Fermilab

TM-800
6065.000
June 1978

Development of a High Power Flux Pump
(A Progress Report)

Carl Akerlof
University of Michigan
Ann Arbor, Michigan 48109

Thomas Droege and Age Visser
Fermi National Accelerator Laboratory
Batavia, Illinois 60510

and

Richard Britton
Britton Engines Co.
Converse, Texas 78109

ABSTRACT

During the last nine months considerable progress has been achieved in designing and constructing components for a magnetically switched flux pump A description of these components is given along with comments on alternative designs.

The advent of high current superconducting magnets for new particle accelerators has posed the technical problem of how one might use such magnets for beam transport optics One major difficulty encumbered by high currents is the large heat load imposed by the power leads communicating between the superconducting coil at 4.2°K and the external power supply bus at room temperature. In order to solve this particular problem as well as provide a highly stable current supply, a group of us at Fermilab has attempted to design and construct a flux pump capable of driving a 100 millihenry magnet from zero to 5000 amperes in 45 minutes with thermal losses not to exceed 5 watts.

The starting point for this project was a detailed examination of the flux pump electrical behavior for which the equivalent circuit is shown in Figure 1. Two modes of excitation were studied: (1) sinusoidal, and (2) aperiodic square wave with inductive current commutation every half-cycle. It rapidly became clear that a sinusoidally driven system could never hope to function with output currents of several thousand amperes. This is most simply understood by calculating the magnetic field energy which must be quenched in one loop of the secondary circuit when the transformer phase goes through zero. For a typical secondary inductance, $L_1 = 100\ \mu$ henrys, and $i = 5000$ amperes,more than a kilojoule of energy must be dissipated into the open cryotron switch at every half-cycle.

The alternative requires a programmable bipolar power source which can drive the flux pump transformer through a six step cycle. During charging when the primary current has reached the maximum allowed value, the primary voltage is turned off and both cryotrons are relaxed to the closed switch condition As soon as both switches are superconducting, a commutating pulse is applied to inductively transfer the magnet current to the opposite secondary loop. Thus when the previously superconducting cryotron is switched normal there is no magnetic energy in the loop to be dissipated.

The optimum frequency of operation is determined by cryotron characteristics, transformer losses and size constraints. As will be discussed later it seems reasonable to expect a cryotron with a normal to superconducting relaxation time of 2 seconds or less and a normal state resistance of 100 milliohms. Under these circumstances a 100 ampere 25 volt power source will energize a 100 millihenry magnet to 4500 amperes in 2800 seconds as indicated by the waveforms in Figure 2. The volume of such a device is about 2 cubic feet and will require about 600 pounds of iron to confine the magnetic fluxes in the transformer and cryotrons.

Two possible approaches were considered for the cryotron design, using either thermal or magnetic switching between normal and superconducting states. The thermal technique was considered technically easier since there was no doubt that one could heat up and cool off a strip of superconductor. However possibly long cooling times as well as excessive thermal dissipation made this the less attractive alternative.

To pursue the magnetically switched cryotron, Fermilab contracted Britton Engines to improve a cryotron design developed earlier at Brookhaven National Laboratories. The criteria for the switch was an off-state resistance of 100 milliohms and an on-state current capacity of 5000 amperes with less than 1 watt thermal loss.

In addition to the cryotrons, two other superconducting components were required. The largest of these is the transformer, shown in cross-section in Figure 3. The turns ratio of 500:1 was chosen to match a 24 volt, 20 ampere operational amplifier to the job of charging a load magnet to 5000 amperes. The primary inductance of 10 henrys was set by the requirement of sustaining a cycle time of the order of 10 seconds. The transformer has an air core to provide the maximum energy density and is encased with a 90 pound iron return yoke to keep the magnetic field well confined. The transformer has gone through several tests and has shown no difficulty in achieving its design goals.

Proper control of the operational power supply requires accurate detection of the current in each of the two secondary loops. For this purpose two transductors were built with superconducting servo coils as shown in Figure 4. The basic device worked well but some improvements will be required to stabilize the servo electronics.

