THE DESIGN AND CONSTRUCTION OF A MAGNETIC ANALYZER FOR A TWO MILLION VOLT ELECTROSTATIC ACCELERATOR

by

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INTRODUCTION

Many studies in nuclear physics require the bombardment of a material by a well-defined, monoenergetic beam of particles in order to determine the nuclear properties of matter. At Virginia Polytechnic Institute, a two million volt electrostatic accelerator, nearly completed, will provide a charged particle beam for nuclear research. In conjunction with the accelerator, an analyzing device is needed to focus particles of only one kind on the target. Since the accelerator acts as an energy filter, beam analysis can be accomplished with a properly shaped magnetic field, which acts as a momentum filter.

A magnetic analyzer can perform three functions in addition to beam analysis. First, proper shaping of the magnetic field produces refocusing of a slightly divergent particle beam and increases the intensity of the beam when it is directed against a target distant from the accelerator. Second, sensitive voltage control can be achieved by inserting insulated slit jaws at the magnet focal point and connecting the slit jaws through a feedback system to the accelerator. Third, the energy of the particles can be accurately determined by measurement of the magnetic induction in the air gap. In addition, a well-designed magnetic analyzer can be used away from the accelerator as a particle spectrometer.

Several requirements must be met by a useful magnetic analyzer and its associated equipment. A magnet capable of bending the beam from the accelerator and of refocusing the beam must be designed. An extremely well regulated power supply must be provided since the magnetic field serves as reference for voltage stabilization of the accelerator and since the fluctuation dV/V in accelerating voltage is twice as great as the fluctuation di/i in the magnetizing current.

$$V = \frac{qB^2r^2}{2m}$$

where: V is the accelerating voltage

B is the magnetic induction in the air gap

r is the radius of the particle orbit

q is the electric charge of the particle

m is the mass of the particle

i is the magnetizing current

$$\ln V = \ln \frac{qr^2}{2m} + \ln B^2$$

$$\frac{dV}{V} = 2\,\frac{dB}{B} = 2\,\frac{di}{i}$$

The doubling of error also occurs in the determination of the energy of the particles from a measurement of the magnetic induction. Thus, the field measuring instrument employed must have twice the accuracy desired in beam energy.

REVIEW OF LITERATURE

Charged particles move in a circular path in a uniform magnetic field. Since the radius of the path is a function of the magnetic induction, the particle velocity, and the charge-to-mass ratio of the particle, a magnetic field will sort a monoenergetic beam according to the charge-to-mass ratio of the particles, or a beam of identical particles according to particle velocity. Dempster,[12] in 1918, reported the focusing effect of a uniform magnetic field on a slightly divergent charged particle beam collected 180 degrees from the source. Though the magnetic field provided focusing only in the plane perpendicular to the field and did not produce perfect point focusing, high resolution was attained by introducing slits to limit the divergence of the beam at the source. The focusing effect and the mass and velocity dispersion of magnetic fields were the properties needed for particle spectrometry.

Subsequent work was directed toward increasing the solid angle of beam which could be focused with high resolution. The theory of the focusing effect was extended to include generalized field geometries and generalized source and collector arrangements. Use of a non-uniform magnetic field to increase the solid angle of a single focusing spectrometer was suggested by Bock,[5] who provided an integral equation for the proper field shape. In 1934, Stephens[33] showed the focusing property of a 180 degree uniform field to be a particular case of the more general focusing properties of wedge shaped fields.

Shaping of the entrance and exit magnet faces to provide perfect single focusing was developed by Bainbridge,[1] Speigel,[32] Hitenberger,[15] and Kerwin.[19, 20] The effect of the fringing field on single focusing and the use of the fringing field to provide simultaneous focusing in both vertical and radial planes were worked out by Herzog,[14] Cartan,[7] Cotte,[9] Nier,[24] Coggeshall,[8] Lavatelli,[22] Sternheimer,[34] Cammc,[6] Cross,[10] and Dempsey.[11] Application of the shaping of entrance and exit magnet faces, with corrections for the fringing field, has resulted in single focusing spectrometers corrected through third order in focusing aberrations.

Following the work of Kerst and Serber[18] on electron orbits in the betatron, the double focusing properties of magnetic fields varying radially as the reciprocal of the square root of the radius were suggested independently by McMillan[23] and by Svartholm and Siegbahn.[36] Double focusing was shown to occur in the $1/r^{\frac{1}{2}}$ field when the particles were bent through $2^{\frac{1}{2}}\pi$ radians. Svartholm and Siegbahn[37] constructed a small (r = 12.5cm.) spectrometer of this type to demonstrate the double focusing principle and later built a large (r = 50 cm.) instrument.[38] Shull and Dennison[29] derived the path equation in the $1/r^{\frac{1}{2}}$ field to a second order approximation, generalizing the radial field component in a series expansion including two arbitrary field parameters. Kurie, Osaba, and Slack,[21] designed and completed a $2^{\frac{1}{2}}\pi$ spectrometer based on the work of Shull and Dennison.[29]

Judd[16] and Rosenblum[26] extended the theory to include first and second order focusing conditions for arbitrary magnet angle and external source distance. In constructing a large beta spectrometer, Bartlett and Bainbridge[2] utilized the $2\frac{1}{2}\Pi$ design with the field modifications of Shull and Dennison[29] and the design results of Rosenblum.[26] An external source and collector were employed by Snyder, Rubin, Fowler, and Lauritsen[30] in their 180 degree spectrometer and by Duncan[13] in his 180 degree spectrometer and 90 degree magnetic analyzer. More recently, Sternheimer[34] has suggested the use of the fringing field in conjunction with the $1/r^{\frac{1}{2}}$ field to provide double focusing at a shorter image distance, increasing solid angle and intensity. Optimum focusing for a fixed design has been obtained by Rubin and Sachs,[27] who employed an adjustable air gap and adjustable pole face shims in a 180 degree spectrometer.

