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Publication Date
1949-05-20

UNIVERSITY OF CALIFORNIA

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BERKELEY, CALIFORNIA

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W. R. Baker, R. F. Edwards, Q. A. Kerns and J. Reidel

May 20, 1949

Berkeley, California

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ABSTRACT

This paper describes several high voltage pulse transformers, developed at the Radiation Laboratory of the University of California under the auspices of the Atomic Energy Commission, for use on particle accelerators. Pulse transformers described are: 100 kv Synchrotron Injector Transformers, 500 kv iron and air core Synchrotron Injector Transformers, 100 kv Spark Gap Trigger Transformers, 140 kv 184-Inch Cyclotron Deflector Transformer, 80 kv Insulation Test Transformer and a new type 400 kv Multiple Core Transformer.

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INTRODUCTION

With the operation of particle accelerators, such as the 184-inch cyclotron, synchrotron, and the linear accelerator, on an intermittent or pulsed basis instead of a steady state mode, demands arose for various types of electrostatic pulsing devices. A segment of this demand called for the design and construction of several high voltage pulse transformers ranging from 50 to 500 kv output voltages.

At the start of this work in 1946, the members of the group had little experience with the design of high voltage pulse transformers. In addition, the published data on the subject was quite meager. The net result of this situation was, on the one hand, the origination of new designs, while on the other hand, many mistakes and "bugs" appeared which had to be eliminated before satisfactory operation of the units was secured.

It is the purpose of this paper to describe the designs that reached at least the full scale test stage. The discussion will concern itself primarily with descriptions of the final designs, while the actual procedure in the designing of the transformers will receive secondary consideration.

DESIGN

In general, the design of the transformer was made in two steps. The first step consisted of deciding on the number of turns, and the cross section of the core according to the fundamental equation below, checked with several trial windings, mocked up in a few hours time, for each application.

$$\triangle B = \frac{10^8 \, Vt}{NA}$$

where B = net change of flux in core during pulse, gauss.

V = Voltage per coil, volts.

t = time of pulse, seconds.

N = number of turns on coil.

A = cross sectional area of core, square cm.

The second step consisted of evaluating the relative importance of such constants as primary and secondary impedance, leakage inductance, distributed capacity, efficiency, and selection of the best type of core material, insulation, winding methods, and mounting and lead arrangements for each transformer. As the backlog of experience grew, it became possible to predict many of these factors from previous designs, and thus to rapidly arrive at an adequate solution for new problems as they arose.

There are two factors that are the same for all the transformers to be described. First, all the transformers using solid insulation are vacuum impregnated with ordinary transformer oil at pressures of about 50 microns of mercury. The oil is pumped down in a second vacuum chamber prior to impregnation removing all air, water, and volatile fractions. Second, all the transformers are pulsed with a line type pulse generator of the type commonly used in radar modulators. In many of the circuits the pulse line consists of a storage capacitor only. A diagram of this circuit appears in Figure 1. The circuit can be seen to consist of the transformer, an energy storage device, usually a capacitor or pulse forming network, and a switching device, either a hydrogen thyratron or a spark gap.

The major characterisitics of the various transformers are listed in Table I.

It will be observed that the voltage ratios do not always correspond with the turns ratios. This is because, for some of the transformers, a resonant interchange of energy between the leakage inductance and the secondary capacity results in a peak voltage of up to twice the maximum available according to the turns ratio.

LOW LEVEL SYNCHROTRON INJECTOR TRANSFORMERS. MODELS I, II, AND III.

Transformers for synchrotron injector service have as their prime object the driving of the cathode of an electron gun to a high negative voltage. Hence they are all wound in such a way as to provide filament power for the gun. This is usually done with a bifilar type winding. The load consists chiefly of the capacity to ground of the gun and its associated lead structure, the electron burst being a comparatively small part of the load. Therefore these transformers charge up the load capacity in a short time, hold the voltage constant, and then cause the voltage to fall as quickly as possible. The fast rise time is achieved by keeping the leakage inductance to a minimum while the fast decay is obtained by driving the transformer into saturation at the end of the pulse.

Model I, the first transformer, is wound using a coil type winding. This winding, the details of which are shown in Figure 2, utilizes the same cores simultaneously for the pulse and a 60 cycle filament isolation transformer. By polarizing the flux in the two cores in opposite directions, the net pulse voltage induced in the filament transformer is small, while the pulse winding always has the same amount of net flux change available no matter which part of the 60 cycle wave the pulse appears in. Figure 3 shows the completed transformer, and a view of the transformer installed on the injector gun test rack, for which purposes the transformer is now used.

This type of case has proved quite adaptable and has been used on all the low level injector transformers.

The two later transformers, models II and III, are now in service on the synchrotron (see Figure 4). They are both wound with the aluminum foil, condenser paper type of winding first used on the 184-inch cyclotron deflector transformer. The general shape of this winding and its mounting and lead arrangements are shown in Figure 5. This type of winding has been found generally useful in the high voltage transformers made at the laboratory because of its simplicity, cheapness, ease of construction, and the very high voltage insulation available in a few turns and small space. These transformers both use conventional bifilar windings, the secondary coil on each leg acting as one side of the 60 cycle circuit.

HIGH LEVEL SYNCHROTRON INJECTOR TRANSFORMERS

At one time it was considered advisable to attempt injection into the synchrotron at energies high enough to forestall any loss of the electron beam due to perturbations in the magnetic field at the low level injection point. Two pulse transformers were built to provide the 500 kilovolt pulses decided upon, although as yet, it has not been desirable to use them for actual synchrotron operation.

Photographs of the iron core transformer appear in Figure 6. Some of the features of this transformer are its tapered bifilar ribbon type winding, the corona shields on the secondary and the core, and the fact that it has operated at voltages of up to 800 kilovolts without breakdown. Since the major component of the load is the capacity of the lead structure to the gun, the gun is mounted in the same tank with the transformer. Thus no high voltage appears outside of the case, the only output being bursts of 500 kev electrons. The winding machine shown in Figure 5 was developed for this transformer. The machine automatically cuts the foil conductor and paper insulation in a taper as the coil is wound. Needless to say this machine has proved invaluable in the winding of many other transformers.

While awaiting the completion of the iron core for the transformer above, some preliminary experiments were carried out using the air core transformer shown in Figure 7. This transformer was wound with the primary on the outside, while the high voltage winding starts at the primary and builds up into the center where the high voltage lead can be seen. Because of the poor coupling between primary and secondary it is not possible to load this transformer heavily. However, loading the center of the coil with mo-permalloy improved the coupling to some extent, allowing the transformer to be used on preliminary electron gun experiments. 10

amperes was delivered to the load at full voltage with 85% regulation. In addition, the impedance of the primary circuit is very low and a spark gap was necessary to energize the primary adequately. This transformer, in spite of its small size, generated pulses of 800 kv before breakdown. This particular construction is very adaptable to the generation of high voltage pulsed x-rays. A sketch of a design proved feasible, but not carried to completion during the experiments is shown in Figure 8.

184-INCH CYCLOTRON DEFLECTOR TRANSFORMER

In this application, a maximum rate of change of voltage in a 600 μμf load with a peak voltage of approximately 140 kv is the determining design factor. Since this transformer has been adequately described elsewhere[1], the only reference to it here will be the listing of the characteristics in Table I and the photographs in Figure 9. Some minor changes have been made in the transformer in a redesign of the pulse generator for use on the 184-inch cyclotron after its recent conversion to proton operation. Hence the data in Table I will not correspond with that previously published.

SPARK GAP TRIGGER TRANSFORMERS

The purpose of these transformers is to over voltage or trigger a spark gap used as a switch to connect one circuit to another, much as is done with the hydrogen thyratron in Figure 1. There are two variations of this type of transformer in use at the laboratory at present. The earlier type, shown in Figure 10, was originally used for the pulsed outgassing of GL 434A tubes used in the Linear Accelerator Oscillators. At present it is being used to trigger the main gap connecting the pulse storage lines to the oscillator plate circuit on the Linear Accelerator.

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[1] High Voltage Pulser for 184-Inch Cyclotron Electric Deflector, Q. A. Kerns, et al. Review of Scientific Instruments, Vol. 19, No. 12, pp. 899-904, December, 1948.

The pulse is fed to the spark gap through an isolation capacitor consisting of a piece of RG 17 U cable. The most recent transformer of this type was constructed to trigger the spark gap connecting the plate pulse line with the oscillator plate on the injector cyclotron used for injecting protons into the quarter scale model of the bevatron. This transformer is shown in Figure 11.

Another variation of the spark gap trigger transformer was built for use in various experiments around the shop. It can be seen in Figure 12, and Figure 7. The secondary is connected in series with the main pulse line and a voltage is developed across the secondary that causes the spark gap switch to break down. The main pulse current then flows through the secondary, quickly saturating the core of the transformer and reducing the inductance of the secondary or series winding to a low value, effectively removing the transformer from the circuit after it has performed its function. A low number of secondary turns is used to keep the inductance to as low a value as possible. Permalloy cores are also used because of the low value of coercive force necessary to saturate them. To eliminate the possibility of high voltages being generated in the primary circuit due to air core coupling with the main current pulse through the secondary after the core is saturated, the primary is wound on the bottom leg of the core. This reduces the air core coupling between primary and secondary to a minimum.

184-INCH CYCLOTRON DEE PULSING TRANSFORMER

This transformer was originally built to drive the dee structure of the 184-inch cyclotron to a voltage of 50 kv or more. The dee structure represented a capacity load of 5000 $\mu\mu f$. The chief feature of this winding is the use of the condenser paper-aluminum foil type of winding in a coil with 1000 turns on the secondary. Lately this transformer has been used as an insulation test transformer and to outgas the 1 mev injector cyclotron. A photograph of this latest setup is shown in Figure 13.