A first version of the magnetically switched cryotron was tested in April of this year. The switch element incorporated 114 filaments of superconducting wire consisting of Nb-1%Zr embedded in a 0.012" diameter Cu-30% Ni matrix, all wound bifilarly on an 8" diameter fiberglass coil form. For the purposes of these tests only half of the filaments were electrically connected; in this configuration peak currents of about 2000 amperes were achieved before quench. Unfortunately the magnetic control coils were insufficiently cooled and could not produce the required critical field. An improved design is shown in Figure 5; it will be constructed as soon as manpower is available. The superconducting characteristics of the Nb-1%Zr wire are shown in Figure 6.

One graph of our test results is shown in Figure 7. The cryotron was connected across a secondary leg of the transformer and maintained in the superconducting state. With a constant current flowing in the primary circuit the secondary current decayed exponentially due to finite resistances at various solder joints. The decay time is related to the residual resistance by:

$$\tau = \frac{L_1}{R}$$

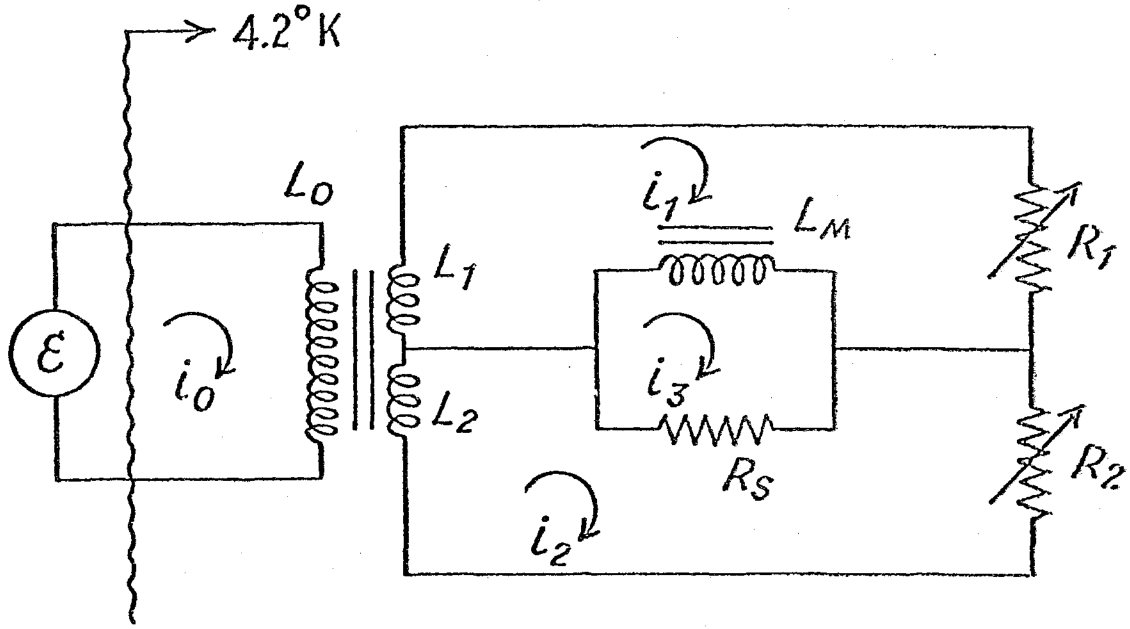
where L_1 is the secondary transformer inductance. The current decay curve thus shows a secondary loop resistance of 1.3×10^{-8} ohms corresponding to a 0.33 watt dissipation at a peak current of 5000 amperes.

The immediate plans of our group are to construct and test an improved cryotron as discussed above. If this is successful, a second switch will be built and a complete flux pump assembled. This will require a substantially larger cryostat to house all the components then any now available to us. It now appears that with a reasonably modest effort a working flux pump system could be completed within a year.

ACKNOWLEDGEMENT

The help of Walt Jaskierny and Robert Innes is greatly appreciated. They assembled and built most of the prototype components, except the cryotron.

