ANALYZING MAGNET SYSTEM FOR THE

ELECTROSTATIC ACCELERATOR

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THESIS

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TABLE OF CONTENTS

		Page
LIST OF ILLUSTRATIONS		iv
Chapter		
I.	INTRODUCTION	1
	The Accelerator Beam Analyzing Devices	
II.	MODIFICATION OF THE ACCELERATOR	6
	The Ion Source The Accelerating Column	
III.	THE MAGNET SYSTEM	11
	General Discussion The Magnet The Power Supply The Ion Path Performance	
APPENDIX		24
BIBLIOGRAPHY		25

LIST OF ILLUSTRATIONS

Figure		Page
1.	Electrostatic Analyzer	3
2.	Magnetic Analyzer	3
3.	Radio-Frequency Oscillator	7
4.	Ionization Chamber	7
5.	Accelerator Column	9
6.	Magnet Components (I)	13
7.	Magnet Components (II)	15
8.	Magnet Support Mechanism	17
9.	Assembled Magnet and Support	19
10.	Magnet Power Supply	20
11.	Drift Tube Assembly	21
12.	Plot of Magnetic Induction	23

CHAPTER I

INTRODUCTION

The Accelerator

Low energy positive-ion accelerators have recently come into rather common use as sources of mono-energetic neutrons. Using ions with energies ranging from fifty kev to a few hundred kev it is possible to produce neutrons with energies up to 13.5 mev. Two common examples of this neutron production process are the $H^2(d,n)He^3$ reaction, which produces 2.5 mev neutrons, and the $H^3(d,n)He^4$ reaction, which produces 13.5 mev neutrons. The existence of this process makes possible the construction of a relatively inexpensive source of a large flux of mono-energetic neutrons. This neutron flux may be controlled by regulating the intensity of the beam reaching the target.

The components of the usual linear accelerator are a positive-ion source, a high voltage supply, an accelerating column, the necessary associated vacuum system, and a beam analyzing device. The first four components listed have been designed and constructed.[1] The ion source and

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[1]Pat M. Windham, "A Deuterium-Deuterium Type Neutron Source," Unpublished Master's thesis, Department of Physics, North Texas State College, 1951.

Kenneth W. Hannah, "A Positive Ion Source," Unpublished accelerating column as originally constructed have been modified to facilitate assembly and operation of the accelerator. These modifications are discussed in Chapter II.

Beam Analyzing Devices

Either electrostatic or electromagnetic deflection principles may be used as the basis for the design of equipment for separating beams of charged particles according to mass, charge, and velocity. An electrostatic device operates as an energy analyzer, whereas a magnetic device is a momentum analyzer. Relativistic effects are negligible in either case since the maximum velocity of the particles of interest is less than 2 per cent of the velocity of light.

An electrostatic analyzer (see Figure 1) consists of two concentric arcs, situated so as to form a portion of a cylindrical condenser, with the beam path between them. The force exerted on a charged particle moving along the ideal path (see Figure 1) between the surfaces is eV/x, where e is the charge on the particle, V is the potential difference between the arcs, and x is the radial separation of the arcs. The force required to keep a particle in this

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Master's thesis, Department of Physics, North Texas State College, 1948.

George T. Paulissen, "Operation and Control of a Radio-Frequency Ion Source," Unpublished Master's thesis, Department of Physics, North Texas State College, 1953.

Vern A. McKay, "Design and Testing of a Positive Ion Accelerator and Necessary Vacuum System," Unpublished Master's thesis, Department of Physics, North Texas State College, 1953.