MULTIPLE CORE TRANSFORMER

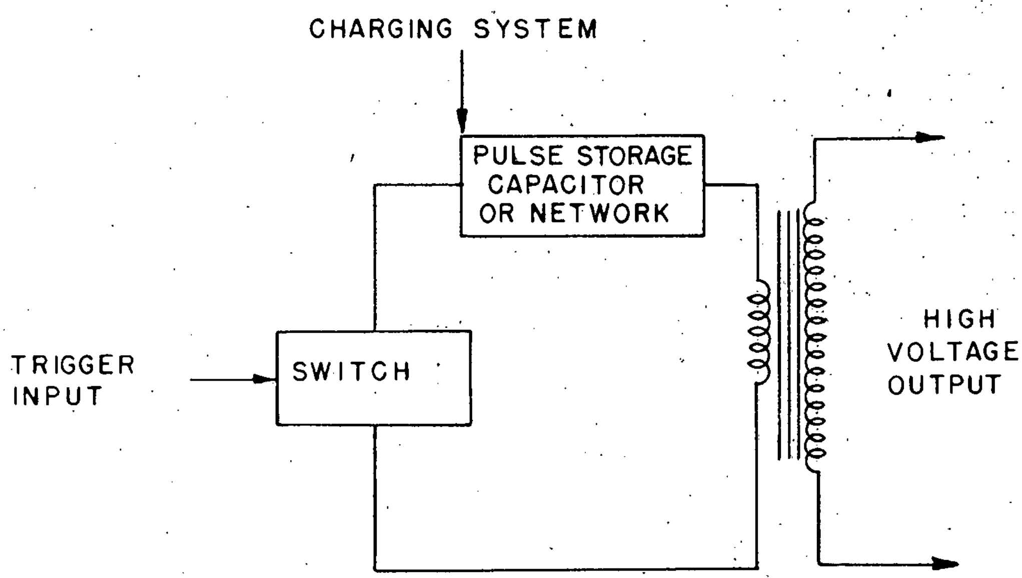
During experiments to determine the fastest possible type of high voltage pulse generator for the 184-inch cyclotron electrostatic deflector, the multiple core pulse transformer (shown in Figure 14) was developed. Since the leakage inductance of a transformer is the basic limitation on the rate of rise of voltage in the secondary, assuming an infinitely fast pulse in the primary, and, as is well known, the leakage inductance varies as the square of the number of turns, the lowest possible leakage inductance, and the fastest pulse will be obtained when the number of turns is one. With this in mind, Q. A. Kerns suggested the multiple core transformer that has a one turn secondary and a fractional number of primary turns. Figure 15 shows cross-sectional views illustrating the various uses to which this type of transformer has been and can be put. These uses are: A singly polarized step up transformer, a push pull transformer with nearly double the output voltage of the singly polarized type, an electromagnetic pulsed particle accelerator, and as the accelerating electrode in a proton synchrotron.

The test push pull transformer shown in Figure 14 worked quite well. The chief difficulty encountered was the energizing of the primary circuit since, with the 300 $\mu\mu f$ load shown, the primary impedance was of the order of .02 ohms. This implies that for a primary voltage of 20 kv a current switch capable of passing 100,000 amperes was required. Both spark gaps and two of the special gas discharge tubes[2] shown in the photograph worked adequately at low repetition rates. The high energy, very fast primary pulses are coupled into the primary through broad flat copper sheet conductors. The primary turns themselves simulate iron loaded cavities in order to pass what amounts to very high frequency energy, while the secondary consists of a large copper rod passing through the center of the core openings. Since the

2 An article describing this tube has been prepared and is to be published in the near future.

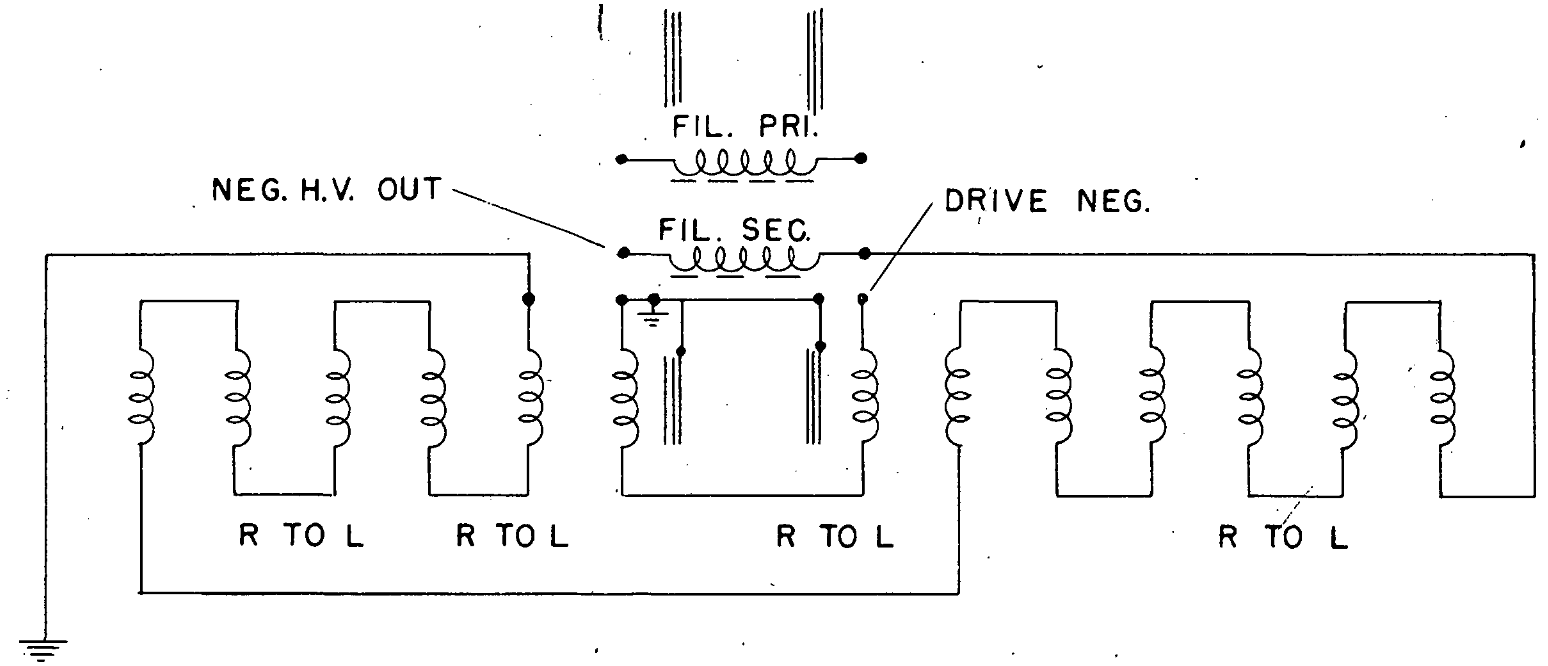
Table I (Continued)

Transformer	Turns Ratio Step-up	Type of Coil Winding	Type of Solid Insulation (All Windings Vacuum impregnated with xfmr Oil)	Leakage Inductance Referred to Secondary	Core Material	Core Window size inches	Core Cross-section inches
Synchrotron Injector, Model I	10	enameled wire	Polystyrene Tape	-	0.002" Oriented Hypersil	2 x 3	1 x 1 1/2
Synchrotron Injector, Model II	5.9	Bifilar tapered Al. foil	Condenser Paper	64 μh	0.002" Oriented Hypersil	3 x 3	1 1/2x1 1/2 in two 3/4 x 1 1/2 sections
Synchrotron Injector, Model III	7.1	Twin Bifilar Tapered Al. foil	same as above	490 μh	same as above		
Synchrotron Injector, 500 KV	50	same as above	same as above	-	same as above	9 x 9	3 x 3
Synchrotron Injector, Air Core	64.3	Al. foil	Condenser paper	-	-	-	-
184-Inch Cyclotron Deflector	8.5	Tapered Al. foil	Polystyrene Tape	7 μh	0.001" Oriented Hypersil	3 x 3	1 1/2x1 1/2 in two 3/4 x 1 1/2 segments
Spark Gap Trigger, Linear Accelerator	6.7	same as above	same as above	-	0.002" Oriented Hypersil	1 x 3	1 x 5/8
Spark Gap Trigger, Injector Cyclotron	10	Al. ribbon	Condenser paper	-	same as above		
Spark Gap Trigger, Saturating Type	4.7	copper foil	Polystyrene Tape	-	0.001" mo-perm-alloy	Toroid ID 1 7/8 OD 3 3/8	3/4 x 3/4
184-Inch Cyclotron Dee Pulsing	10	Al condenser foil	Condenser Paper	55 mh	0.013" hypersil	7 x 4	2 x 2
Multiple Core	20	-	xfmr. Oil	-	3 Cores Per Section 0.001" mo-perm-alloy	Toroid ID 3 1/8 OD 6 1/4	1/2 x 1 1/2