DESIGN OF THE MAGNETIC ANALYZER

Choice of a particular type of analyzing magnet is based upon the requirements of the electrostatic accelerator, the existing facilities for construction of the magnet, and the desire to build an instrument generally useful in the laboratory as a particle spectrometer. Though the V.P I. accelerator is now a horizontal, two million volt machine, vertical mounting of the accelerator and the increase of its voltage to four million volts are planned for the future. The vertical mounting dictates a 90 degree analyzing magnet to provide a horizontal beam, and the energy of the accelerator requires a field sufficiently strong to bend four million volt deuterons. Double focusing is desirable in order to provide maximum beam intensity at the target. The analyzing magnet of Duncan meets these requirements and, in addition, is a useful particle spectrometer. Success of the design has been proven at the University of Kentucky[17] and at California Institute of Technology.[13]

The magnet is of the circumferential yoke type with a 16 inch radius and a 0.75 inch air gap. Two cavaties, 2.50 inches wide and 2.25 inches high, hold the C-shaped current coils and a coil cooling system. The completed magnet is shown in Figure 1, and drawings of the magnet are inserted in a pocket in the back cover.

Current Coils

The force of the magnetic field on the deuterons must balance the centrifugal force of four million volt deuterons traveling in a circle of 16 inch radius.

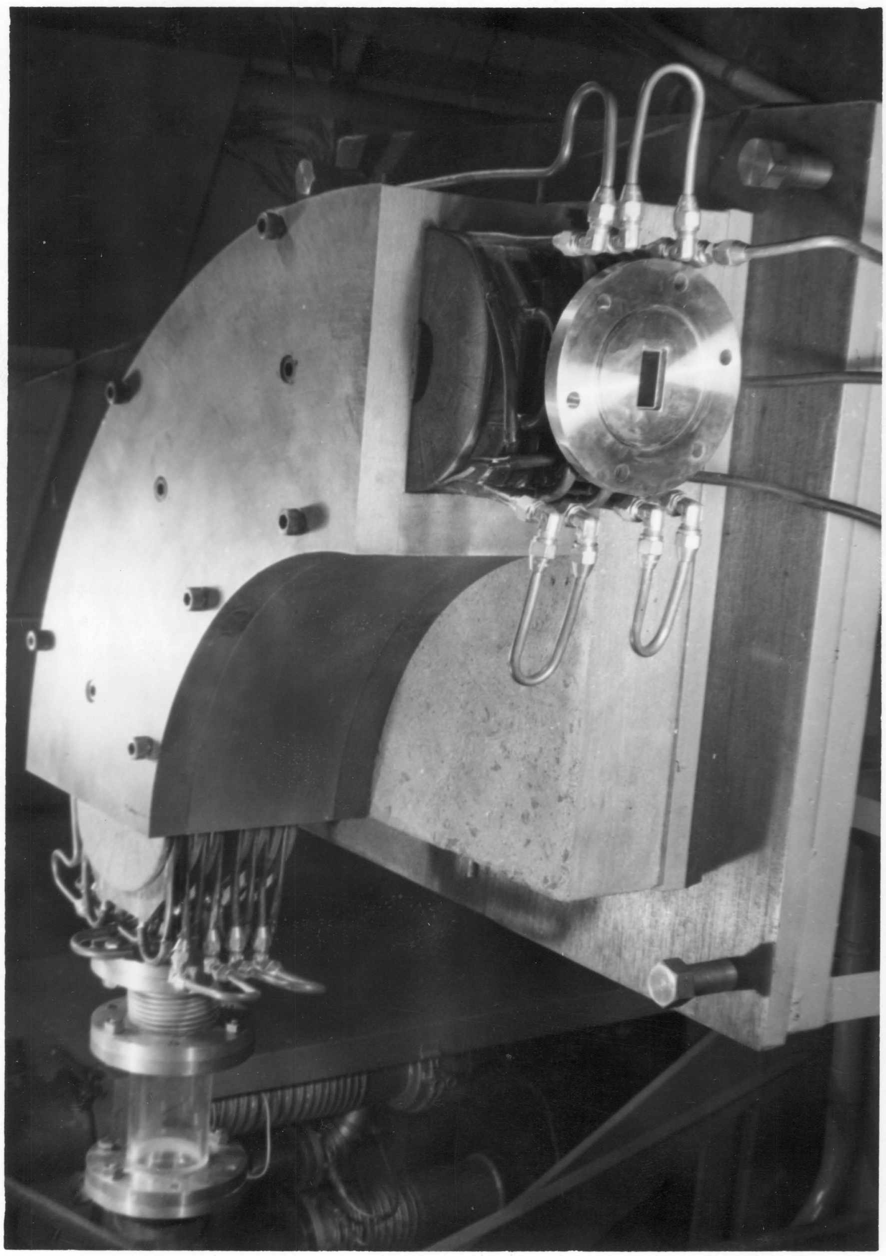


Fig. 1 Completed Magnet

$$qvB = mv^2/r \quad \text{and} \quad \tfrac{1}{2} mv^2 = qV$$

$$B = \frac{1}{r} (2Vm/q)^{\frac{1}{2}}$$

where: q = the electric charge of a deuteron

m = the mass of a deuteron

v = the velocity of a deuteron

B = the magnetic induction

r = the radius of the deuteron path

V = the accelerator voltage

Substitution of the magnet parameters into the above equation gives a value of 10,100 gauss for the required magnetic induction. Since mild steel, which begins to saturate slightly above 10,000 gauss, is the magnet structural material, the reluctance of the yoke may be neglected with respect to the air gap reluctance.

$$\oint B \cdot dl = \mu_0 ni \qquad \text{Ampere's Law}$$

$$Bg \doteq \mu_0 ni$$

$$ni \doteq Bg/\mu_0$$

where: B = the magnetic induction

l = the path length around the magnetic circuit

μ_0 = the permeability of air

n = the total number of coil turns

i = the magnetizing current

Direct substitution showed that 15,300 ampere turns were needed for analysis of the four million volt beam, and a preliminary computation indicated that approximately three kilowatts would be required for excitation of the magnet at 120 volts. Since a motor generator set of this rating was available for transfer from its installation in another building to the Nuclear Accelerator Laboratory, the magnet coils were designed for series operation with the three kilowatt source in anticipation of connecting them in parallel later for use with a 120 volt power supply of larger current capacity. Although highest fields could be attained by using a low voltage power supply and large conductors, fields much above 10,000 gauss were not considered because saturation of the yoke causes a small increase in field for a large increase in ampere turns and because saturation of the pole pieces distorts the field in the air gap and introduces defocusing.