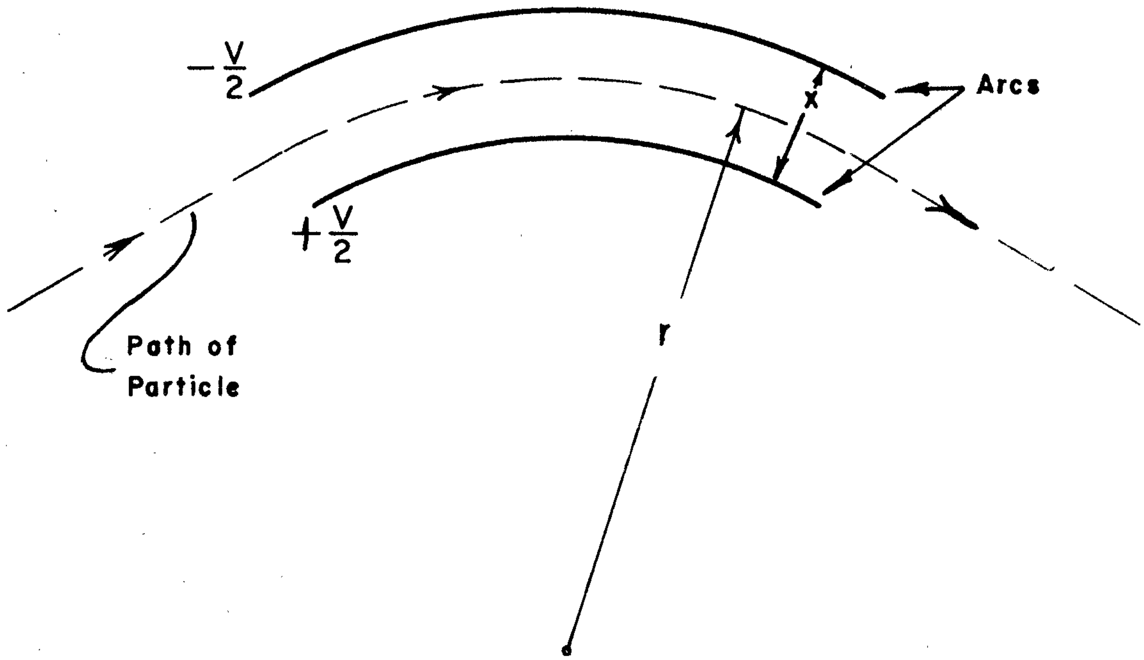

Fig. 1. ——Schematic Diagram of an Electrostatic Analyzer

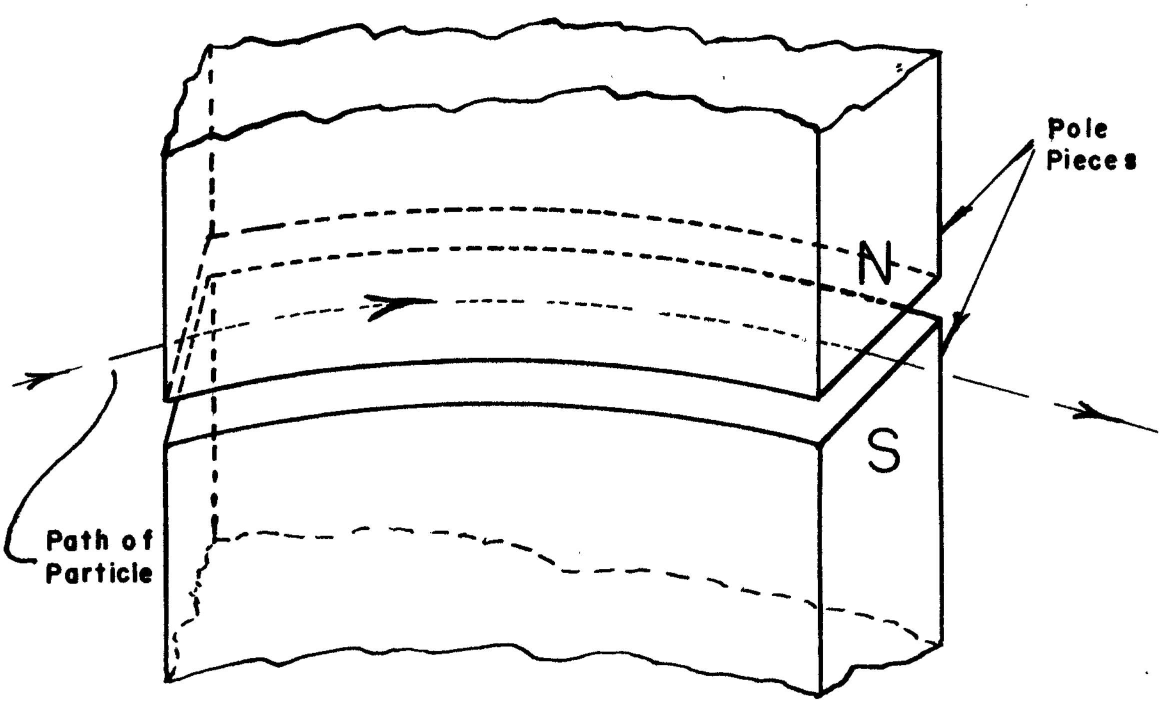

Fig. 2. ——Schematic Diagram of a Magnetic Analyzer

circular orbit is just the centripetal force, mv^2/r. Equating the above expressions gives

$$r = (2x/eV)(mv^2/2). \qquad 1.1$$

The radius of the orbit is seen to be a linear function of kinetic energy. This analyzer also provides a certain amount of space focusing in the plane of the beam.[2]

A magnetic analyzer consists of an electromagnet with parallel pole faces situated so as to create a magnetic field at right angles to the path of the particles (see Figure 2). The force exerted on each charged particle is Bev, where B is the magnitude of the magnetic induction vector. Equating this expression to the centripetal force gives

$$r = (1/Be)(mv) \qquad 1.2$$

In this case the radius of the orbit is a linear function of momentum. In addition, the magnetic analyzer provides the possibility of focusing the beam in the plane tangent to the curved part of the pole pieces and parallel to the direction of the magnetic induction as well as in the plane of the beam.[3]

The accelerator under construction will produce substantial quantities of both D_2^+ and D^+ ions. It is desirable

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[2] A. L. Hughes and V. Rojansky, "On the Analysis of Electronic Velocities by Electrostatic Means," Physical Review, XXXIV(July 15, 1929), 284.

[3] Morton Camac, "Double Focusing with Wedge Shaped Magnetic Fields," Rev. of Sci. Inst., XXII(March, 1951), 297.

to keep D_2^+ ions from reaching the target since they heat the target without adding appreciably to the neutron flux. Since both the D_2^+ and D^+ ions are accelerated to the same energies, it is clear that an electrostatic analyzer could not possibly be used to separate these two components of the ion beam. Thus, the necessity of using a magnetic beam analyzer with the linear accelerator in neutron production applications is evident. In addition, the focusing flexibility of the magnetic analyzer is advantageous.

CHAPTER II

MODIFICATION OF THE ACCELERATOR

The Ion Source

As originally designed,[1] the ion source required several hundred watts of electrical power and this, of necessity, isolated at 250 kilovolts above ground. Furthermore, the nature of this radio-frequency ion source was such as to require a continuous and complex tuning procedure during the operation of the accelerator.

A new radio-frequency exciter of very simple design has been constructed. The circuit for this oscillator is shown in Figure 3. All the high voltage power necessary for its operation is supplied by a small twenty-seven-volt d.c. dynamotor requiring a total power input of less than fifty watts. The oscillator furnishes all the radio-frequency power necessary to ionize the gas in a chamber modeled after the Oak Ridge ionization chamber described by Moak.[2] This source is powered from storage batteries, which are easily isolated at 250 kilovolts from ground.

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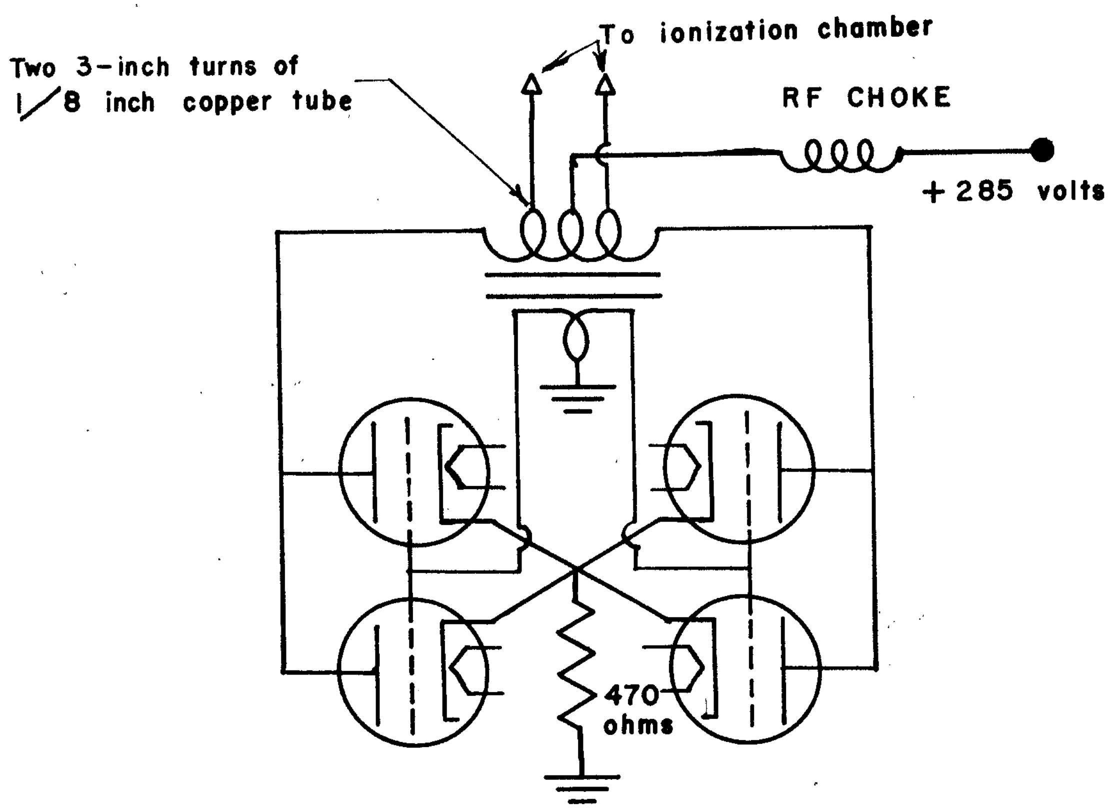
[1]Paulissen, op. cit., p. 5.