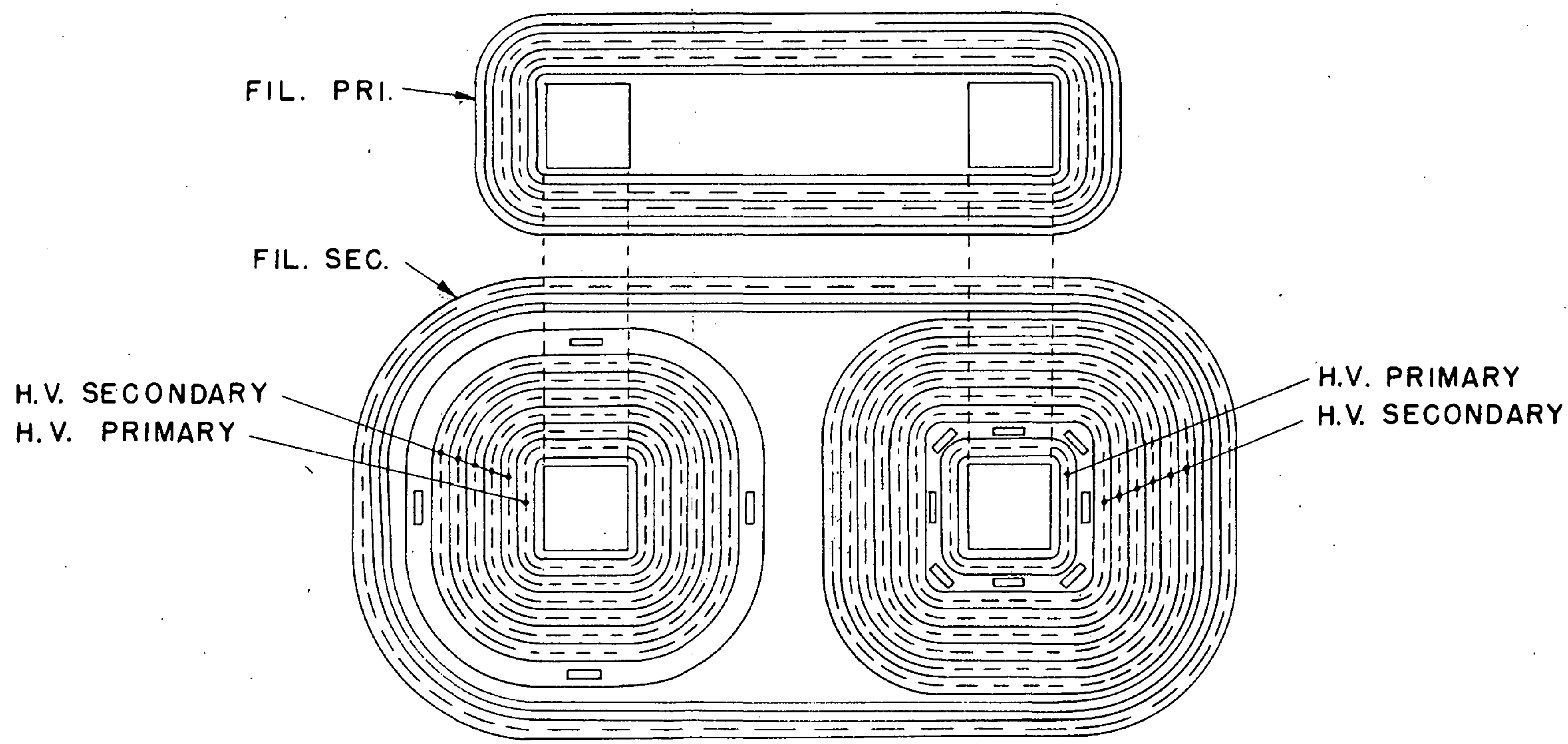


BASIC CIRCUIT FOR ENERGIZING THE PRIMARY CIRCUITS OF THE PULSE TRANSFORMERS.

FIG. 1



WINDING DIRECTIONS



CROSS SECTION OF WINDINGS & INSULATION

WINDING ARRANGEMENT IN SYNCHROTRON INJECTOR TRANSFORMER, MODEL I

FIG. 2

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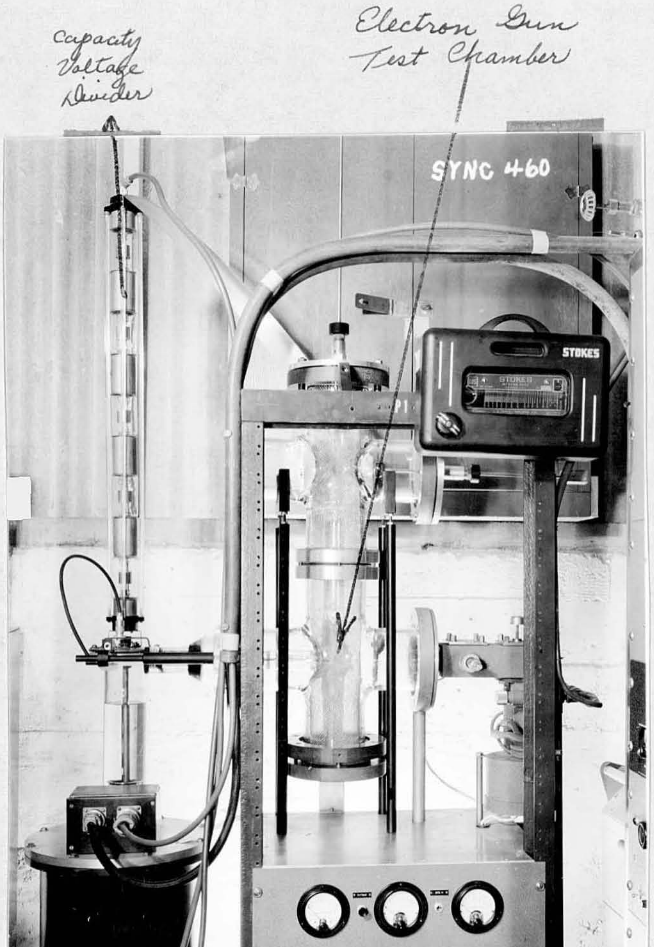
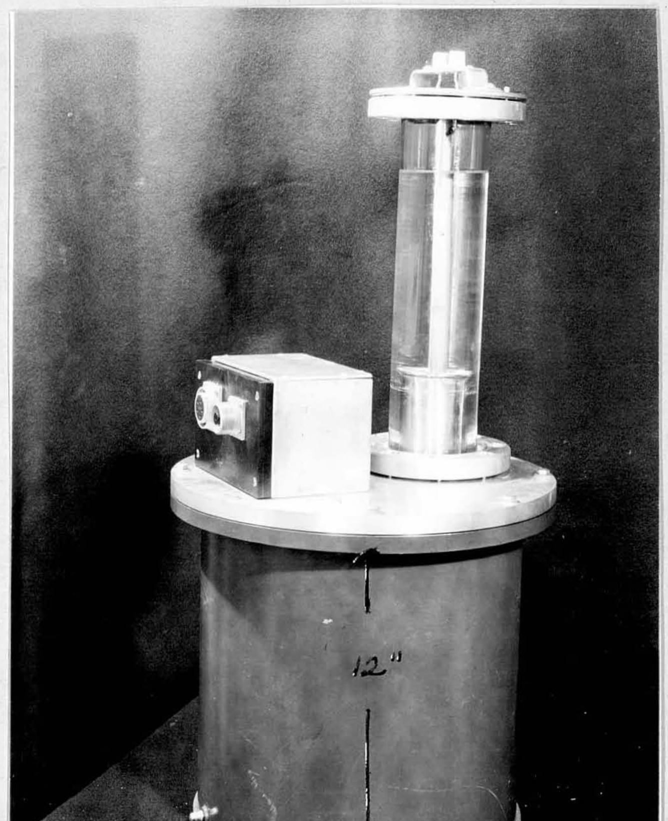




(b) (a)

(a) COMPLETED SYNCROTRON INJECTOR PULSE TRANSFORMER, MODEL I

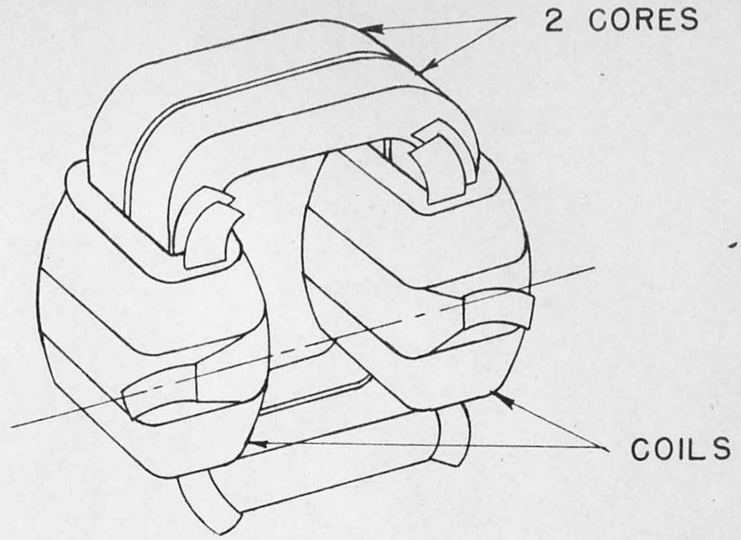
(b) TRANSFORMER INSTALLED ON INJECTOR TEST RACK

FIG. 3

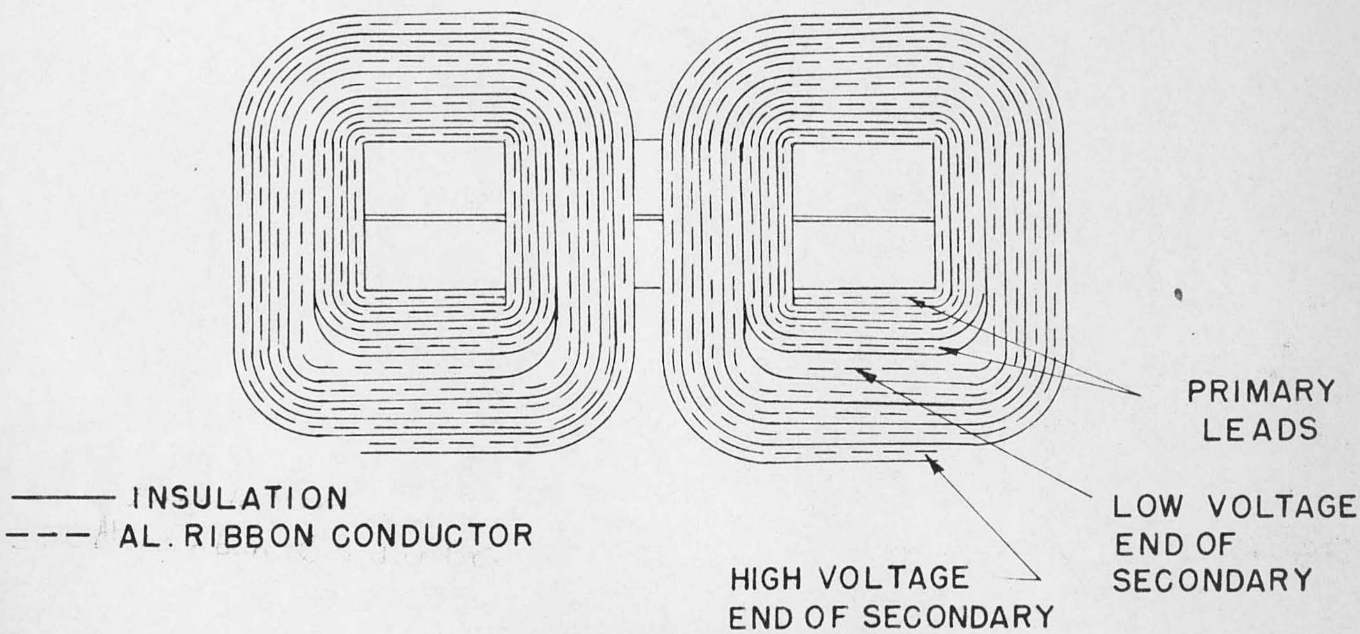
Figure 4.