LIST OF FIGURES



R_1, R_2 = CRYOTRON SWITCHES

L_M = LOAD MAGNET

R_S = PROTECTIVE SHUNT RESISTANCE

FLUX PUMP EQUIVALENT CIRCUIT

FIGURE 1

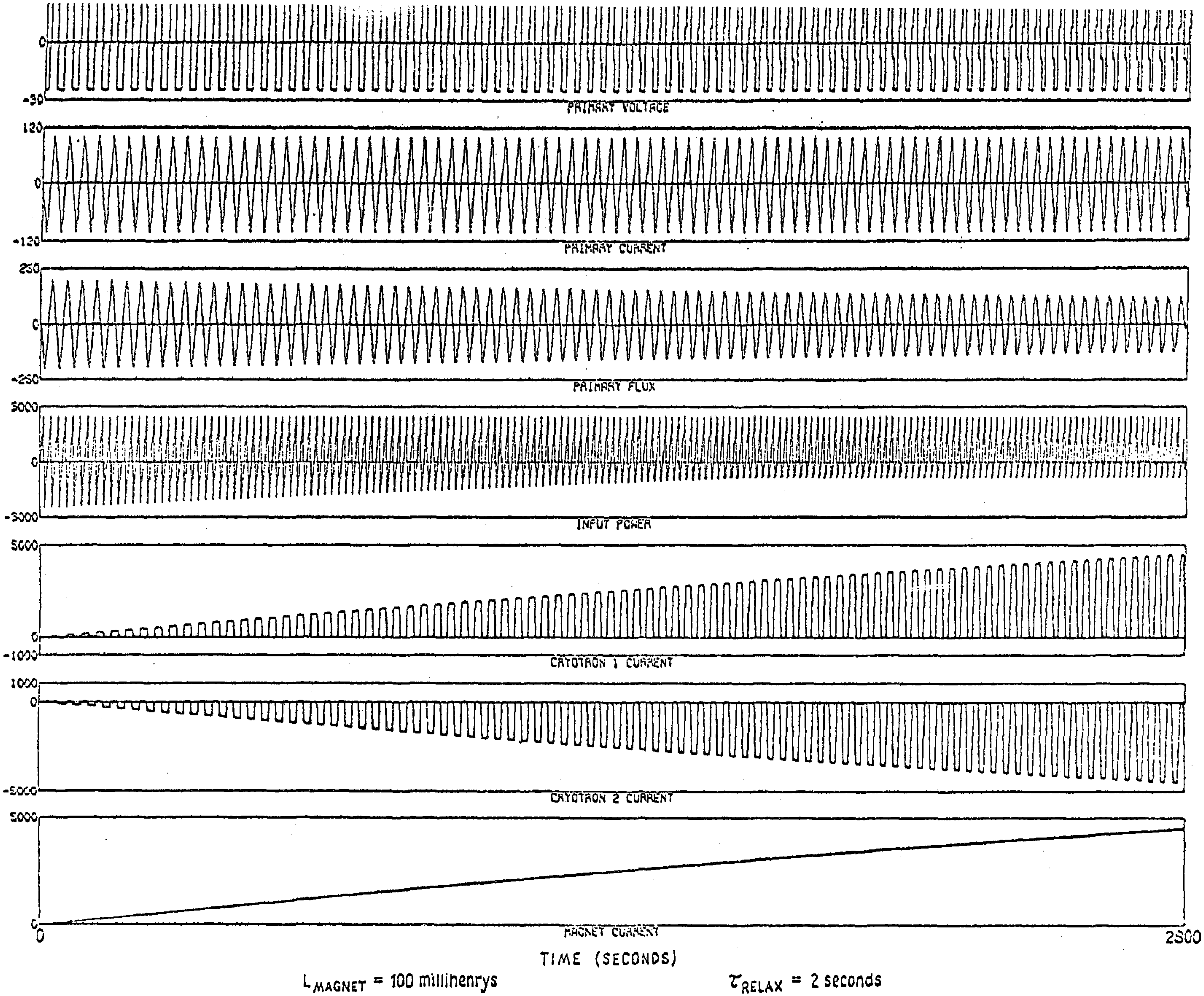
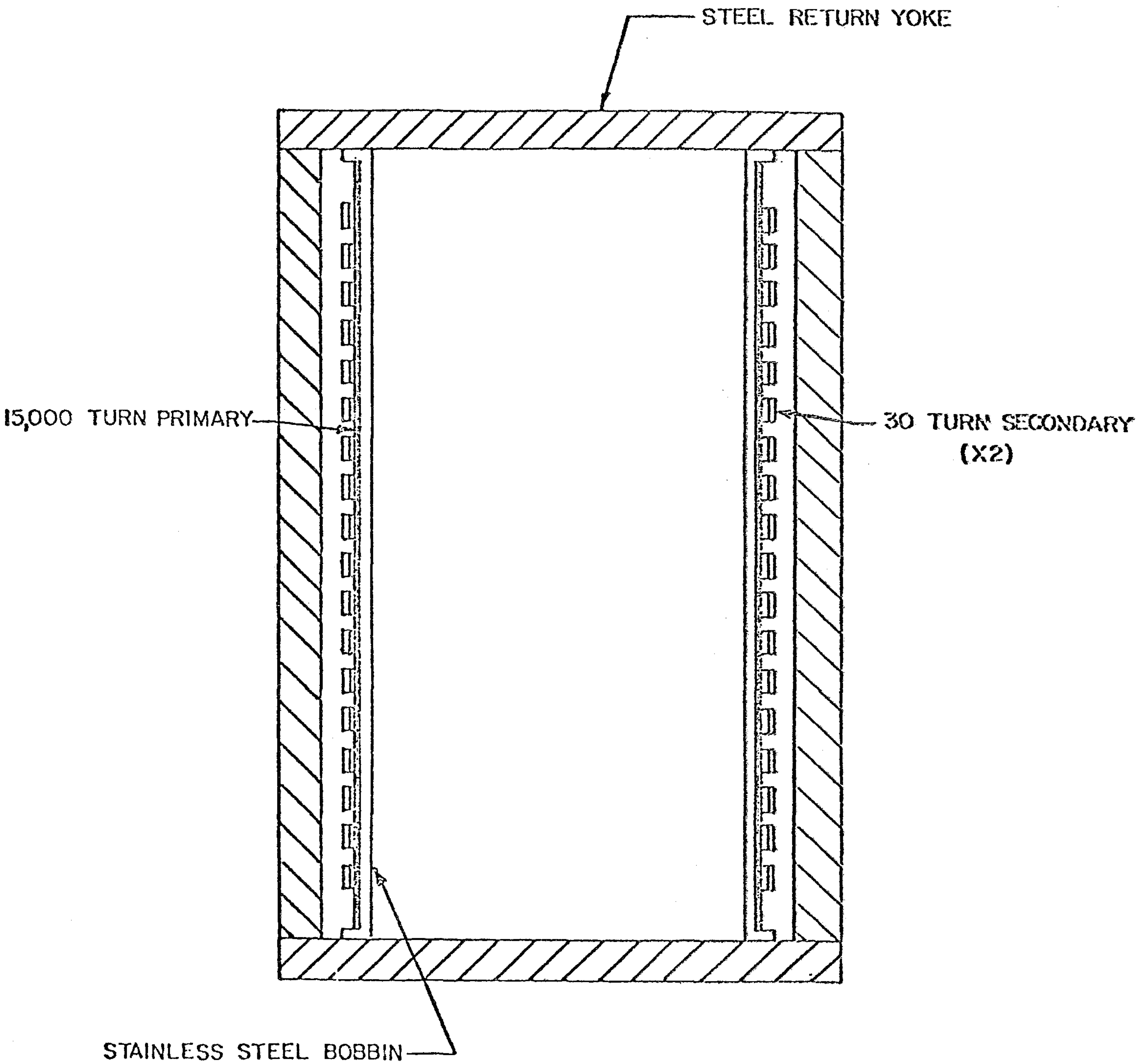
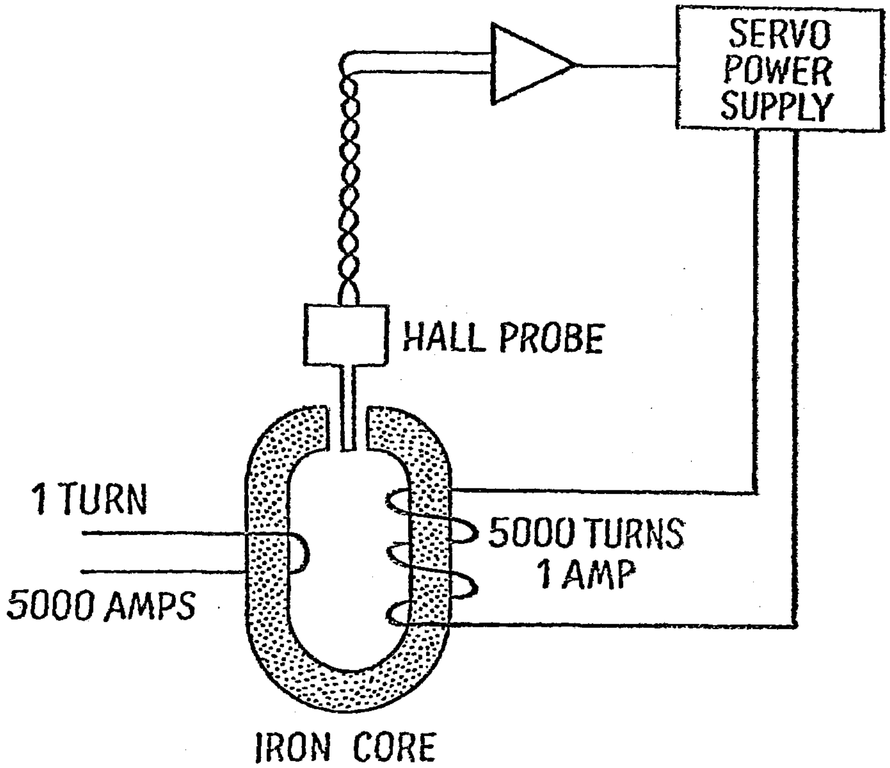