[2]C. D. Moak, H. Reese, and W. M. Good, "Design and Operation of a Radio Frequency Ion Source for Particle Accelerators," Nucleonics, IX (September, 1951), 18-23.



(All tubes are 2C22's)
(Filaments are connected in series.)

Fig. 3.--Circuit Diagram of Radio-Frequency Oscillator

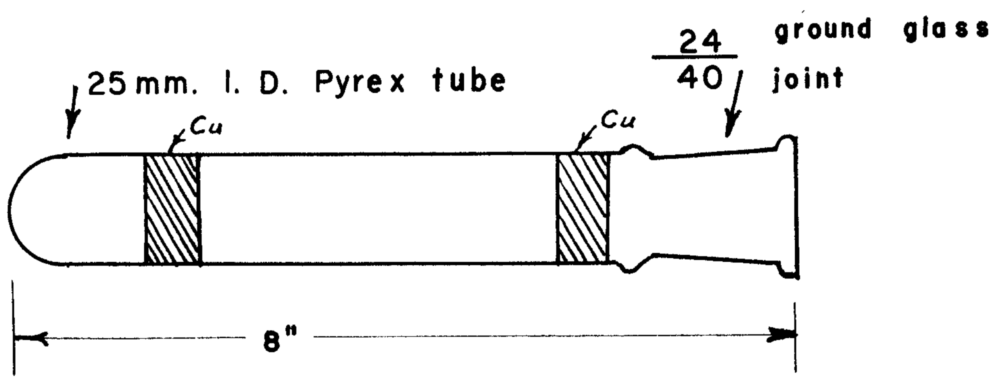


Fig. 4.--Ionization Chamber

The oscillator operates at approximately eighty megacycles. It does not require tuning in order to remain in operation, since there is a single tuned circuit consisting of a three-inch coil and the inter-electrode capacitances of the tubes plus the distributed capacitances of the circuit wiring. Necessary adjustment in operating frequency may be made by changing the dimensions of the coil.

The radio-frequency oscillator is capacitively coupled to the ionization chamber by two copper straps around the chamber as shown in Figure 4. These straps are tapped across the oscillator coil at points which were experimentally determined as those giving the maximum tolerable oscillator loading consistent with stability.

The Accelerating Column

A recent change in the location of the accelerator necessitated a horizontal position for the column rather than the vertical arrangement as specified by McKay.[3] The horizontal arrangement required a sealing compound with a much higher tensile strength than the Apiezon W with which the column was originally sealed. Several unsuccessful attempts were made to seal a column with Araldite 100, which requires a high curing temperature (110°C), but in each case uneven cooling of the sealed column caused the porcelains to

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[3]McKay, *op. cit.*, pp. 8-15.

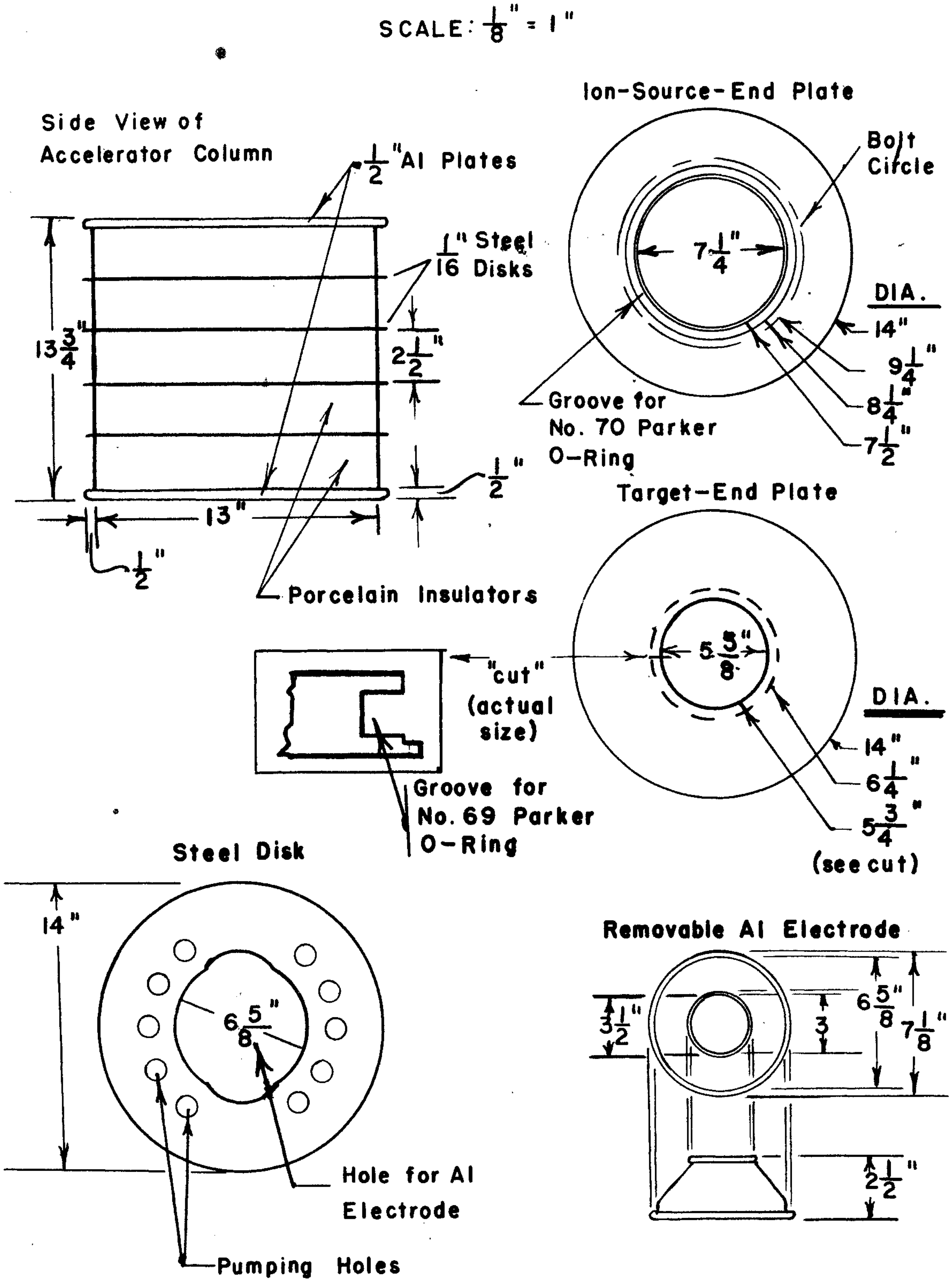

Fig. 5. --The Accelerator Column

crack. A modified column (see Figure 5) was constructed at the Balconis Research Center of The University of Texas with the help and advice of E. L. Hudspeth and J. Peoples.

CHAPTER III

THE MAGNET SYSTEM

General Discussion

A relatively simple magnet design was chosen so that the various parts could be machined on available equipment. The first detail to be considered in the magnet design was the relationship between the radius of curvature of the beam path and the number of ampere-turns required in the coils. It was obviously desirable to use the least radius consistent with a relatively low power dissipation in the windings. A few simple computations indicated that a radius of ten inches would meet all the requirements for the present system.