Synchrotron Injector Transformer Model II and Pulsing Circuits

Installed on Synchrotron



CROSS-SECTION OF CORES AND WINDINGS



METHOD OF WINDING FOIL-PAPER HIGH VOLTAGE PULSE TRANSFORMERS.

FIG. 5

Figure 6

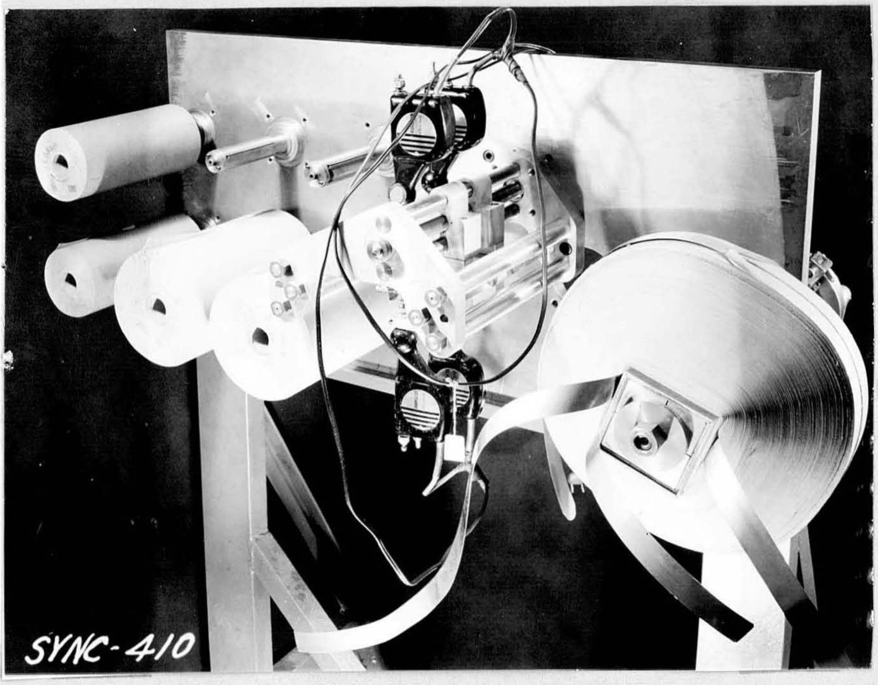
500 KV Synchrotron Injector Transformer

(a) Completed coil on taper cutting winding machine

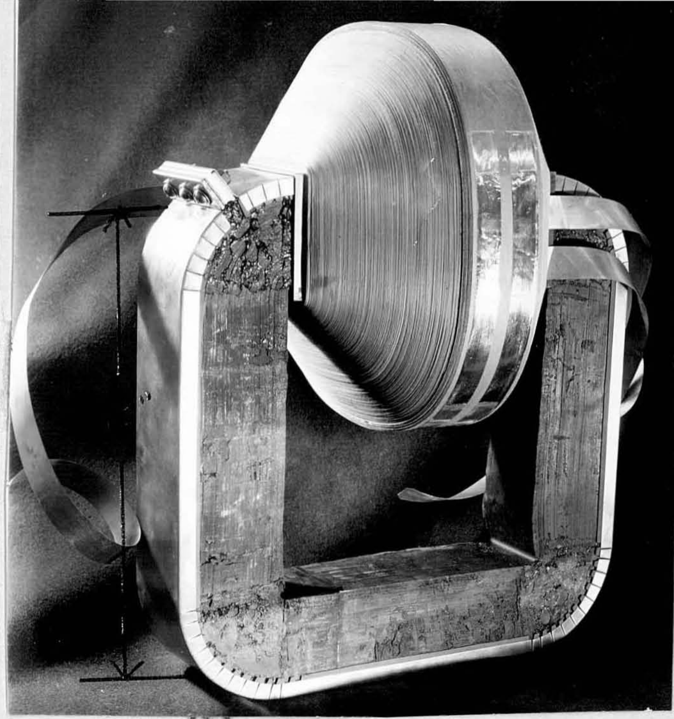
(b) Coil assembled on core

(c) Core and coil assembly mounted in tank prior to impregnation with transformer oil

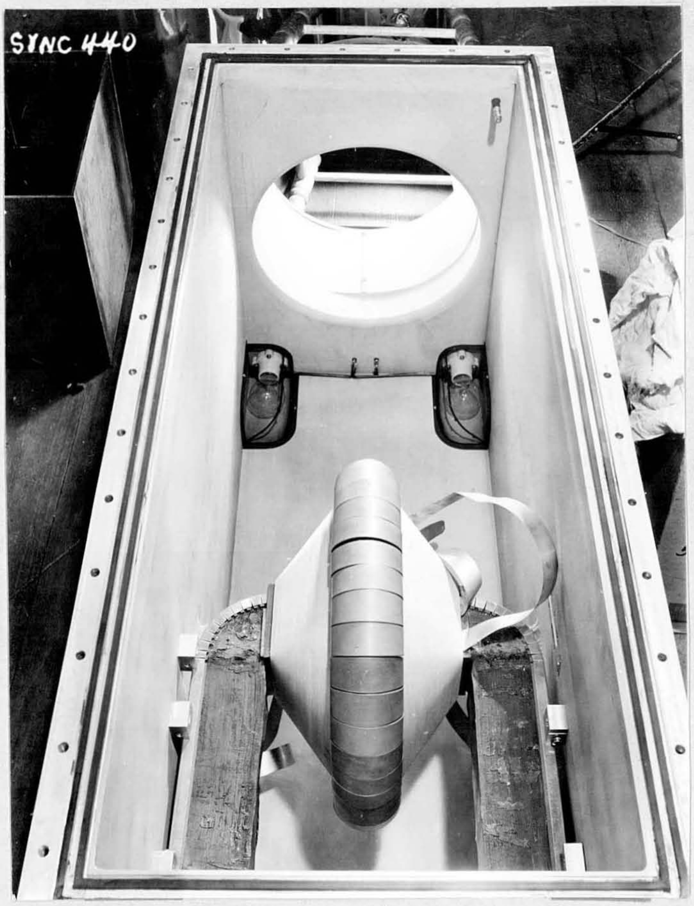
(d) Completed unit with transformer, electron gun and associated vacuum system



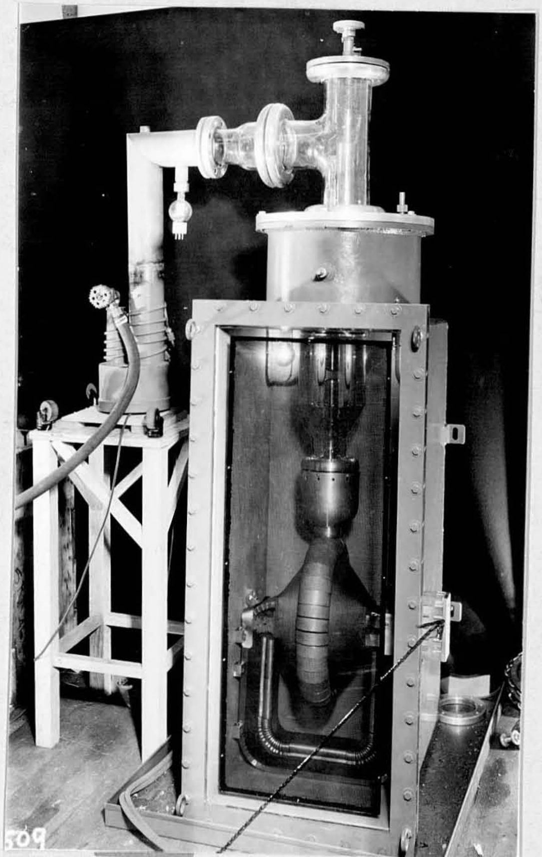
(a)



(b)



(c)



Primary Lead Bushing

(d)

Figure 7.