Table 1 contains an outline of the coil design computation; the values shown are the results of two trial calculations. Coil resistance is set at 4.9 ohms by the 120 volt, 24.5 ampere rating of the generator. The requirement of 15,300 ampere turns indicates that at least 630 turns are needed. Eight C-shaped pancake coil assemblies wound with 84 turns of 0.044 x 0.156 inch flat copper wire comprise the winding design. These windings fill the entire width of the coil cavities and allow 0.75 inches height in each cavity for cooling purposes.

Cooling System

Four 3/16 inch thick copper plates can be fitted between the coil assemblies in each cavity as shown in Figure 2. Cooling is accomplished by passing water through 5/16 inch copper tubing, silver soldered around the inside and outside of the plates and flattened to plate thickness, Figure 3. Soldered copper elbows, bent from 3/8 inch copper tubing, close the tubing on each plate, and the plates are interconnected with flared fittings. In Table 2 the adequacy of the cooling system is compared with the system employed by Snyder, Rubin, Fowler, and Lauritsen[30] in their 180 degree spectrometer.

Vacuum Chamber

The vacuum chamber is chosen for its simplicity, a 37 inch section of 3/4 x 1-1/2 x 1/16 inch rectangular wave guide bent in a 90 degree arc of 16 inch radius. The wave guide extends approximately six inches beyond each end of the magnet. Standard size flanges, shown in Figure 4, are soft soldered to the wave guide, and two flanged bellows, Figure 5, are provided to connect the vacuum chamber to the vacuum system, yet permit alignment of the magnet.

Support Table

The support table must be capable of holding the assembled magnet, which weighs more than 500 pounds, and must allow leveling of the magnet and alignment with the accelerating tube. The table, shown in Figure 6, is built of 1¼ inch angle iron welded together and bolted to the floor. A 1 x 28 x 28 inch steel plate is supported above the table on 4 one inch bolts which level the magnet. A 1 x 17 x 17 inch steel plate slides on the leveling plate to provide horizontal alignment. To prevent stray field from the magnet to the plates, a 4 x 17 x 17 inch concrete block separates the magnet from the plates.