The magnet must be capable of bending the most magnetically rigid ions encountered into the ten-inch orbit when they have an energy of 250 kev. A rearrangement of Equation 1.2 gives

$$B = mv/re \qquad 2.1$$

as the magnitude of the required magnetic induction. Furthermore, the relation of energy to velocity is

$$v = \sqrt{2Ve/m}\,. \qquad 2.2$$

Equation 2.2 gives a velocity of 3.46×10^6 m/sec for D_2^+ ions accelerated to 250 kev. Then Equation 2.1 shows that a magnetic field strength of 5690 gauss is required to bend these particles into a circular orbit of ten-inch radius.

An approximation to the required magnetomotive force (mmf) was obtained by using the equation for an idealized magnetic circuit,[1]

$$\text{mmf} = Ni = B(s/\mu + d/\mu_0) \text{ ampere-turns,} \qquad 2.3$$

where N is the number of turns in the winding, i is the current in each turn, s is the length of the flux path in the steel, d is the air-gap width, μ_0 is the magnetic permeability of free space, and μ is the permeability of mild steel ($188\mu_0$).[2] A set of magnet dimensions, s = 0.65 meters and d = 0.0127 meters, chosen by a series of trial calculations gives, from Equation 2.3,

$$\text{mmf} = 7320 \text{ ampere-turns.} \qquad 2.4$$

The Magnet

Flux Path

The magnet proper was constructed of commercial-grade mild steel, which has a carbon content of not more than 0.30 per cent. A carbon content much greater than this seriously affects the permeability of steel.[3] The steel parts of the magnet are shown in Figure 6. Half-inch steel bolts were

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[1]Nathaniel H. Frank, Introduction to Electricity and Optics, 1950, p. 271.

[2]Arthur W. Smith, E. D. Campbell, and W. L. Fink, "The Effect of Changes in Total Carbon and in the Condition of Carbides on the Magnetic Properties of Steel," Physical Review, XXIII(March, 1924), 377-85.

[3]Ibid.

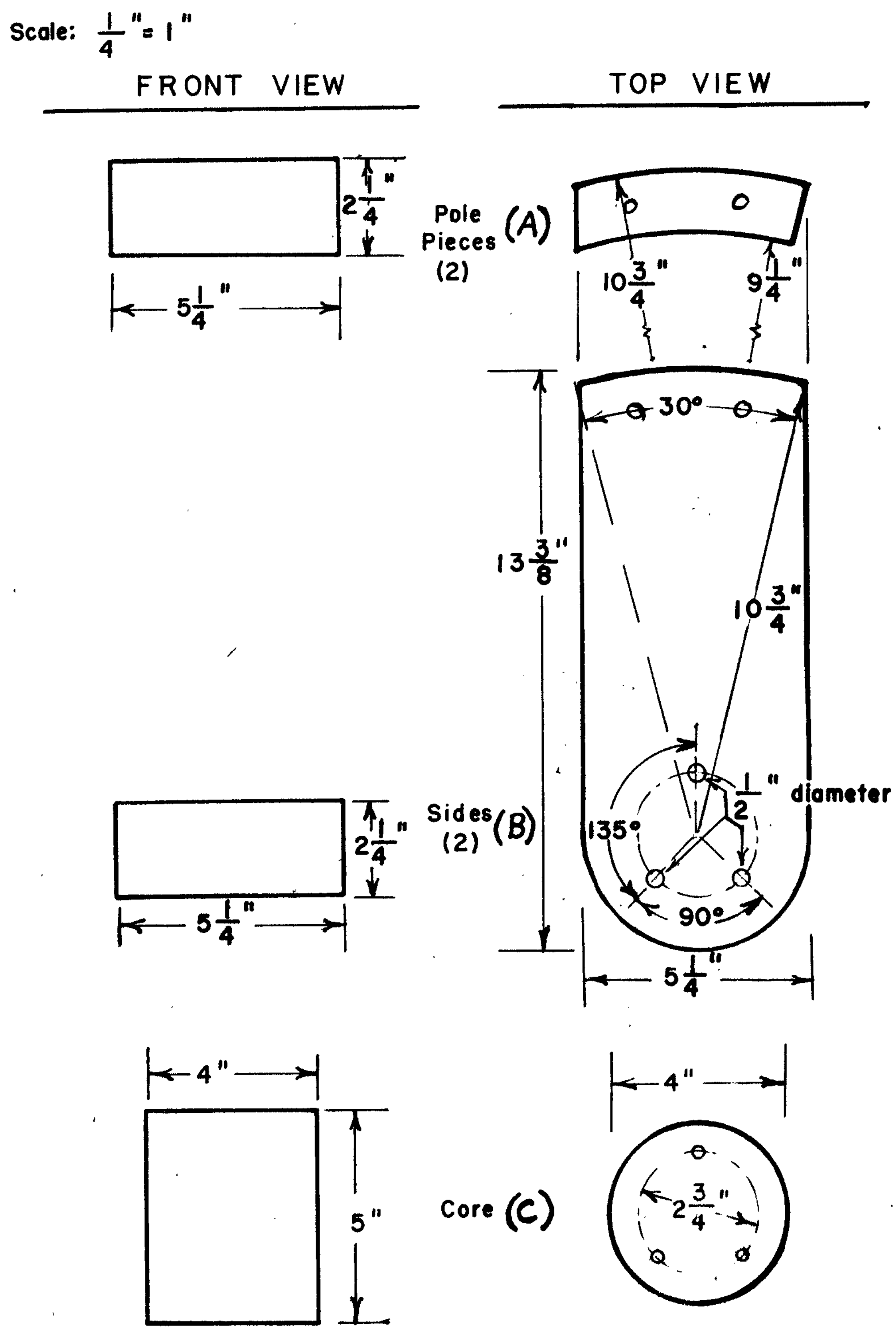

Fig. 6. --Magnet Components (I)

used to fasten the sides (B) to the central core (C), around which the coil forms fit, and to fasten the pole pieces (A) to the sides. All surfaces in direct contact with other surfaces were machined to an accuracy of two thousandths of an inch. Other surfaces were sawed to shape on a band saw and ground to a smooth finish.

Should future applications of the accelerator require sharper focusing of the beam, Camac's equations[4] could be used as a guide for reshaping the pole pieces.

Winding

The winding was divided evenly among three coils of approximately 1500 turns each, for a total of 4500 turns. Therefore, a current of approximately 1.65 amperes is required to produce the maximum of 5690 gauss needed to deflect 250 kev D_2^+ ions into the ten-inch orbit.

The coil forms were constructed of aluminum disks mounted on steel cylinders which were made to fit closely around the central steel core to prevent movement of the coils (see Figure 7). The finished forms were lined with heavy fish paper before being wound with 16-gauge General Electric "Heavy Formex" wire. The ends of each length of wire were connected to a "Textolite" binding post attached to the outer edges of the aluminum disks. A potential

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[4] Camac, op. cit., 297-304.