0
-30
PRIMARY VOLTAGE
120
0
-120
PRIMARY CURRENT
250
0
-250
PRIMARY FLUX
5000
0
-5000
INPUT POWER
5000
0
-1000
CRYOTRON 1 CURRENT
1000
0
-5000
CRYOTRON 2 CURRENT
5000
0
MAGNET CURRENT
0
2500
TIME (SECONDS)
L_{MAGNET} = 100 millihenrys
τ_{RELAX} = 2 seconds

FIGURE 2



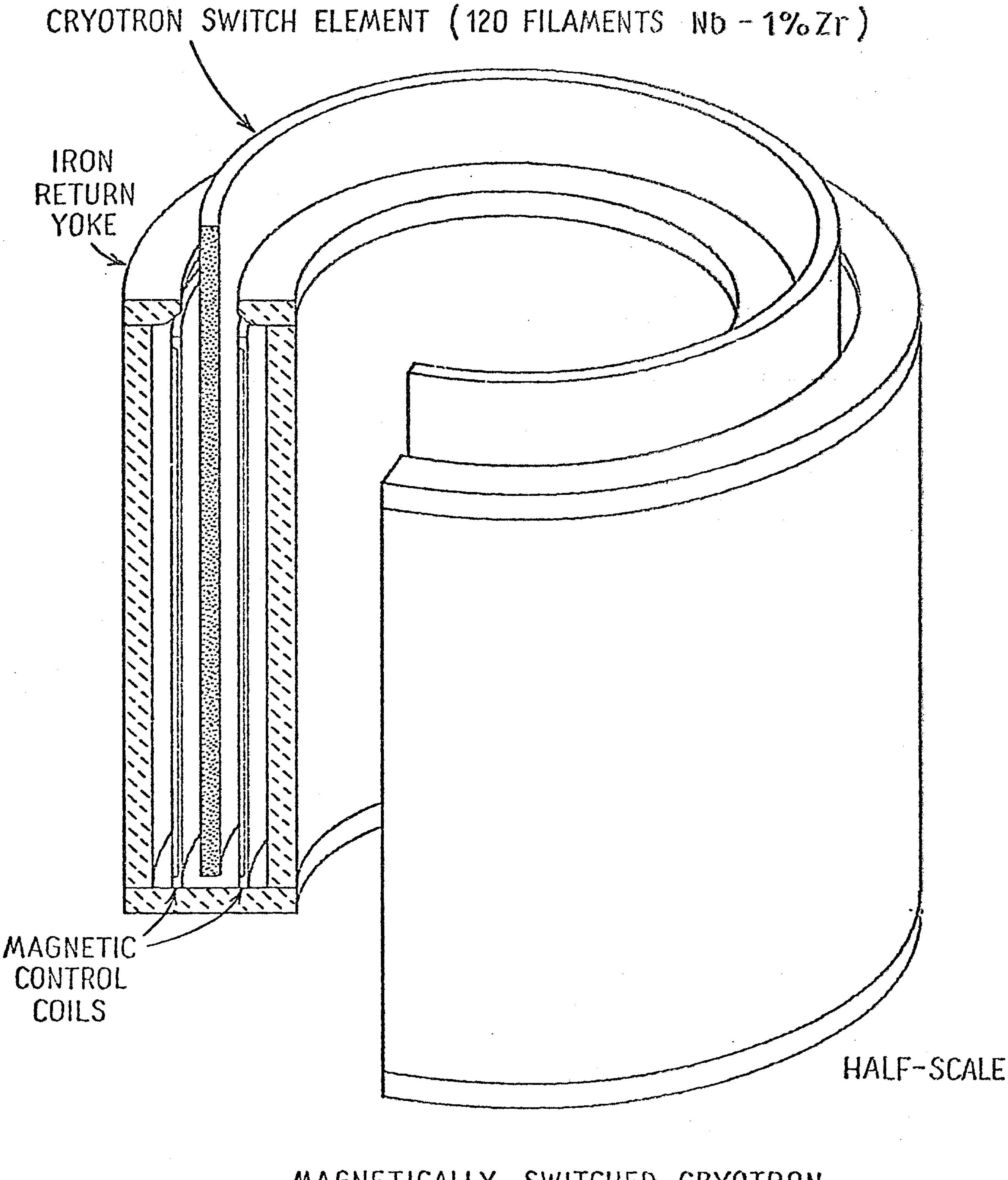
FLUX PUMP TRANSFORMER

FIGURE 3



SUPERCONDUCTING TRANSDUCTOR

FIGURE 4



MAGNETICALLY SWITCHED CRYOTRON

FIGURE 5

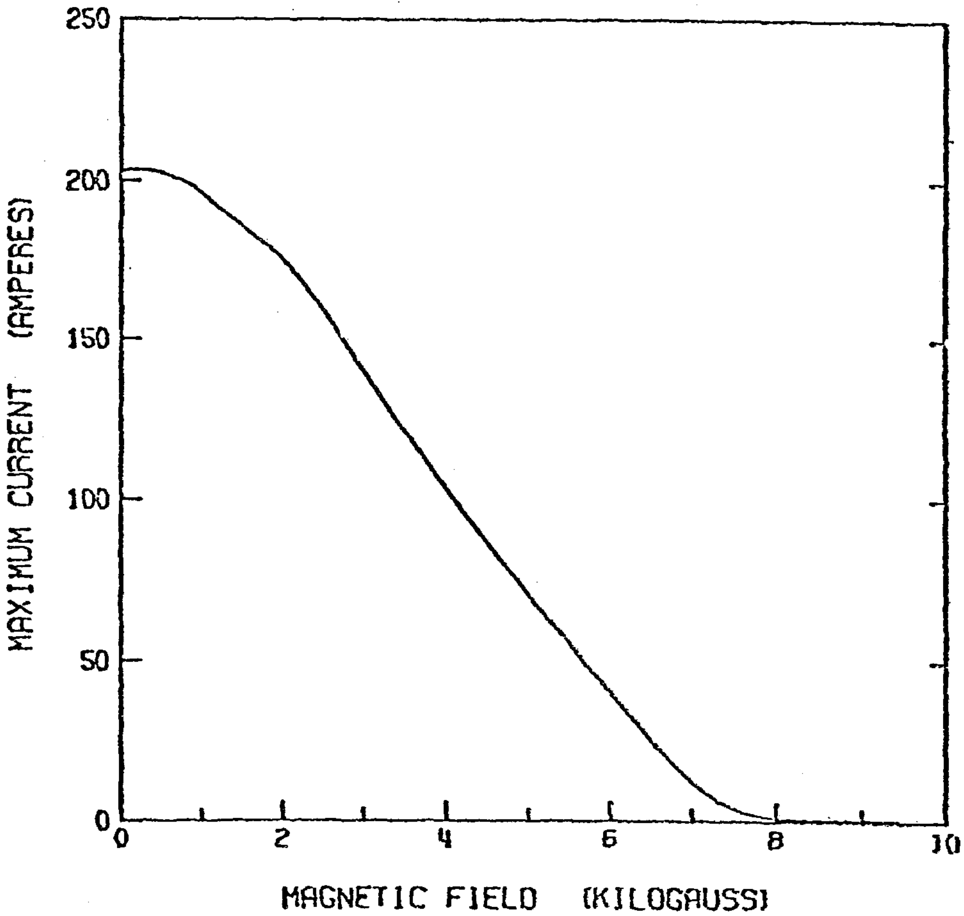

250
200
150