500 KV Air Core Trnasformer

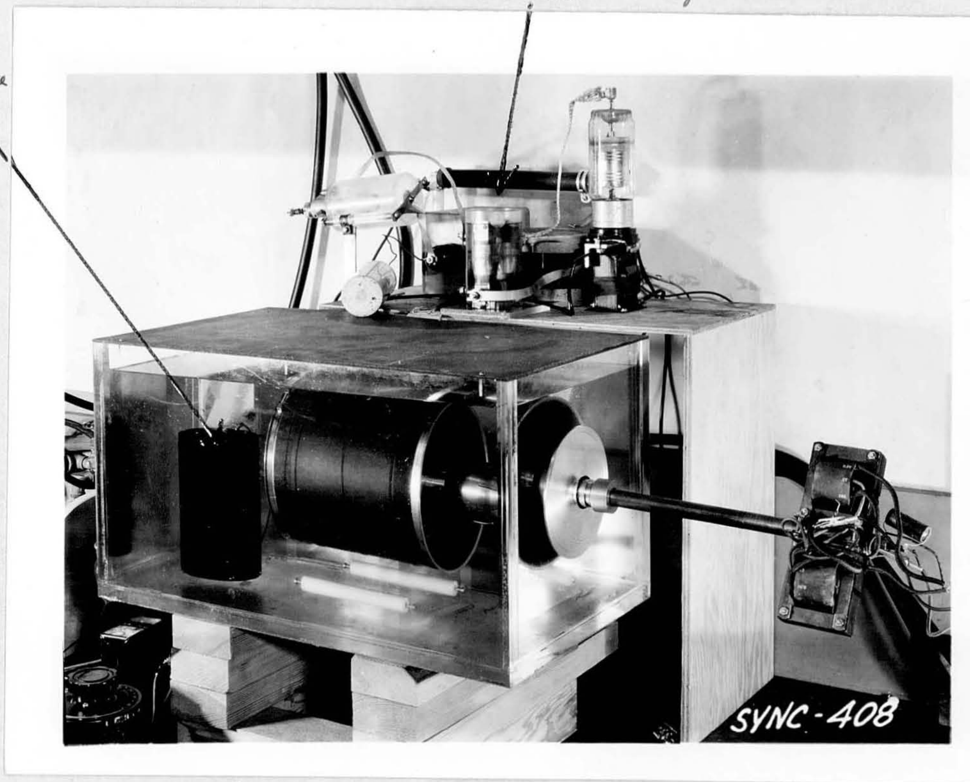
(a) Coil Assembly

(b) Transformer in test setup to drive electron gun

(a)

Saturating Spark Gap Trigger Transformer

Isolating Choke for Electron Gun Filament Power



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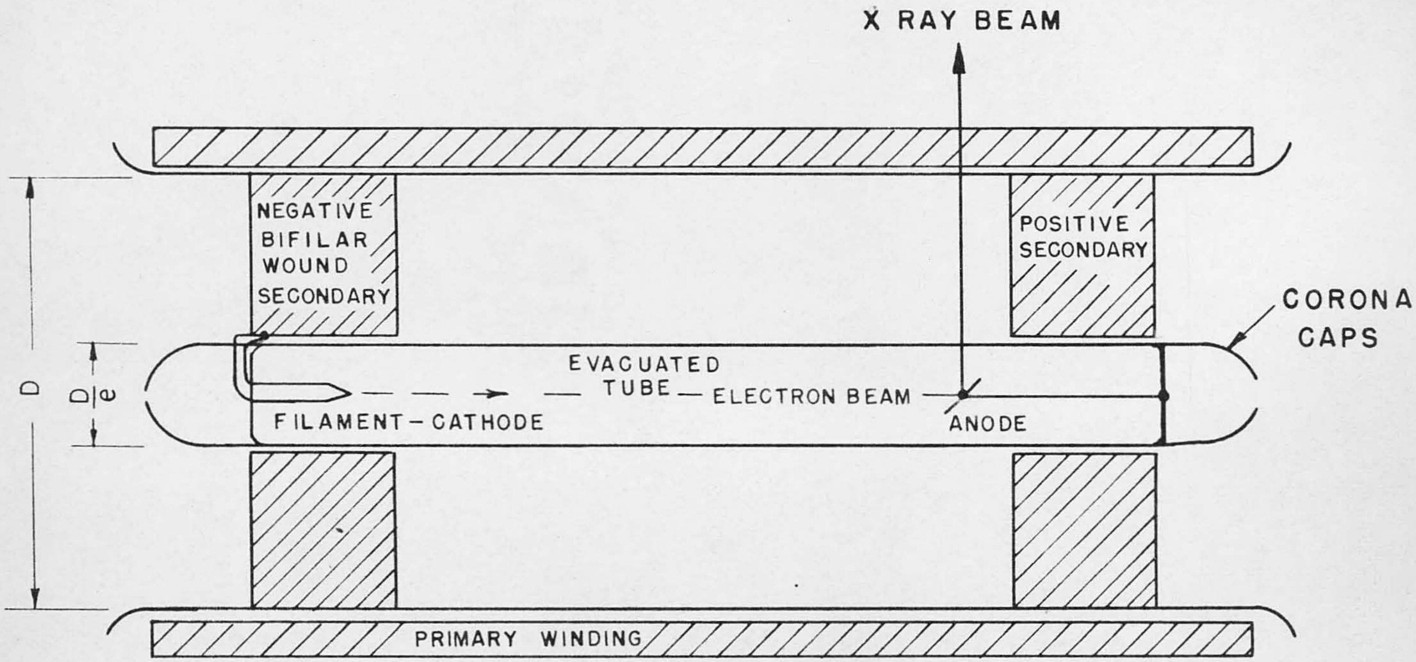


WHOLE ASSEMBLY IMPREGNATED
WITH TRANSFORMER OIL

CROSS-SECTION OF FEASIBLE 1.5 MEV PULSED X-RAY GENERATOR

FIG. 8

Figure 9.

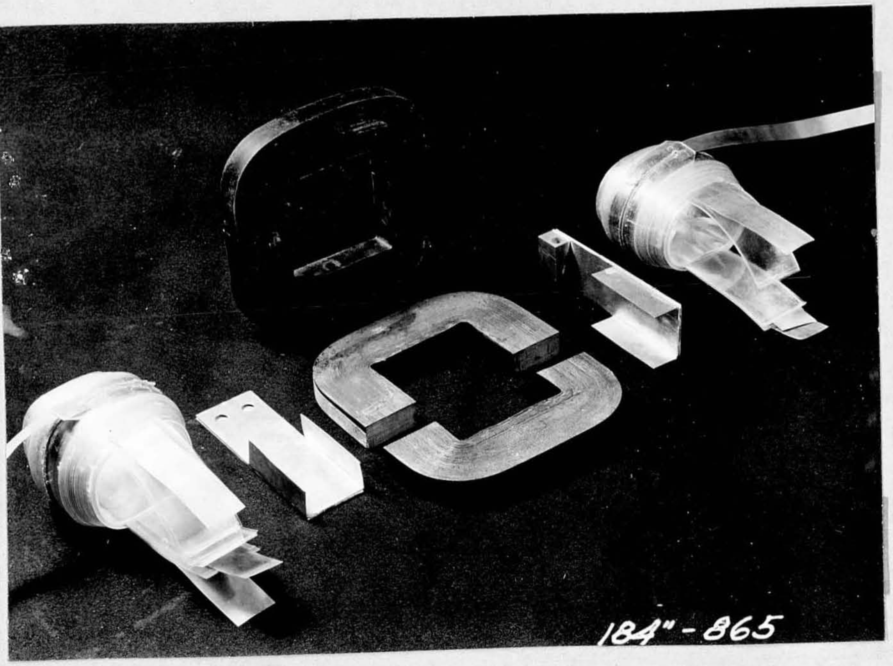
184-Inch Cyclotron Deflector Transformer

(a) Cores, coils and cooling water jackets prior to assembly

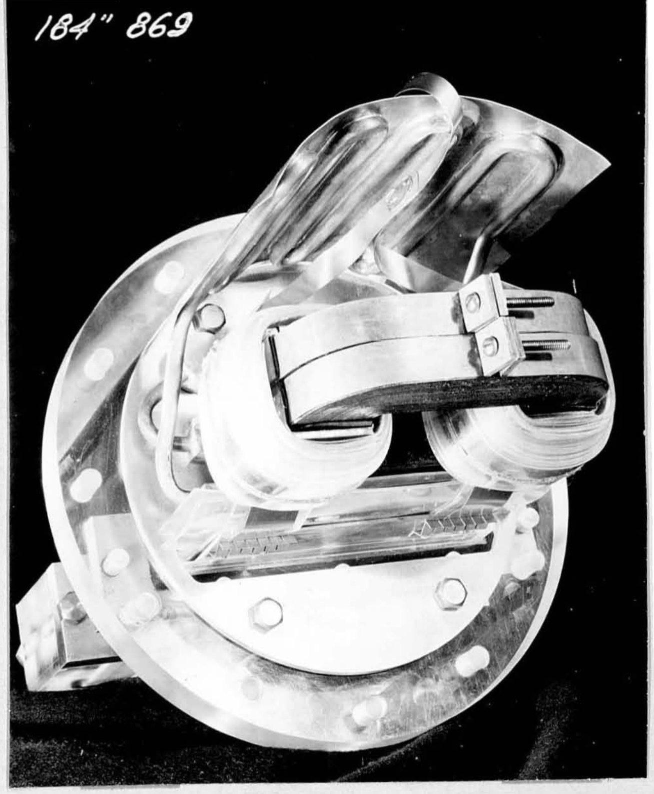
(b) Parts in (a) assembled

(c) Completed Transformer

(d) Transformers installed on pulse generating unit



(a)