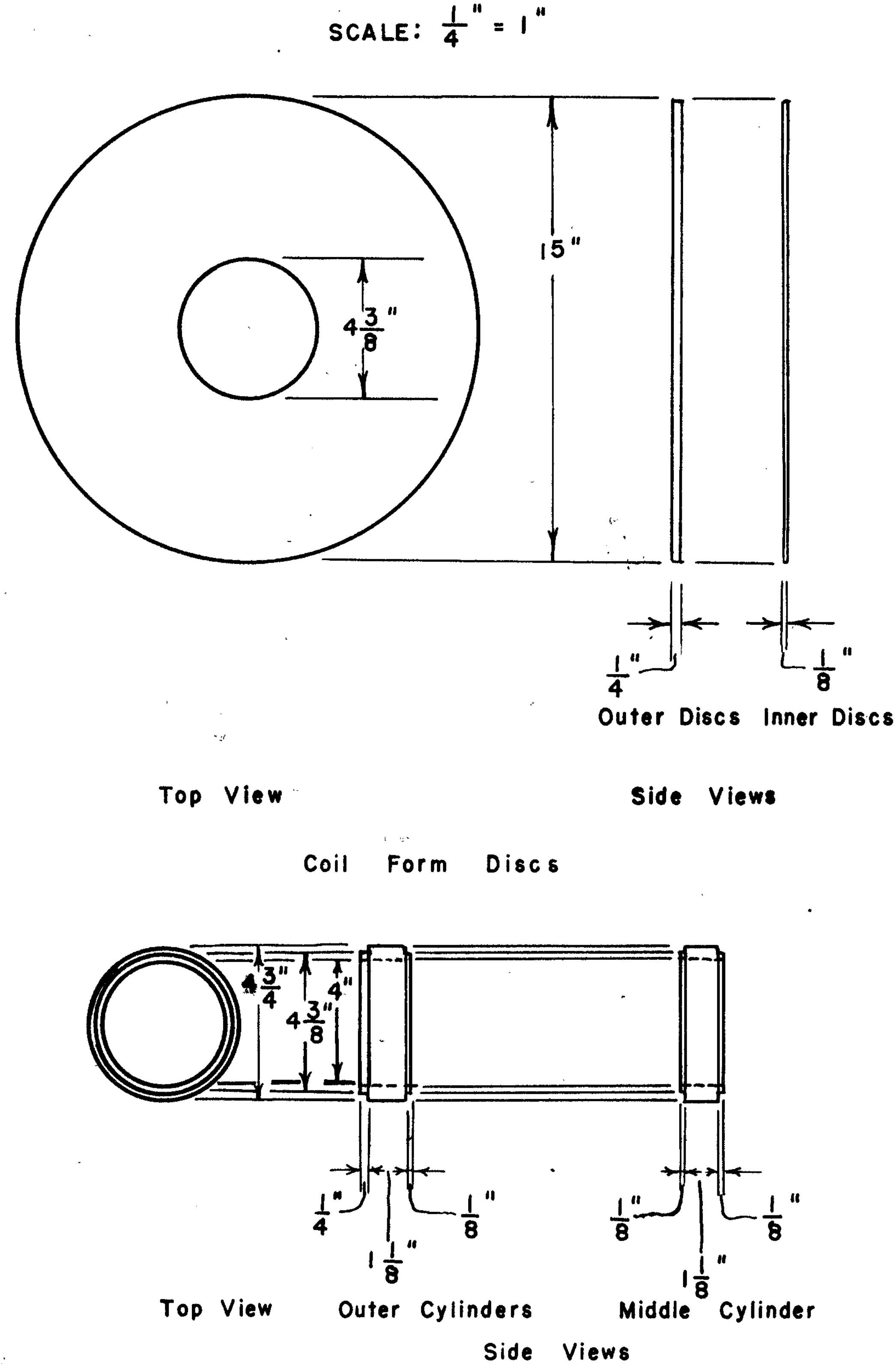

Fig. 7 --Magnet Components (II)

difference of approximately fifty volts is required across the terminals of the winding, which consists of the three coils connected in series.

Support

In order to facilitate alignment of the magnet a support was designed which allows movement in the horizontal plane, both parallel and at right angles to the length of the column, in addition to providing for rotation of the magnet about a vertical axis. The support also permits limited movement in the vertical direction.

All parts of the support (see Figure 8) near the magnet are made of brass, because of its magnetic properties. A disk (A) 5.5 inches in diameter is attached to the lower side of the magnet with four machine screws. To this is soldered a brass pipe (B) of 5.75 inches outside diameter. A six-inch ring of eighth-inch stock is soldered at the bottom of this pipe so that it extends one-eighth-inch beyond the pipe. Three layers (D,E,F) of brass plate form a support for the ring. The ring rests on the solid plate (F), fitting into the plates (E), which also rest on (F), The top plate (D) fits around the brass pipe (B) and is bolted to the lower plates. In order to facilitate angular movement of the magnet a rod (I) is attached to the lower part of the brass pipe. A clamping device (H) is provided with which the end of the rod is held, thereby holding the magnet in the correct

