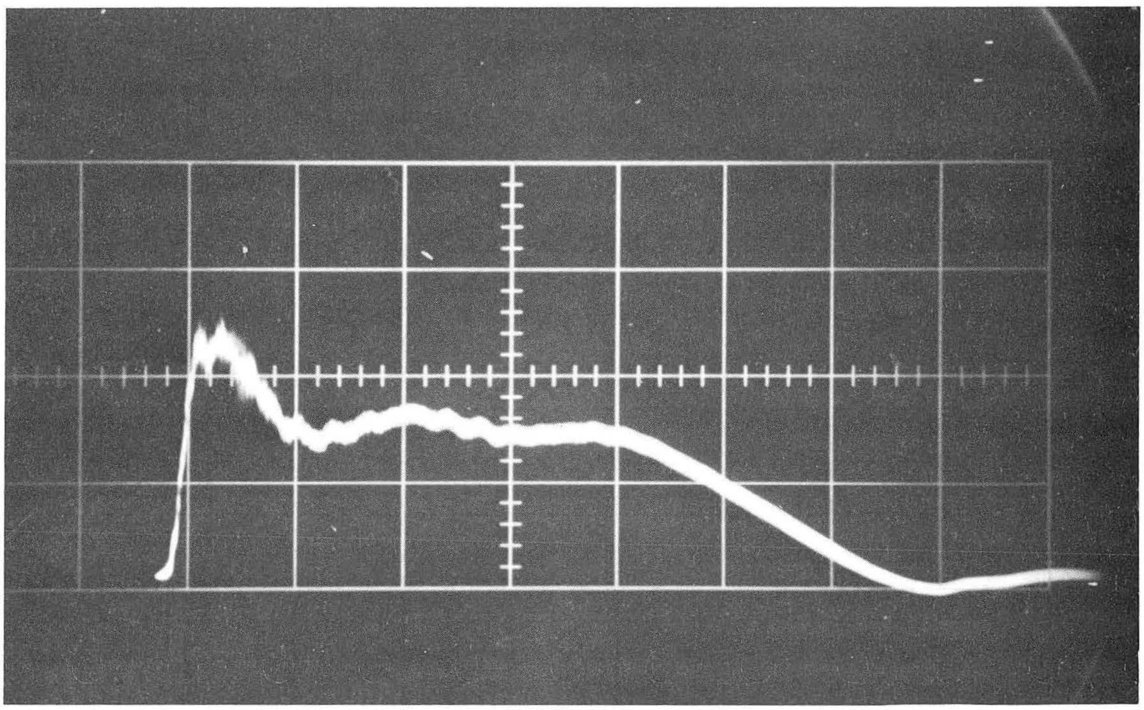

NEMA G-10
Ceramic capacitor
Pulse-line inductance
50 1/4"
Inner cylinder
Outer cylinder
40 7/8"
Ground housing
Resistor
Resistor
25 Coaxial cables to ferrite magnet
NEMA G-10
LCW
Anode
Gradient grid
Ceramic insulator
7 1/2"
Rubber hose
Rubber hose
LCW
Control grid
Low-conductivity water (LCW)
Hydrogen thyratron
Cathode
Low-conductivity water
LCW

Fig. 4



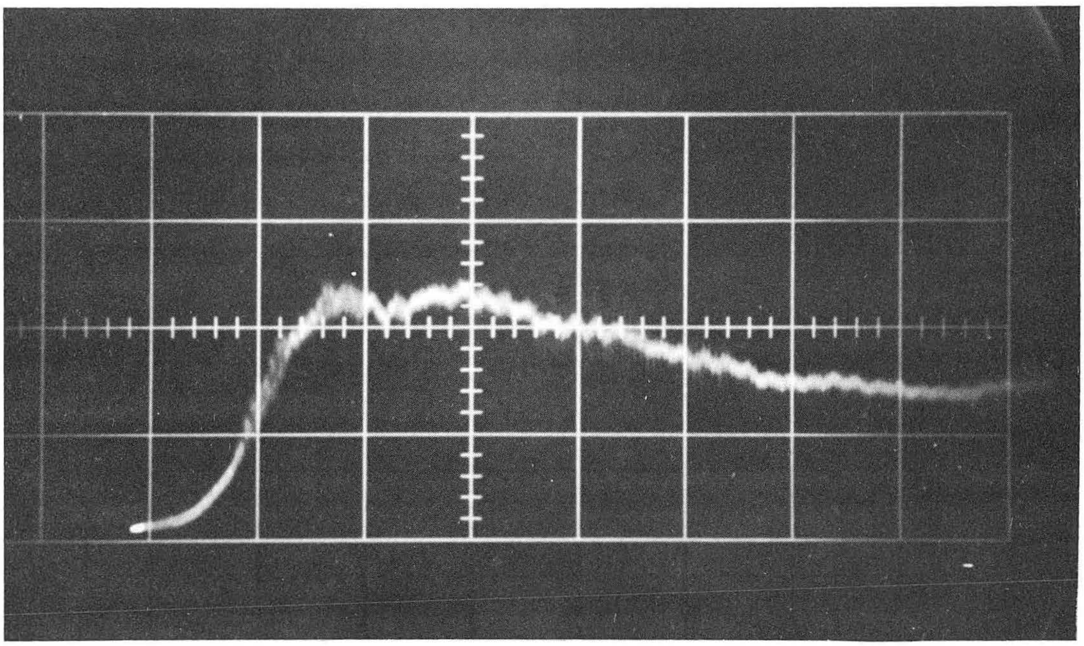
ZN-5128

Fig. 5



ZN-5129

Fig. 6



ZN-5130

Fig. 7