100
50
0
MAXIMUM CURRENT (AMPERES)
0
2
4
6
8
10
MAGNETIC FIELD (KILOGAUSS)

FIGURE 6

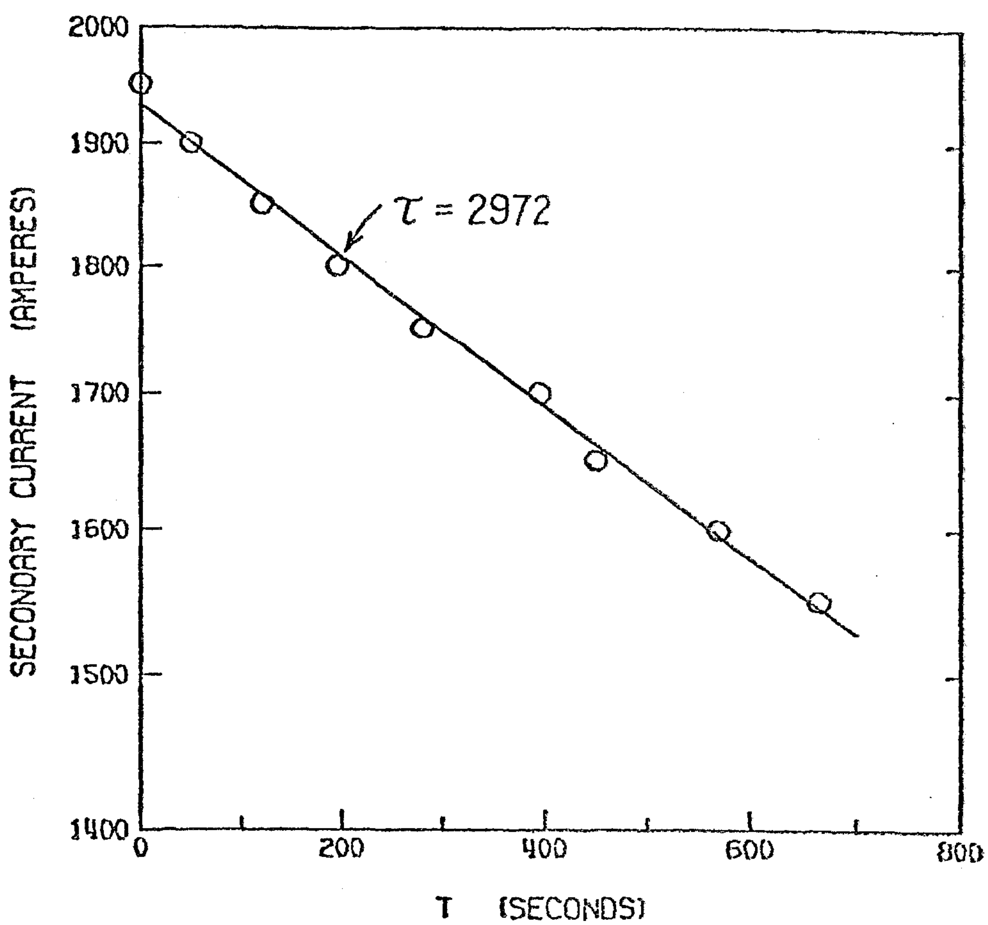

2000
1900
1800
1700
1600
1500
1400
SECONDARY CURRENT (AMPERES)
τ = 2972
0
200
400
600
800
T (SECONDS)

FIGURE 7