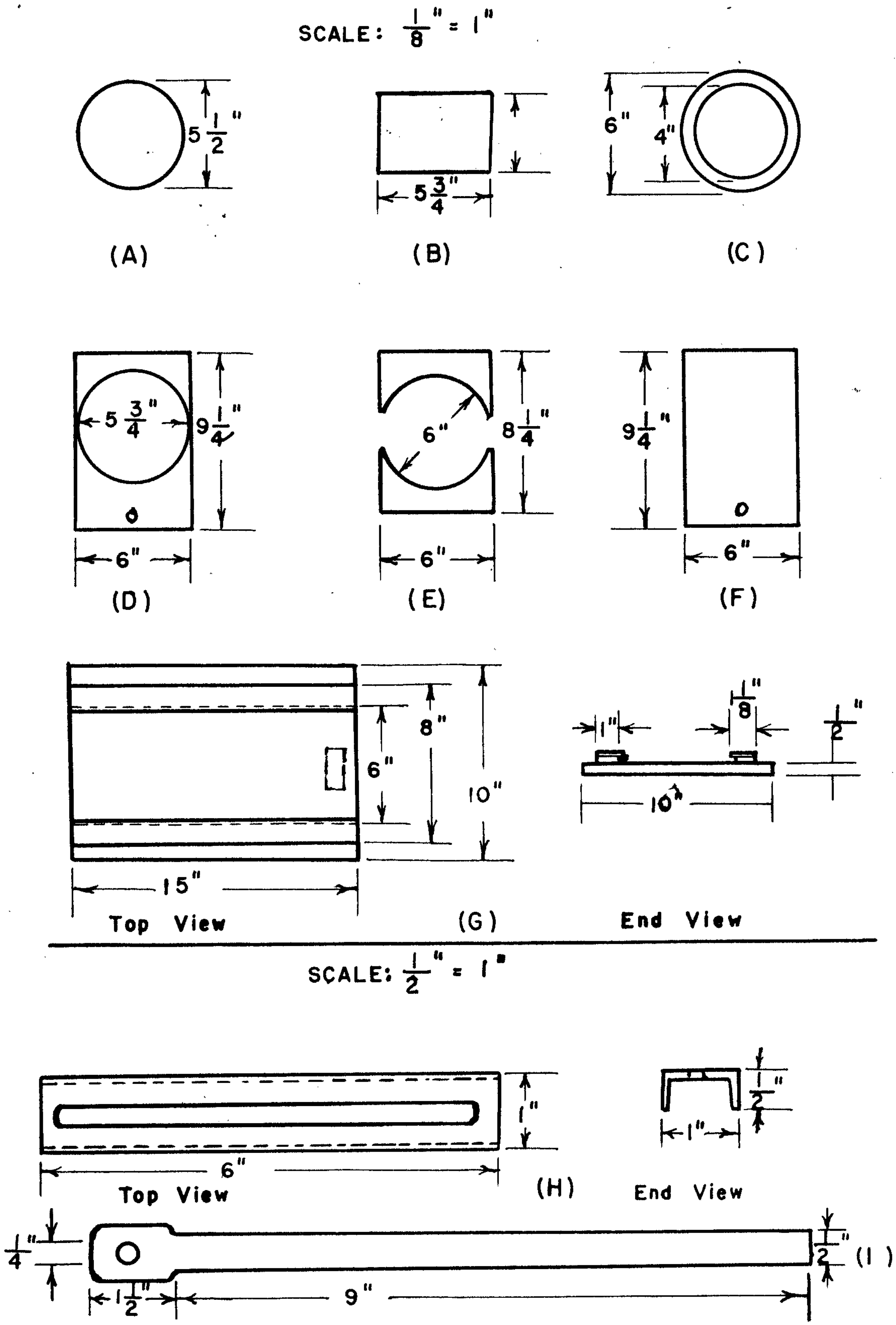

Fig. 8.--Magnet Support and Adjustment Mechanism

angular position. The lower brass plate rests on a half-inch steel plate (G) upon which it slides to provide adjustment at right angles to the accelerator axis. The steel plate is mounted on angle-irons so that it can be moved in a direction parallel to the accelerator axis by means of a threaded rod. Small changes in the vertical position of the steel plate can be made by adjusting four supporting screws.

Power Supply

The magnet power supply consists of a conventional full-wave bridge rectifier using "Tungar" diodes (see Figure 10). The filament power is obtained from a transformer with a single primary and four isolated secondary windings. The output voltage is controlled by a variable transformer. Fine adjustment is provided by a two-ohm power resistor connected in series with the output. Power for both filaments and a.c. input is controlled by a single master switch. Smoothing of the d.c. output is accomplished by a small L-section filter and a large condenser in parallel with the magnet load.

The Ion Path

The beam emerges from the vacuum pump manifold through a small hole in the wall opposite that connected to the accelerating column. It then enters the drift tube, which carries it between the pole faces and on to the target. The drift tube (see Figure 11) is constructed of 1.375 inch