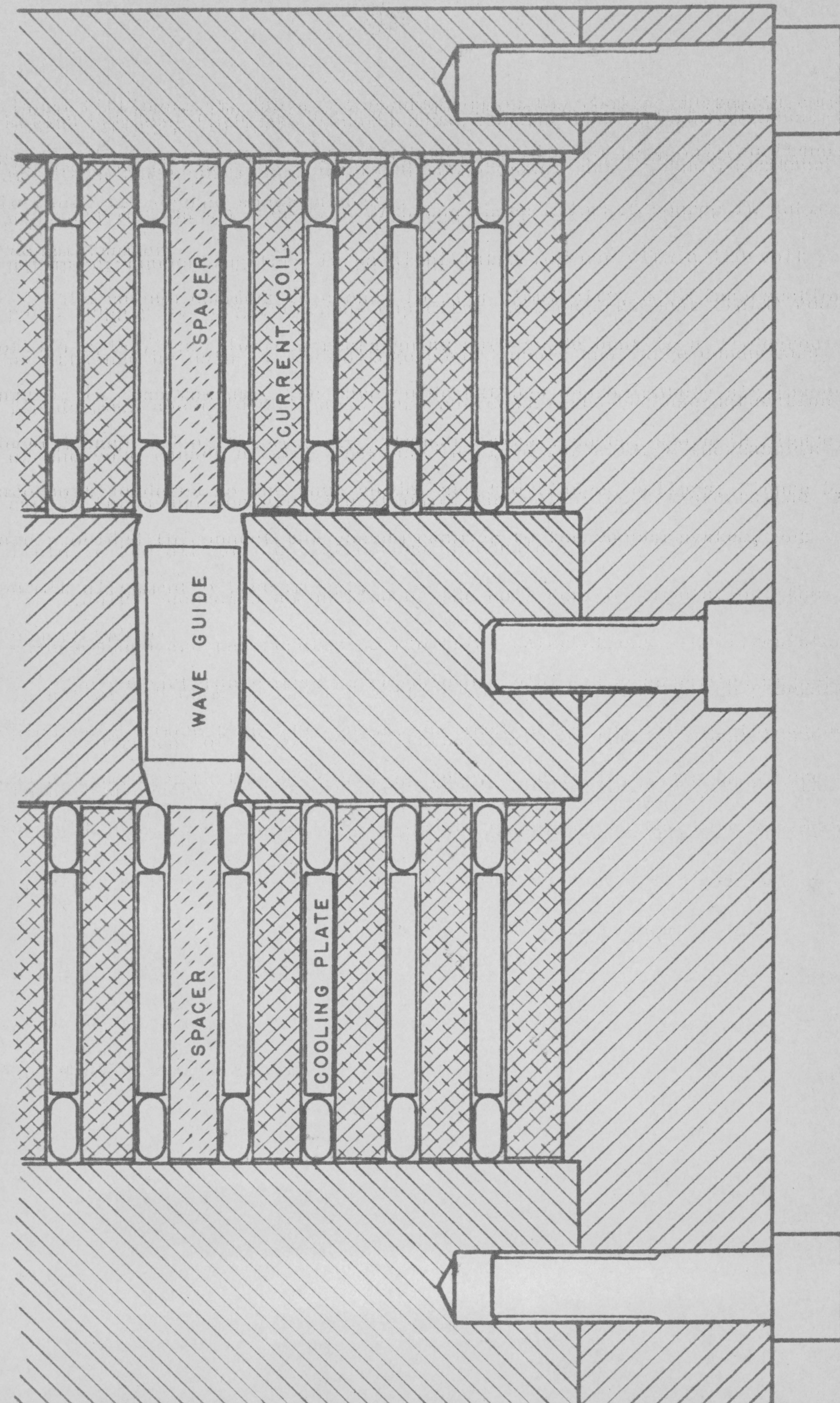


FIG. 2 COILS AND COOLING SYSTEM ASSEMBLED

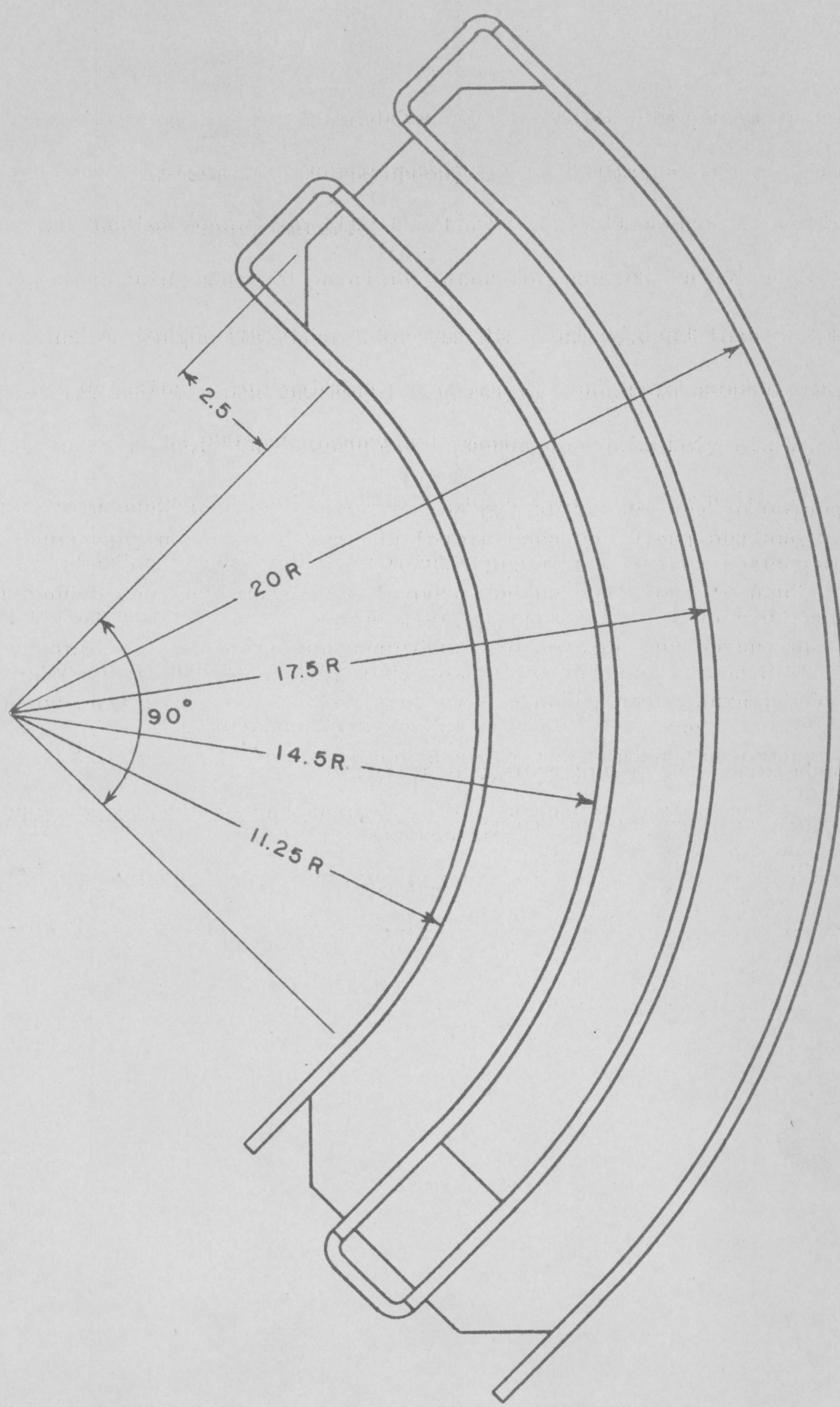


FIG. 3 COOLING PLATE DESIGN

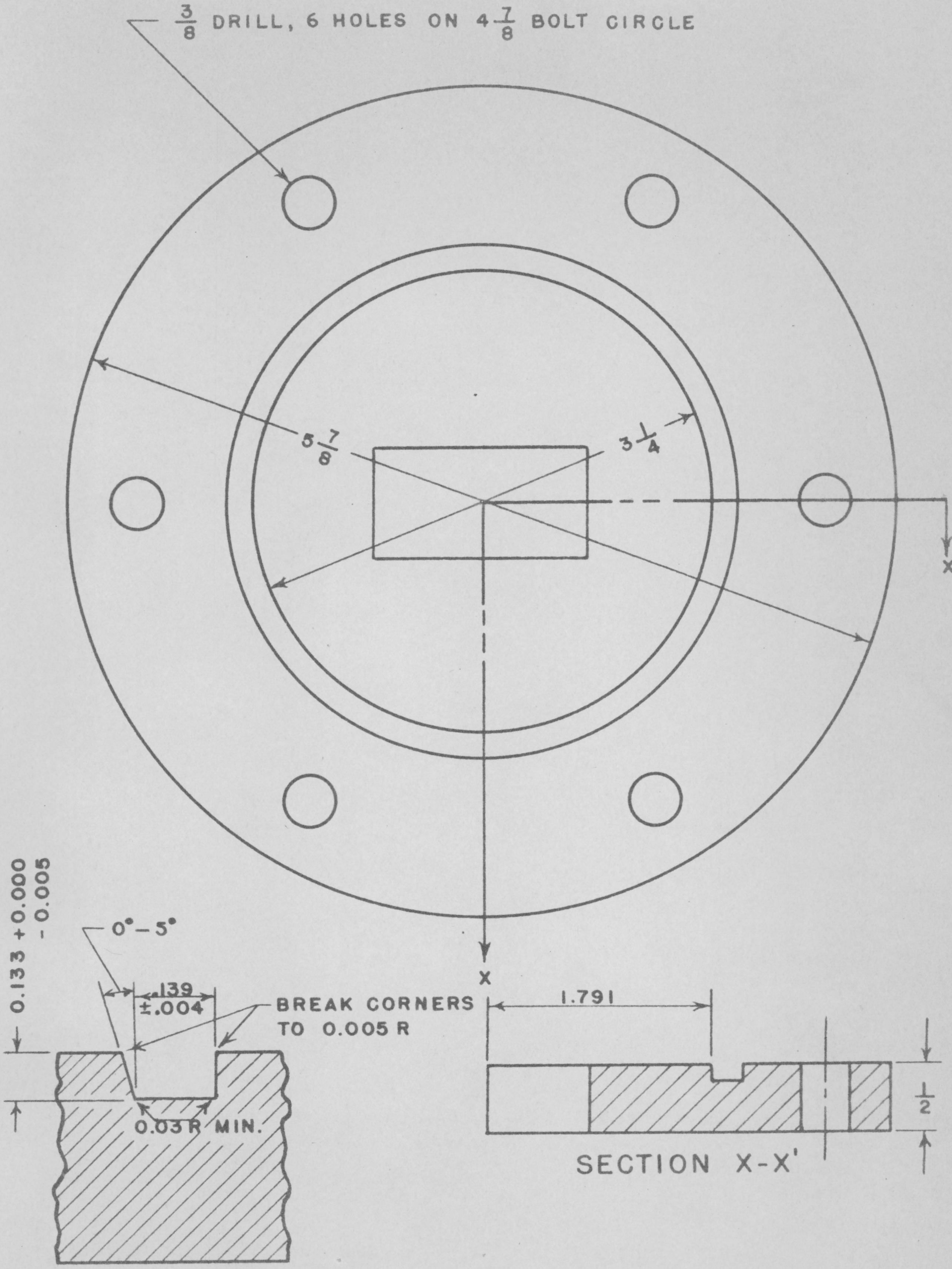


FIG. 4 STANDARD FLANGE DESIGN

Fig. 5 Flanged Bellows

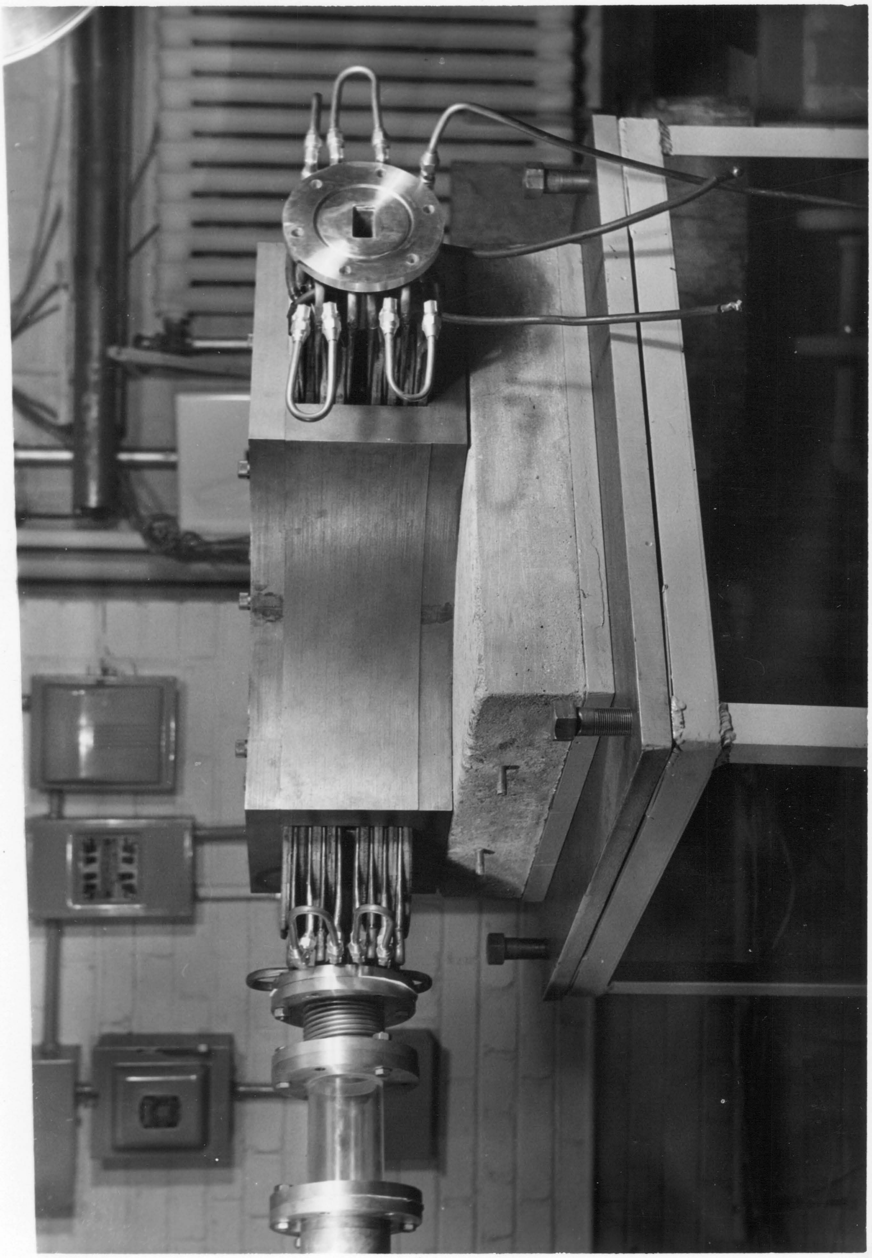


Fig. 6 Support Table

Table 1

Design Computation for Coils

Generator rating:	3 Kw, 125 volts, 24 amp.
Maximum series coil resistance:	5.2 ohms
Ampere turns required:	15,300 ampere turns
Minimum turns required:	635 turns
Number of pancake coils:	16 coils
Wire size, rectangular:	0.044 x 0.156 inches
Double cotton covering additions*:	0.014, 0.014 inches
Overall wire size:	0.058 x 0.170 inches
Cavity size:	two 2.50 x 2.24 inch cavaties
Turns per coil:	2.50/0.058 = 42 turns per coil
Allowance for gauze wrappings:	0.15 inches
Space for cooling system:	(2.25 - 0.15 - 8 x 0.170) = 0.75 inches per cavity
Total turns:	16 x 42 = 672 turns
Mean turn length:	4.9 feet per turn
Total wire length:	3,290 feet
Resistance per 1,000 ft.*:	1.51 ohms per 1,000 ft.
Total coil resistance:	4.96 ohms
Ampere turns obtainable:	672 x 24 = 16,100 ampere turns