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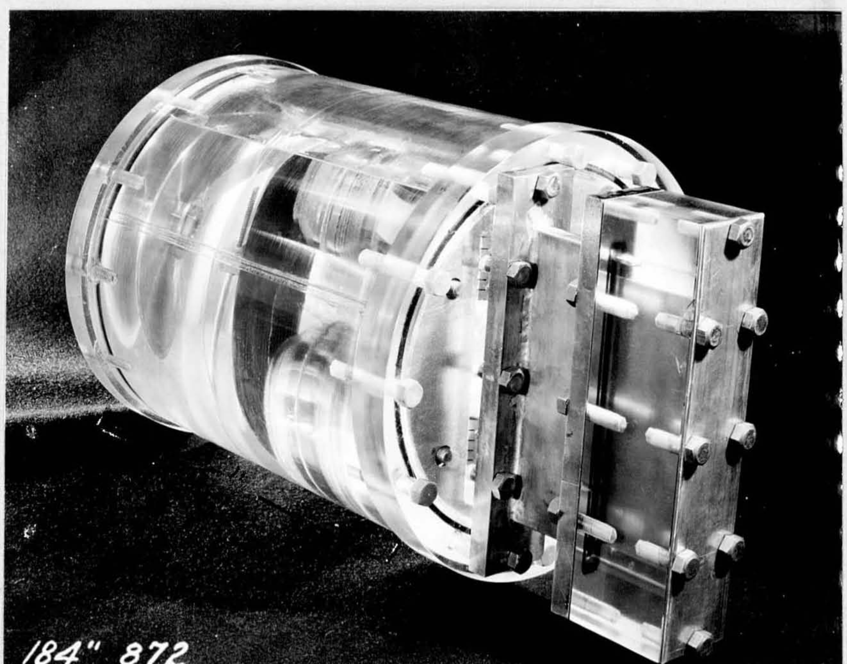
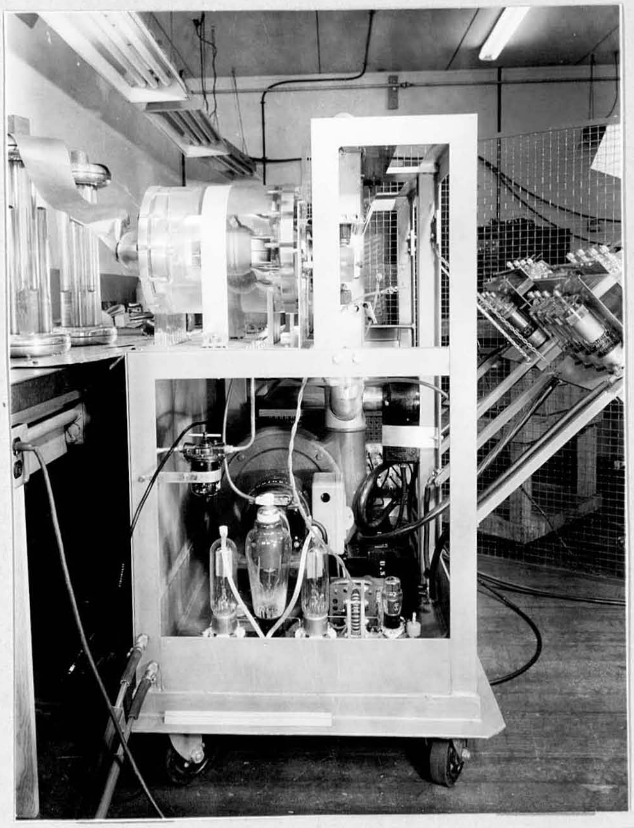


(c)

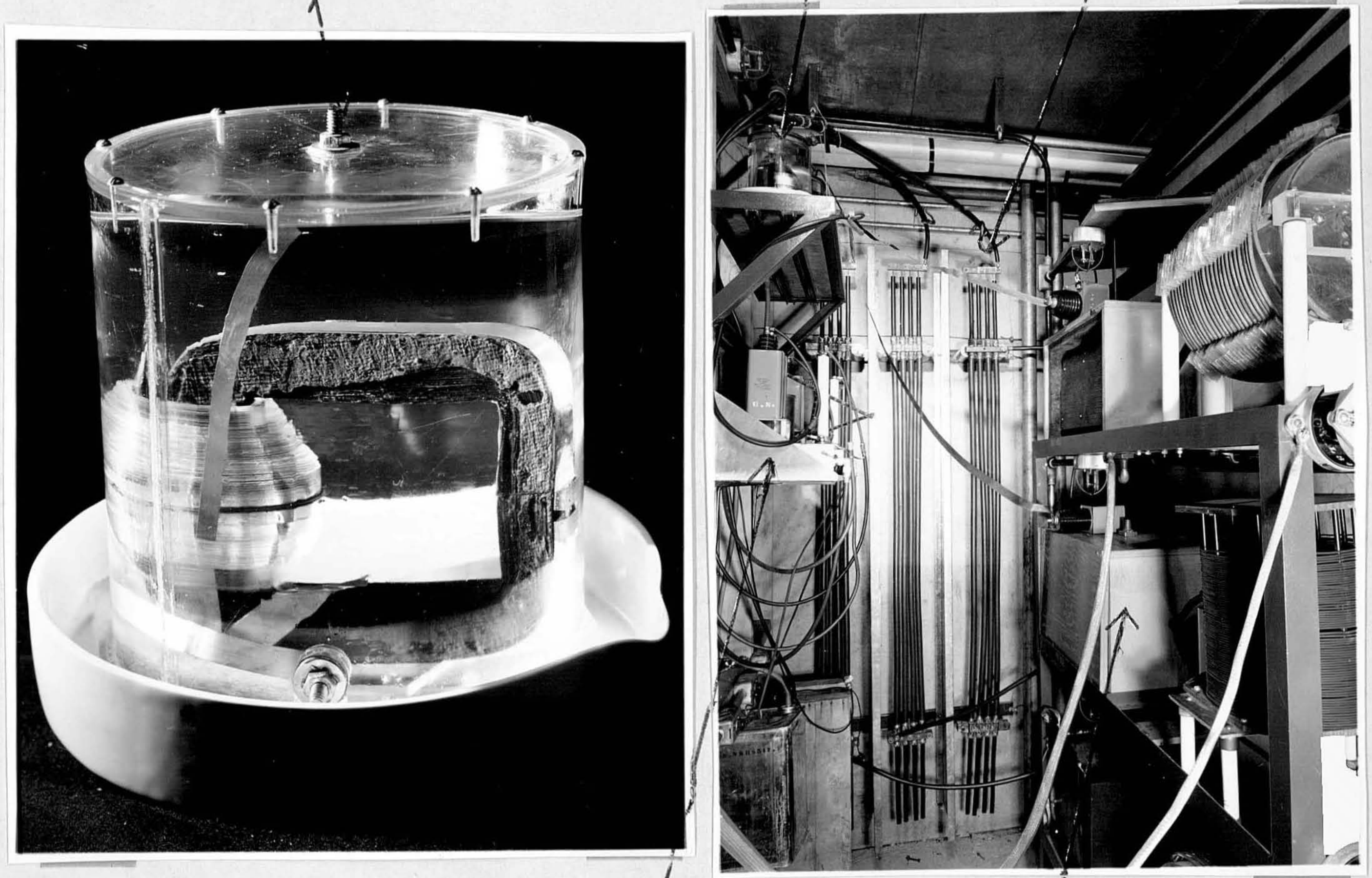


(d)

HIGH VOLTAGE LEAD

TRIGGER TRANSFORMER

RG17V ISOLATION CAPACITORS



(a)

Pulse Chassis

(b) Spark Gap in Soundproof box

LINEAR ACCELERATOR SPARK GAP TRIGGER TRANSFORMER

(a) COMPLETED TRANSFORMER

(b) TRANSFORMER IN INSTALLATION ON LINEAR ACCELERATOR

FIG.10

Figure 11.

Spark Gap Trigger Transformer for Injector Cyclotron Oscillator

Plate Pulse Line

Figure 12.

Saturating Type Spark Gap Trigger Transformer

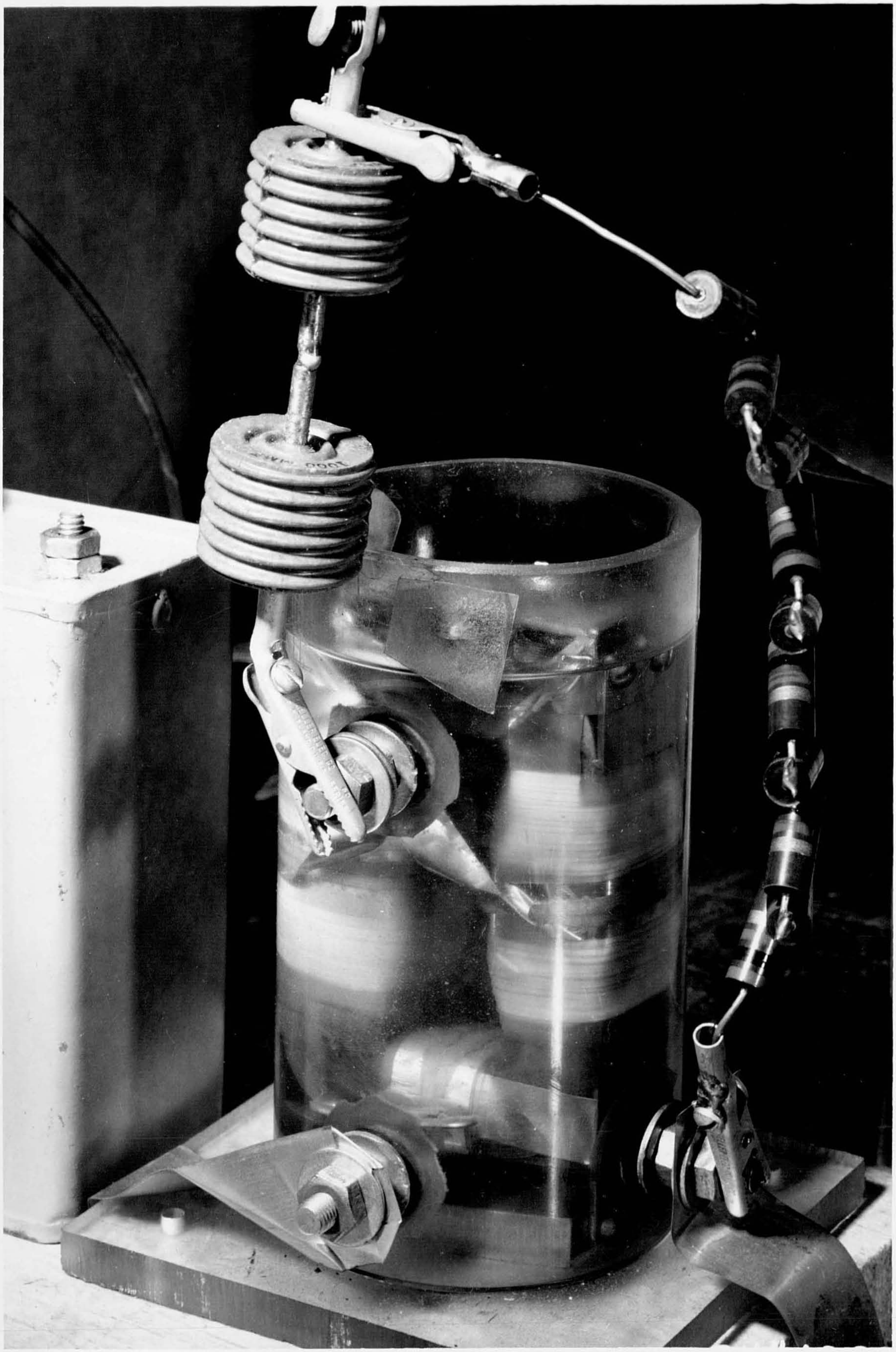
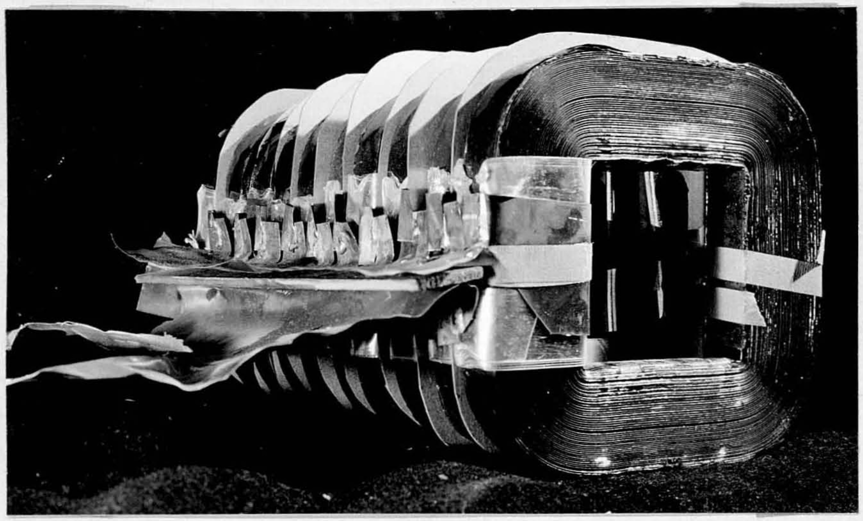
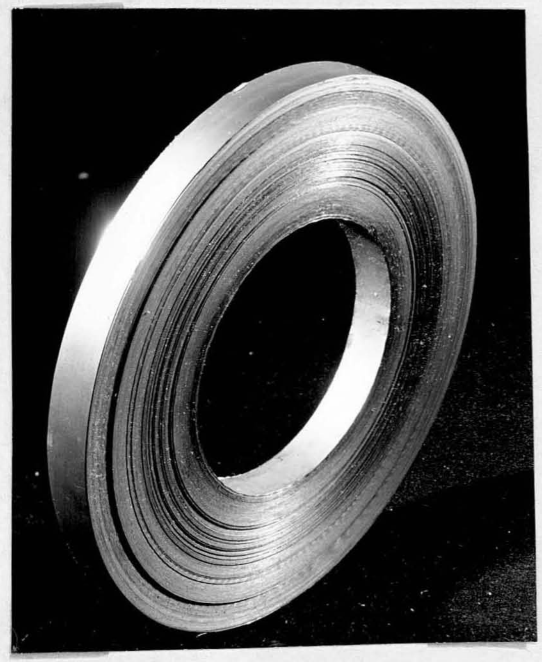