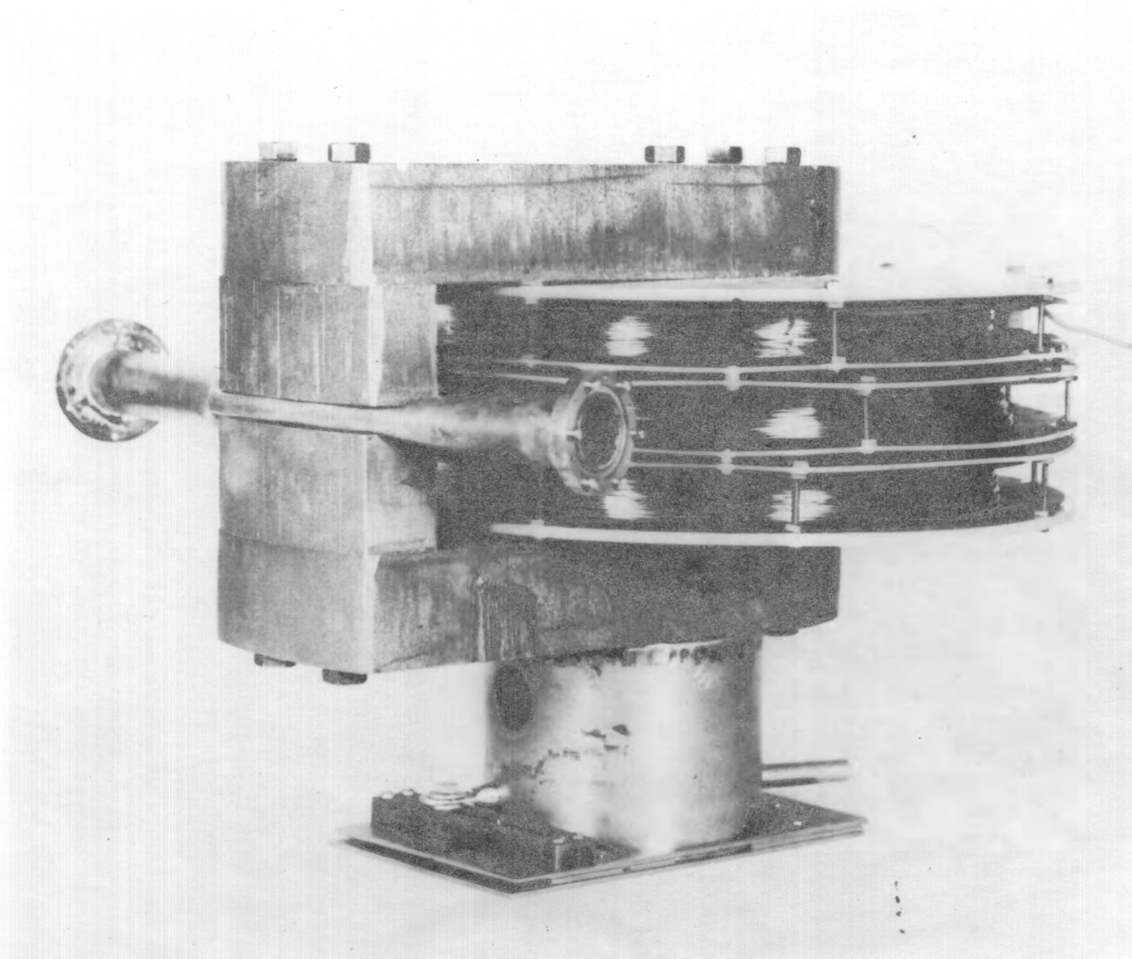

Fig. 9. --Assembled Magnet and Support

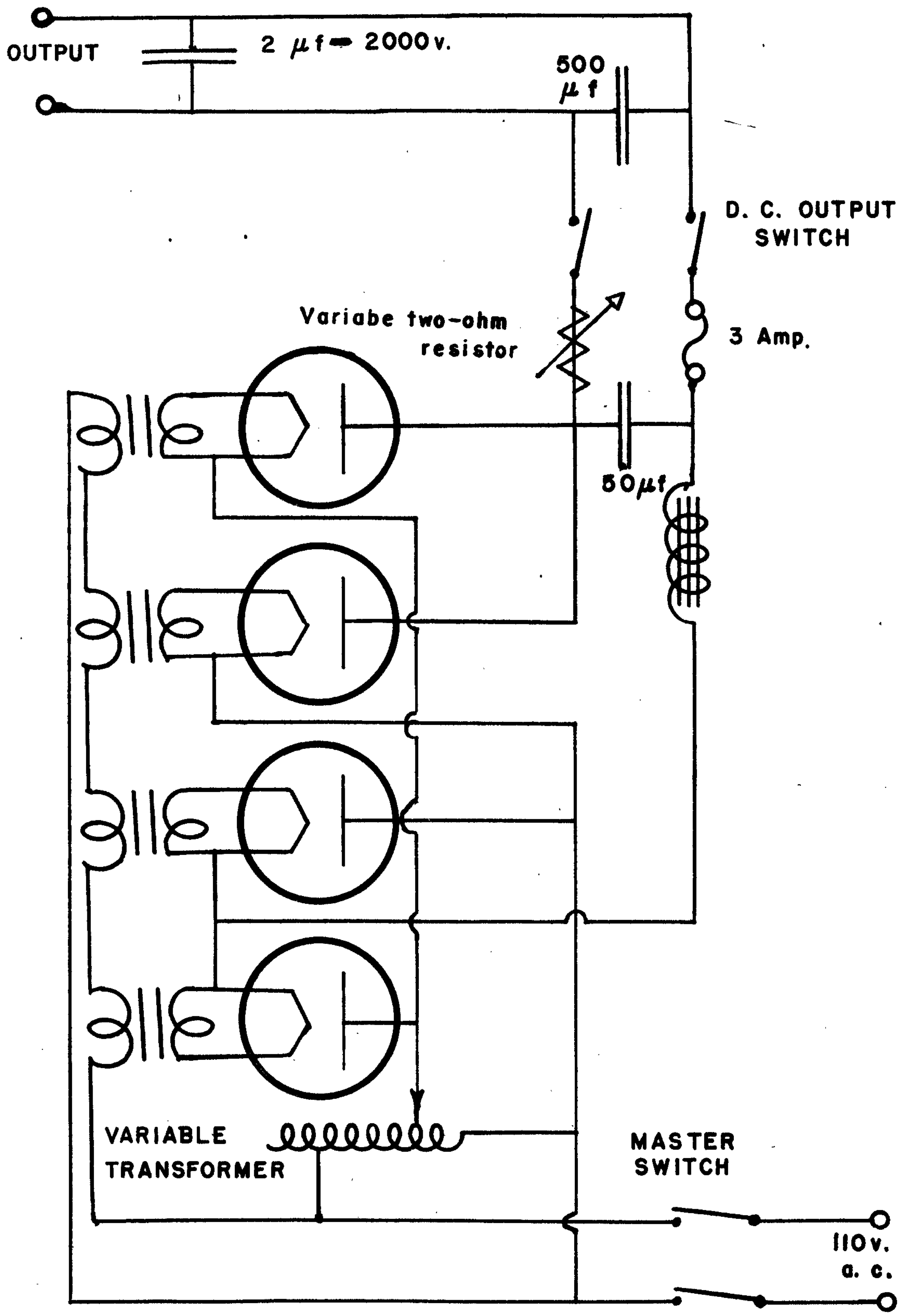

Fig. 10. --Magnet Power Supply

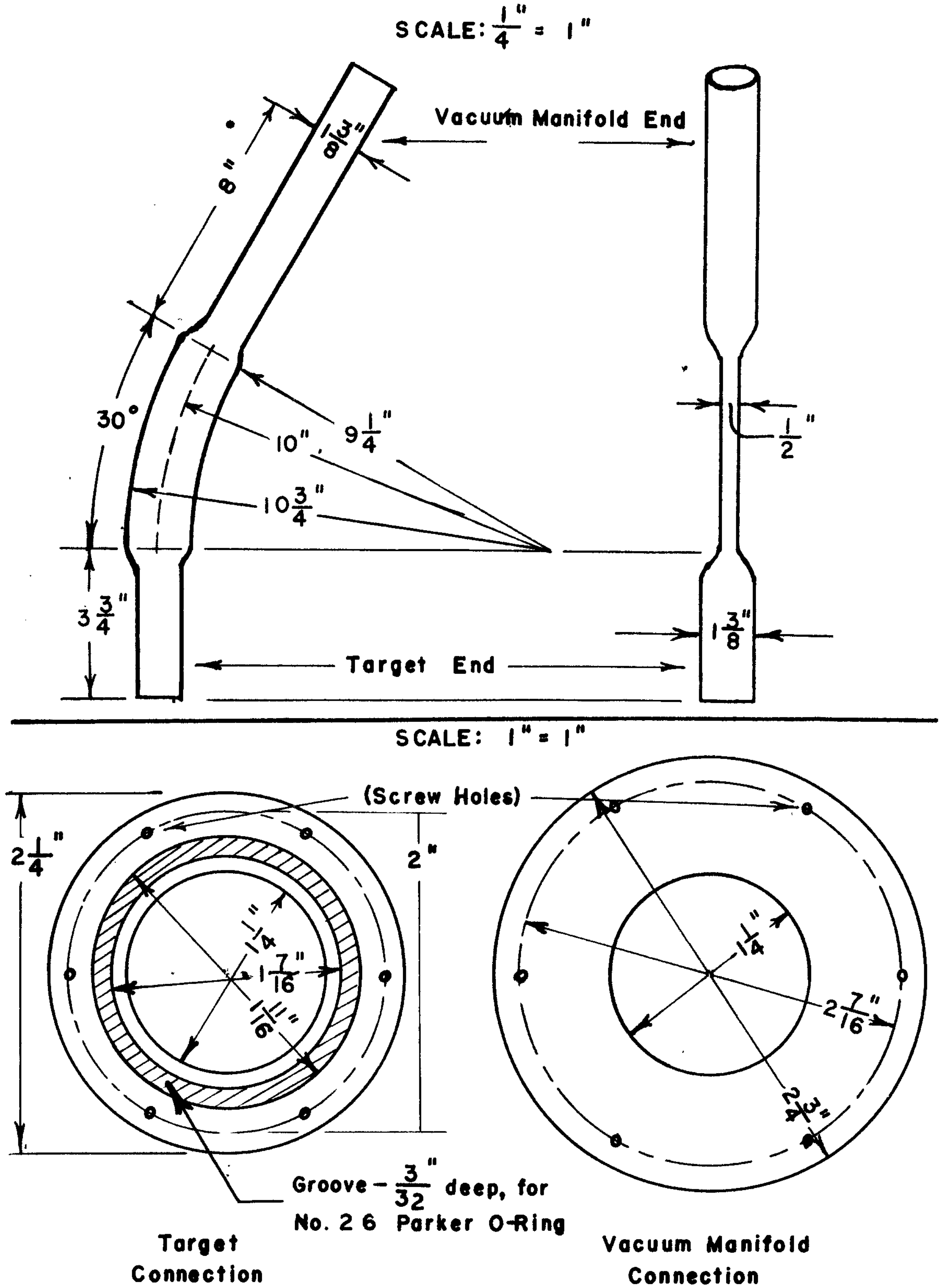

Fig. II. --Drift Tube Assembly

copper tubing. Machined brass discs were soldered to the end of this tube to form O-Ring joints, with the pump manifold on one end and the target assembly on the other.