Field obtainable:	10,600 gauss
Deuteron energy:	4.4 MEV

* These values were taken from the supplier's catalog.

Table 2

Design Computation for Cooling System

Space for cooling system:	0.75 inches per cavity
Plate thickness:	3/16 inch
Total number of plates:	8 plates
Area of plate side:	144 inch^2 per plate side
Total cooling area:	2,020 inch^2
Maximum power input:	3,000 watts
Power dissipation per unit area:	1.5 watts per inch^2
Maximum current:	24 amperes
Wire area:	0.00688 inch^2
Maximum current density:	3,500 amperes per inch^2
Cooling System of Snyder, et al.	
Maximum power input:	15,000 watts
Power dissipation per unit area:	1.5 watts per inch^2
Current density:	6,000 amperes per inch^2

CONSTRUCTION OF THE MAGNETIC ANALYZER

Support Table and Magnet

Mr. Barnett, machinist for the V.P.I. Physics Department, fabricated the support table. The concrete block was cast upside down around brass reinforcing rod in a wooden form. Six pegs in the bottom of the form provided wells in the block for the bolt heads on the bottom of the magnet. Since no lathe at Virginia Polytechnic Institute would swing the magnet parts, they were machined from mild steel by the Virginia Bridge Company of Roanoke, Virginia, and donated to the Physics Department. To insure matching of the pole pieces and the top and bottom plates, complete cylinders were turned, and two 90 degree sectors were cut from the cylinders to form the matching parts. The Virginia Bridge Company donated, also, the leveling plate and the alignment plate, after machining their sliding surfaces.

Current Coils

A completed coil is shown in Figure 7. The 0.044 x 0.156 inch wire was found to be too flexible to be pressed into place around the pole pieces and could not be wound about the poles directly, because tension on the wire during winding pulled the wire away from the inner 15 inch radius of the poles. The wire was wound on an elliptical form, shown in Figure 8, and then formed in a jig to provide the necessary C-shape of the coils.

The perimeter of turns wound directly on a crescent shaped form, such as the magnet pole pieces, remains very nearly constant from turn to turn because the inner radius decreases as rapidly as the outer radius