Figure 13.

Insulation Test Transformer and Associated Circuits

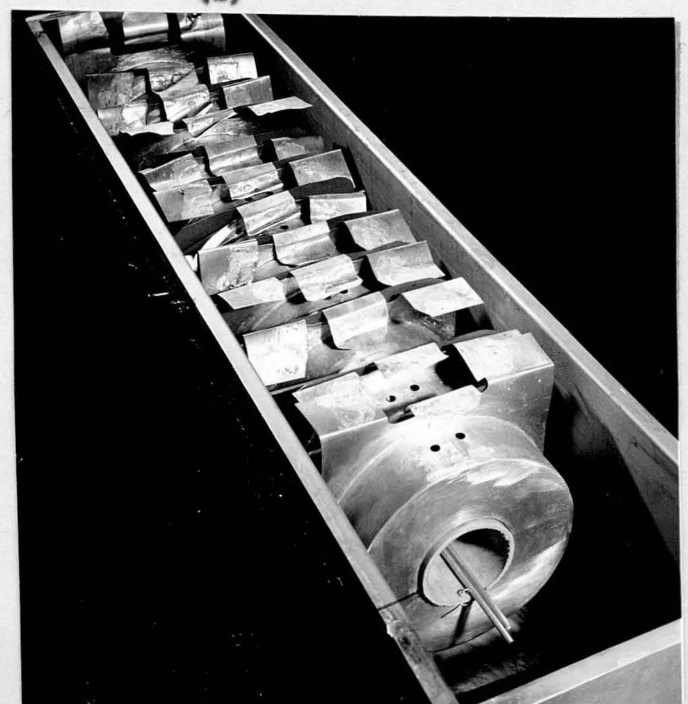


(a)



(b)

(c)



(d)

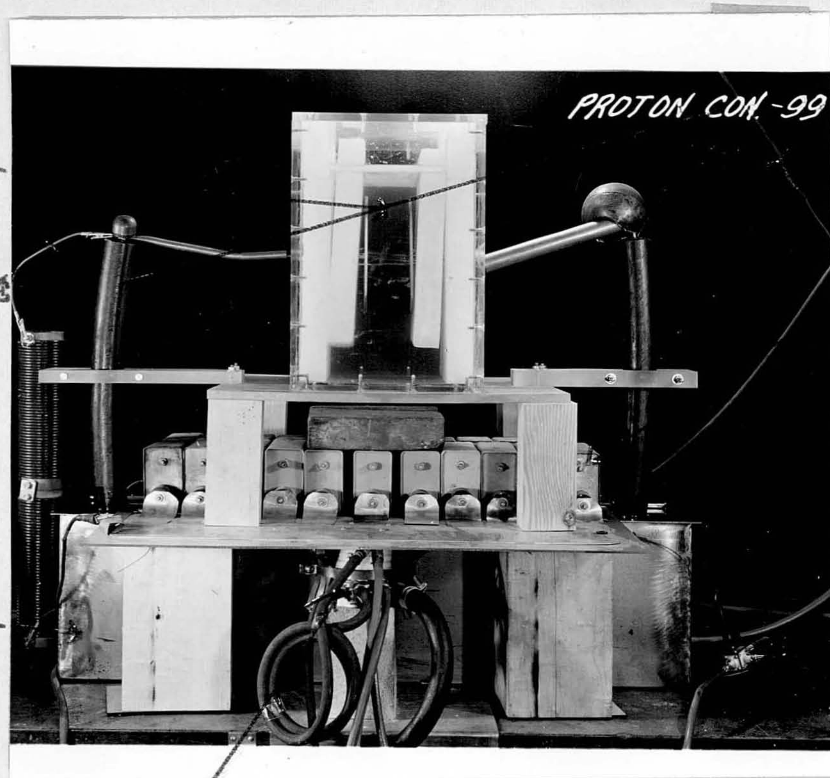
300 μμf, 400kV
Glycerine Filled Load
Test Capacitor

CHOKE COIL FOR
FEEDING IN CORE
BIAS CURRENT

DS

PULSE STORAGE
CAPACITORS

TRANSFORMER
CONTAINER



SPECIAL GAS
DISCHARGE TUBE

(e)

MULTIPLE CORE PULSE TRANSFORMER

(a) FIRST EXPLORATORY MODEL
(b) 0.001" MO-PERMALLY CORE USED IN TRANSFORMER
(c) ONE PRIMARY UNIT OF TRANSFORMER (3 CORES) SHOWING LOW INDUCTANCE LEAD ARRANGEMENT
(d) ASSEMBLY OF TRANSFORMER.
(e) TRANSFORMER IN TEST SET*Up