The tube was first filled with sand and, after heating, was bent to a thirty-degree angle around a wooden frame. A jig which conformed to the desired shape of the finished tube was used to hold the tube while it was being flattened. Annealing was necessary twice during the shaping process because of work-hardening of the copper.

Performance

Measurements were carried out to check the magnitude and uniformity of the magnetic induction between the pole faces. A plot is shown in Figure 11 of the induction as a function of the current in the winding. It is obvious from this plot that the magnet is capable of producing the necessary flux density.

The first check for uniformity of the magnetic induction was made by determining the flux density at different positions in the air gap. The jerk coil of the flux-meter was then moved along the center of the gap to detect any variation of the induction along the path of the ion beam. Neither of these checks showed any variation of strength with position, which indicates that the magnet should have satisfactory focusing properties.

Operating procedures are given in the appendix.

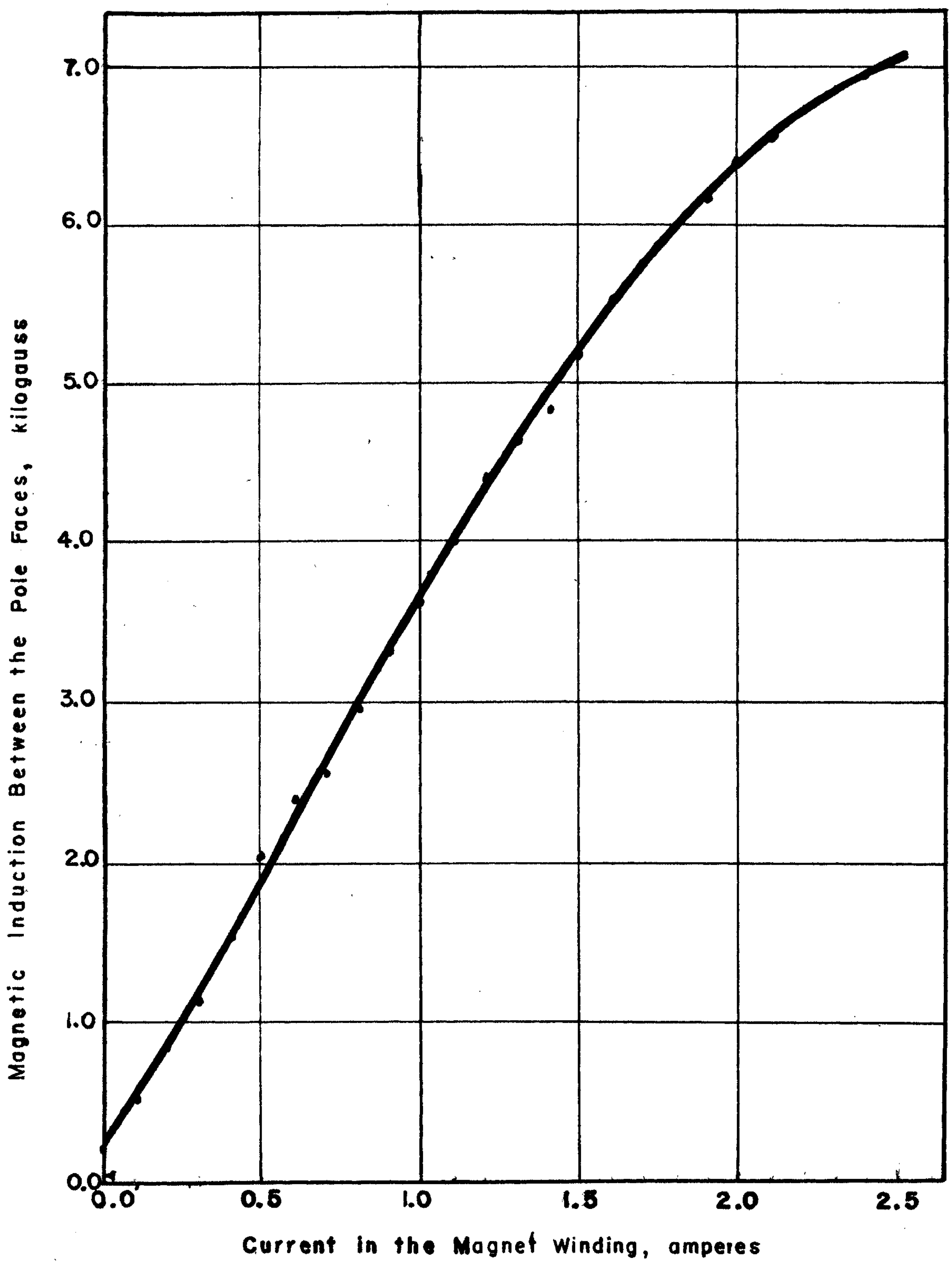

Fig. 12. --A plot of magnetic induction between the poles against current in the winding.

APPENDIX

OPERATION OF THE MAGNET

Starting and Adjustment

The following steps constitute the correct procedure for placing the magnet in operation:

1. Set the variable transformer to "0" volts.
2. Turn the d.c. output switch to "ON".
3. Turn the master switch to "ON".
4. Adjust the variable transformer slowly until approximately the correct d.c. voltage is obtained.
5. Make fine voltage adjustments with the resistor.

Shutdown

Correct shutdown procedure is as follows:

1. Turn the variable transformer slowly to "0" volts.
2. Turn the d.c. output switch to "OFF".
3. Turn the master switch to "OFF".

BIBLIOGRAPHY

Brailsford, F., Magnetic Materials, second edition revised, London, Methuen and Co., 1951.

Camac, Morton, "Double Focusing with Sedge Shaped Magnetic Fields," Review of Scientific Instruments, XXII (March 1951), 297-304.

Frank, Nathaniel H., Introduction to Electricity and Optics, New York, McGraw-Hill Book Co., Inc., 1950.

Hannah, Kenneth W., "A Positive Ion Source," Unpublished Master's thesis, Department of Physics, North Texas State College, 1948.

Hughes, A. L., and Rojansky, V., "On the Analysis of Electronic Velocities by Electrostatic Means," Physical Review, XXXIV (July, 1929), 284-289.

McKay, Vern A., "Design and Testing of a Positive Ion Accelerator and Necessary Vacuum System," Unpublished Master's thesis, Department of Physics, North Texas State College, 1953, pp. 8-15.

Moak, C. C., Reese, H., and Good, W. M., "Design and Operation of a Radio-Frequency Ion Source for Particle Accelerators," Nucleonics, IX (September, 1951), 18-23.

Paulissen, George T., "Operation and Control of a Radio-Frequency Ion Source," Unpublished Master's thesis, Department of Physics, North Texas State College, 1953.

Smith, Arthur W., Campbell, E. D., and Fink, W. L., "The Effect of Changes in Total Carbon and in the Condition of Carbides on the Magnetic Properties of Steel," Physical Review, XXIII (March, 1924), 377-85.

Stoner, Edmund C., Magnetism, London, Methuen and Co., Ltd., 1948.

Windham, Pat M., "A Deuterium-Deuterium Type Neutron Source," Unpublished Master's thesis, Department of Physics, North Texas State College, 1951.