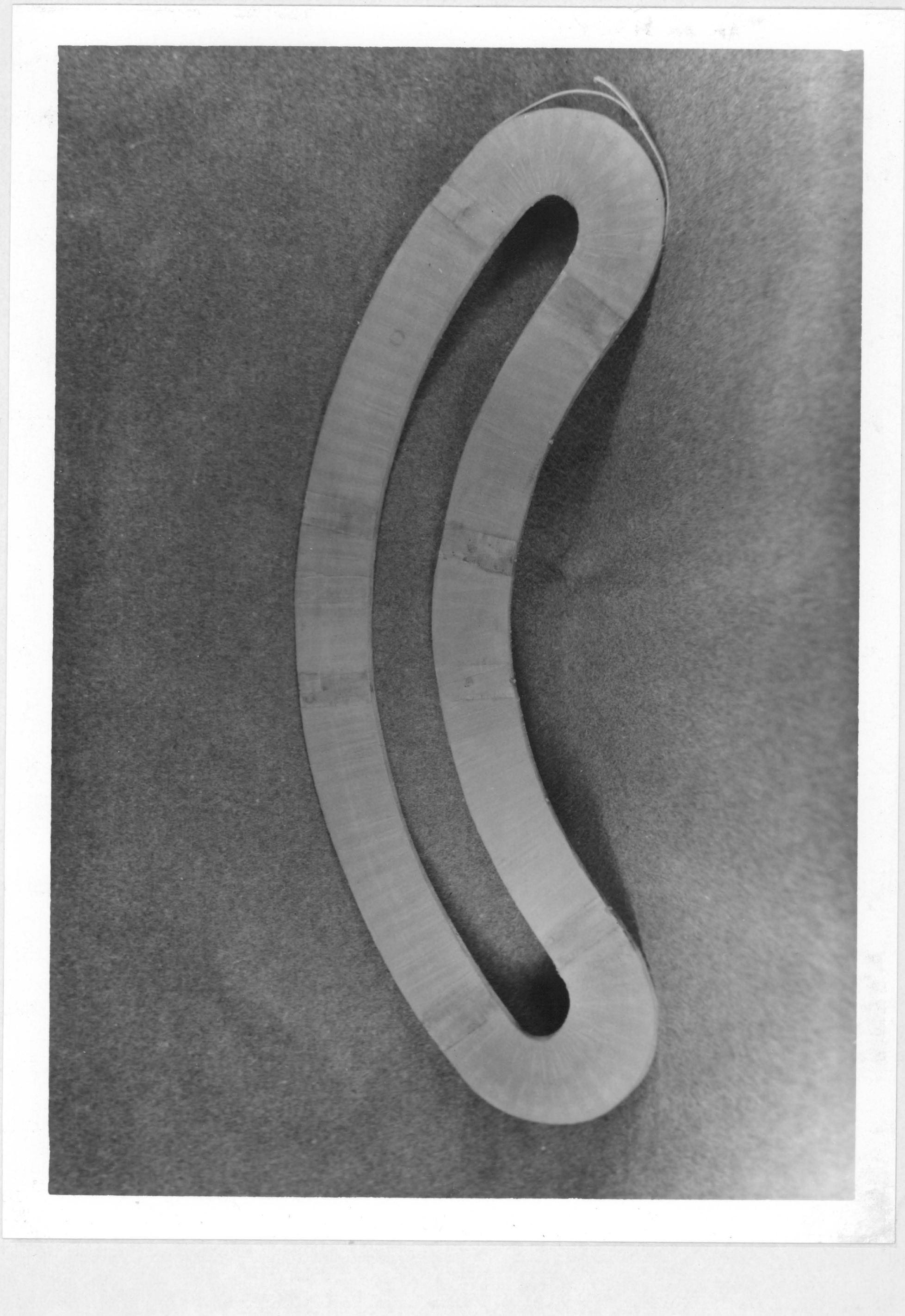


Fig. 7 Completed Coil

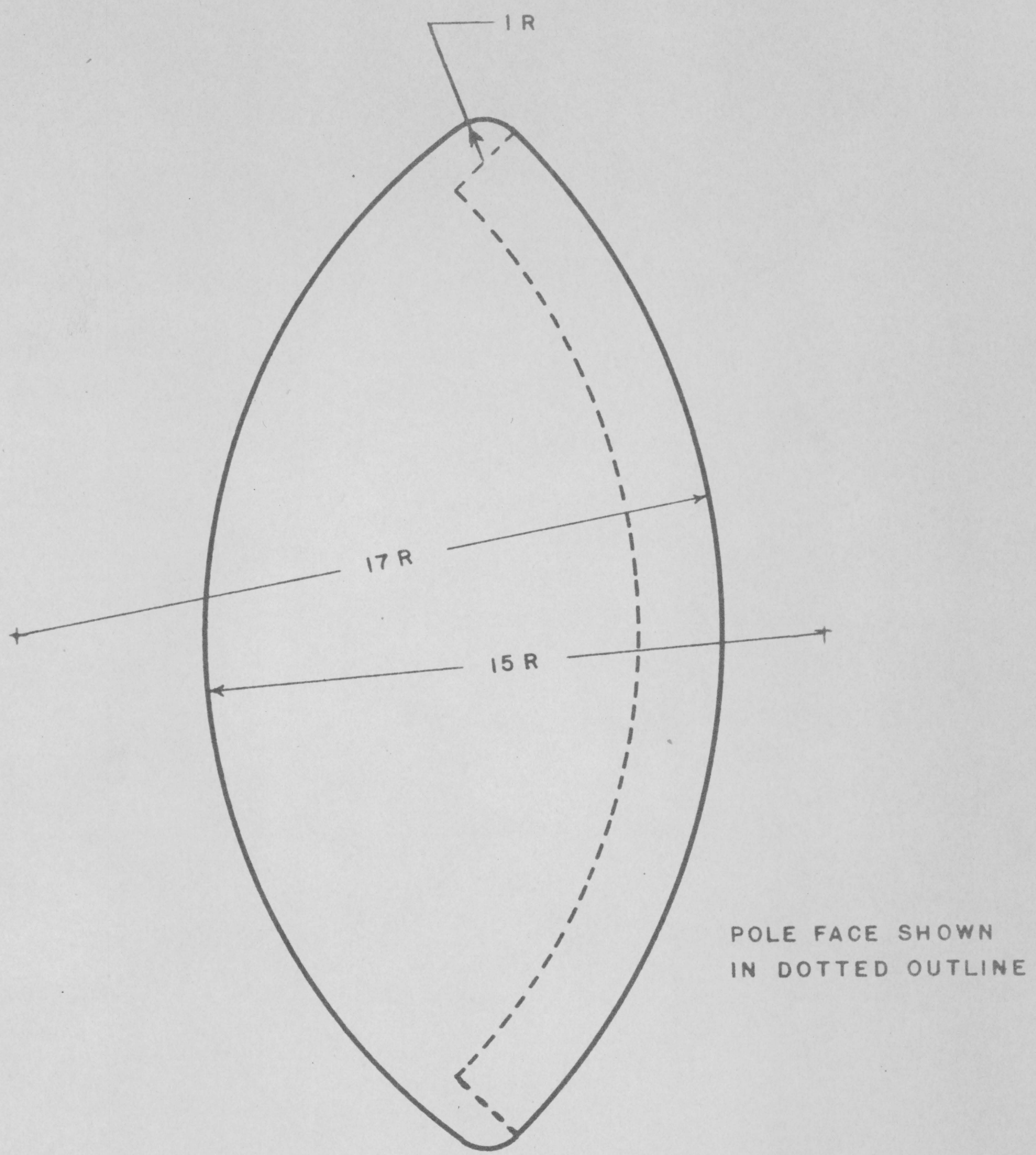


FIG. 8 ELLIPTICAL FORM

increases. For an elliptical form, however, the perimeter of successive turns increases because both radii increase with successive turns. Calculation shows that the turn lengths increase by only about one per cent for the elliptical form of Figure 8 and wire 0.044 inches thick. This small amount of slack aids in the forming of the coils, yet is sufficiently small to leave no observable spaces between turns of the completed coils.

The reel of rectangular wire was supported in a box and provided with a foot operated brake to control tension during winding. A small motor was connected through a V-belt clutch and a worm and wheel speed reducer to power the elliptical form. Forty turns of wire were wound into each of the 16 coils, eight coils wound clockwise and eight, counterclockwise. Two turns were dropped from the design value of 42 turns per coil in order to insure ease of fitting the coils into the cavities.

The forming jig was a one-eighth inch piece of plywood, cut to the crescent shape of the pole faces, fastened securely to a large board, and surrounded with clamps. Coils were formed by clamping the elliptical winding against the convex side of the jig, bending a few wires at a time against the concave surface of the jig, and then clamping the formed side.