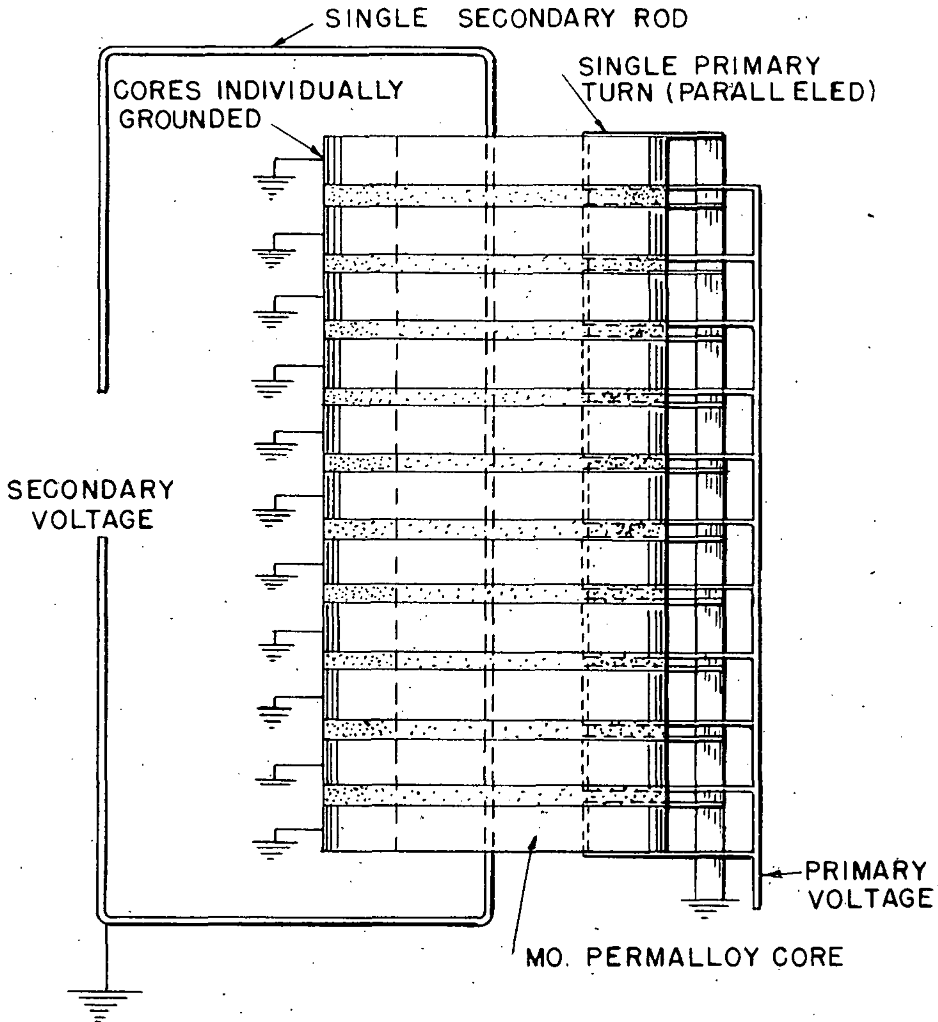


FIG. 15a

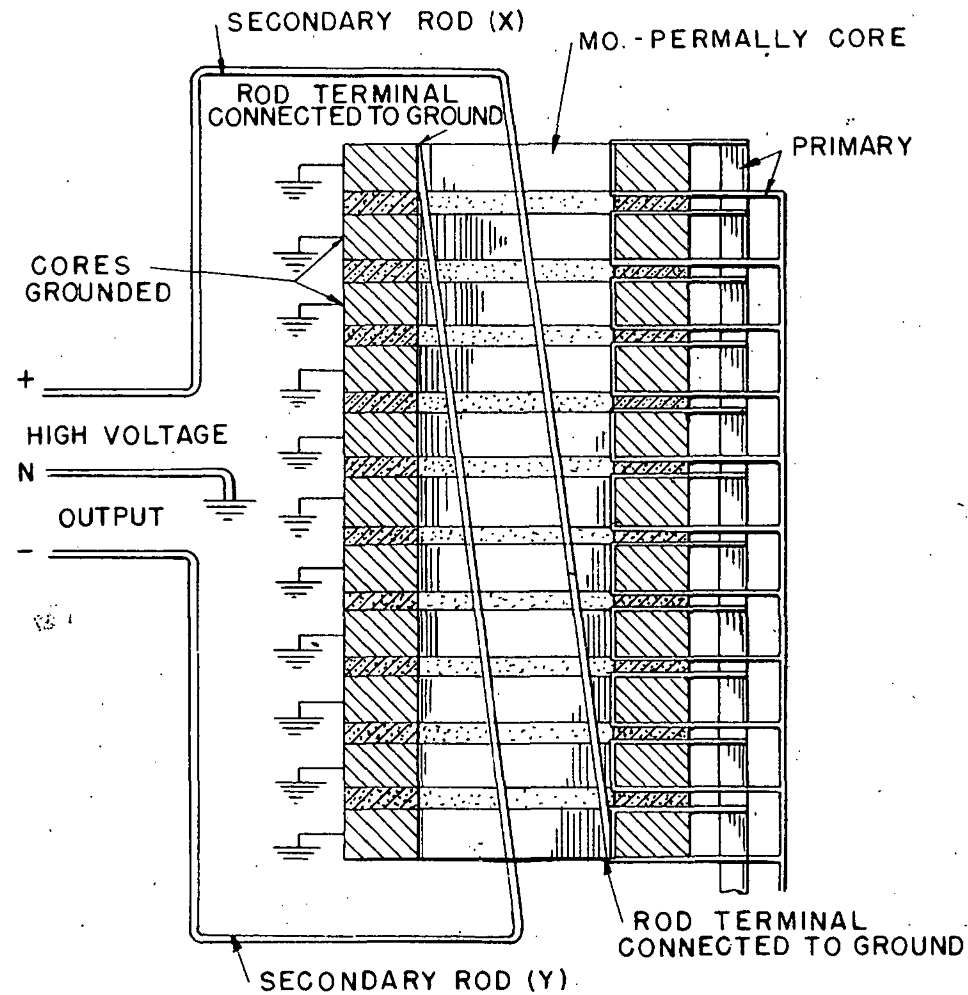


FIG. 15b

MULTIPLE CORE TRANSFORMER USED AS; (a) SINGLY POLARIZED PULSE TRANSFORMER, AND (b) AS PUSH-PULL PULSE TRANSFORMER.

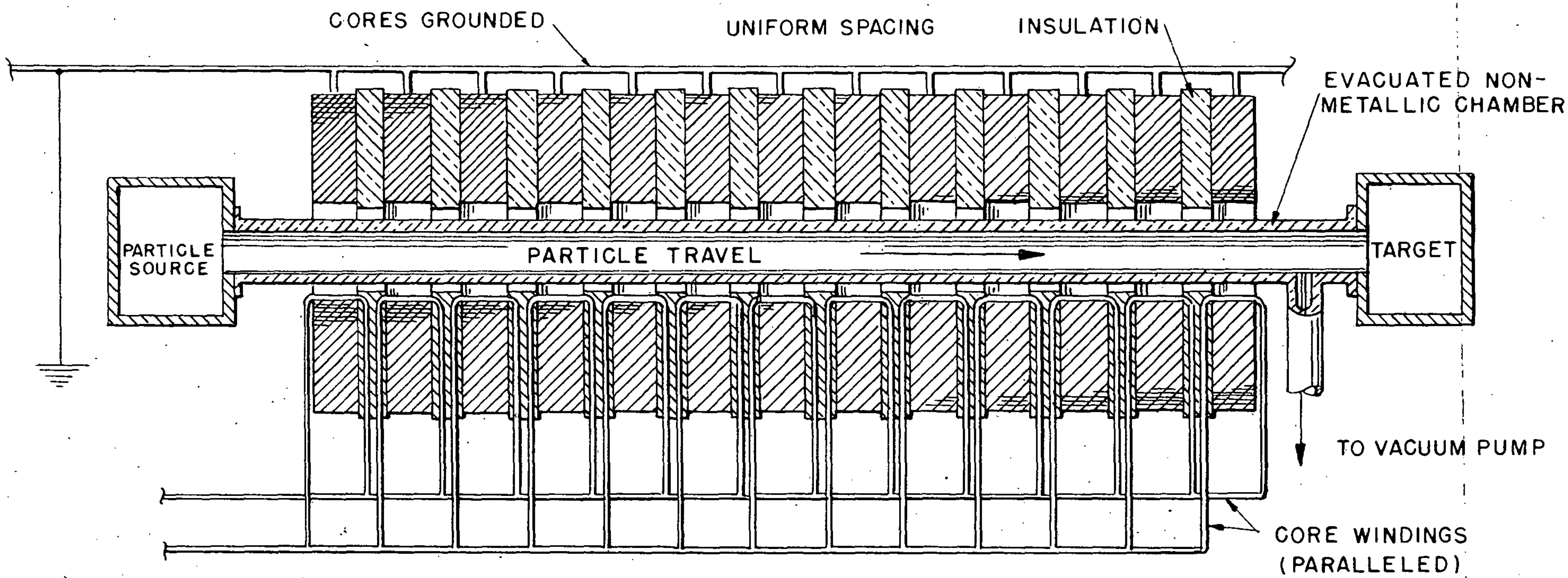


FIG. 15 (c)

MULTIPLE CORE TRANSFORMER USED AS PULSED ELECTROMAGNETIC PARTICLE ACCELERATOR

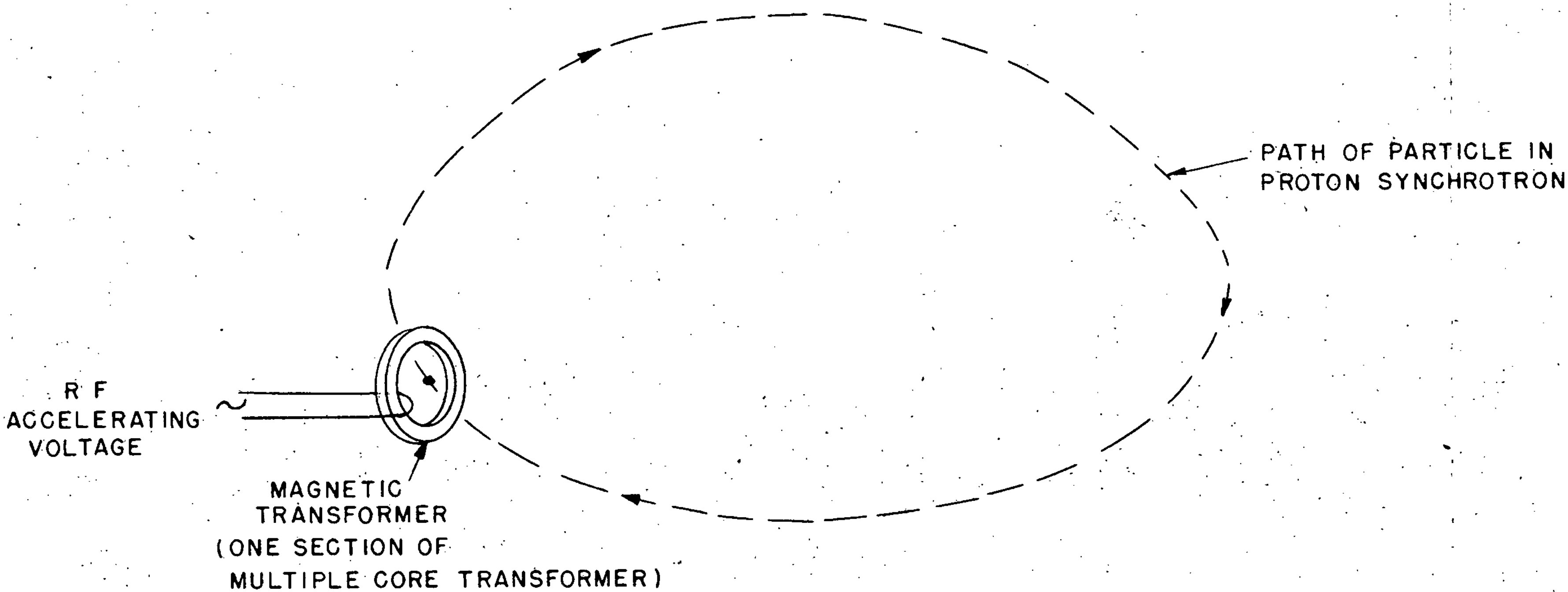


FIG. 15d

MULTIPLE CORE TRANSFORMER USED AS THE ACCELERATING ELECTRODE IN A PROTON SYNCHROTRON PARTICLE ACCELERATOR.