Each coil assembly was made of two coils, one wound clockwise and the other, counterclockwise. The coils were stacked on one another, the two inner leads were soft soldered together, and the assembly was wrapped tightly with gauze. Combination of the coils into assemblies of two brought both current leads to the outside of the assembly, eliminating the necessity of bringing an inner lead over the coil surface after installation in the magnet. The coil assemblies were dipped in Irvington No. 140 Clear Baking Varnish, clamped in a jig to hold their shape, and baked at 120 degrees centigrade for seven hours.

Cooling Plates

The cooling plates were cut from a large sheet of 3/16 inch copper. Copper tubing 5/16 inches in diameter was silver soldered around the inner and outer edges of the plates and hammered to the thickness of the plates. Three elbows of 3/8 inch copper tubing were made for each plate and the plates were assembled with soft solder.

Assembly

Prior to assembly, the coil cavities were painted with glyptol to prevent rusting and consequent damage to the coil insulation. Coil assemblies and cooling plates were alternately placed in the lower coil cavity. When the vacuum chamber was reached, copper spacers were inserted to support the upper coils. The coil and cooling system fitted tightly with the magnet top plate bolted down. The current coils were wired in series and the cooling plates were connected in series to a nearby water outlet.

In the present arrangement, the bottom and top coils are water cooled on one side only and will limit the current capacity of the winding. Assembly showed that a better design of cooling plates would have been achieved by constructing ten 1/8 inch plates with 1/4 inch tubing flattened to plate thickness. The thinner plates could be used to cool both sides of the bottom and top coils. Further improvement could have been attained by bending the copper tubing tightly around the cooling plates during construction to eliminate the soldered elbows, which impede insertion of bolts into the wave guide flanges.

TESTING OF THE MAGNETIC ANALYZER

Tests were performed to determine the magnetization curve of the magnet, the uniformity of the field along the pole face, and the inductance of the windings. A 1.5 kilowatt motor generator set in the Nuclear Accelerator Laboratory provided stable currents up to 15 amperes for testing. A flip coil was constructed for field measurements.

Plan of Field Measurement

The field was measured by the deflection produced on a ballistic galvanometer by rotating a flip coil through 180 degrees in the air gap of the magnet. For an impulsive E.M.F., the deflection of a ballistic galvanometer is proportional to the charge passed through it.

$$KL = Q$$

$$KL = \int \frac{E}{R}\, dt$$

$$KL = \int \frac{1}{R} \left(N \frac{d\phi}{dt} \right) dt$$

$$NA = \frac{RQ}{2B}$$

where: K = the charge sensitivity of the galvanometer

L = the galvanometer deflection

Q = the charge passed through the galvanometer

E = the E.M.F. produced in the flip coil

R = the circuit resistance

t = the time

N = the number of turns on the flip coil where: ϕ = the flux density in the coil

A = the effective area of the coil

B = the average magnetic induction in the coil

A ballistic galvanometer with a 25 centimeter scale, and a period of 25 seconds, was chosen for the measurement. Its charge sensitivity was found to be 0.13 microcoulombs per centimeter, using a standard cell, standard capacitor method of calibration. A wheatstone bridge showed the galvanometer resistance to be 2003 ohms. For full scale deflection at 10,000 gauss, the above equation shows that 33 cm^2 turns are required for the flip coil. A 1.4 cm brass spool was wound with #36 wire to produce about 35 cm^2 turns. The coil, shown in Figure 9, was mounted in a brass housing which could be inserted into the wave guide, and which was provided with a flexible shaft for manual flipping. Two standard magnetron magnets, 4850 gauss, were used to calibrate the flip coil and galvanometer directly, Table 3. Relative measurements are thought to be accurate to one per cent; absolute measurements, to five per cent.

Continuous control of the magnet current was obtained with six variable resistors. The circuit is shown in Figure 10. A reversing switch permitted demagnitization, and a current shunt and a Rubicon portable millivolt potentiometer were used to set the current. A volt box was connected to the magnet and the potentiometer for coil resistance measurement.

A Leeds and Northrup 0.001 ohm N.B.S. type current shunt, and a Leeds and Northrup precision 0.01 ohm, 100 ampere current shunt were available for setting current. Since both shunts were purchased some years ago from the Leeds and Northrup defective stock list and were uncalibrated, their resistance was measured with the Kelvin double bridge and shunt apparatus of the National Bureau of Standards. Table 4 gives the data obtained.

<u>Field Measurement</u>

The field measurements for the magnetization curve were taken with the flip coil centered in the air gap 15 inches from the exit face of the magnet. Demagnetization was accomplished by rapidly reversing the direction of current while slowly decreasing the current from 15 amperes. The data of Table 5 was then obtained by measuring the field at successively higher values of current. The resulting magnetization curve is plotted in Figure 11. After demagnitization, the current was set at ten amperes and galvanometer readings were taken at a number of points along the length of the pole face. The data is contained in Table 6, and the field profile is plotted in Figure 12.

<u>Inductance Measurement</u>

The magnet was energized with 60 cycle 120 volt power, and the impedance of the coils was determined to be 12.6 ohms with a voltmeter and an ammeter. From the impedance of the windings at 60 cycles, and the 4.12 ohm value of resistance from Table 6, the inductance of the windings was found to be 32 millihenries.

<u>Test Results</u>

Tests show the magnetic analyzer to be adequate for use with the electrostatic accelerator. The magnetization curve is in good agreement with the design computations, which predicted 10,600 gauss at 24 amperes.

Extrapolation of the magnetization curve, assuming no saturation of the magnet, gives the values: 10,100 gauss at 24 amperes. The five per cent smaller value of actual field is accounted for by the 640 turns actually wound in the coils as compared to 672 turns estimated in design. The coils can carry 30 amperes in still air and the field profile is uniform to one per cent. Table 6 summarizes the characteristics of the magnet.

Fig. 9 Flip Coil

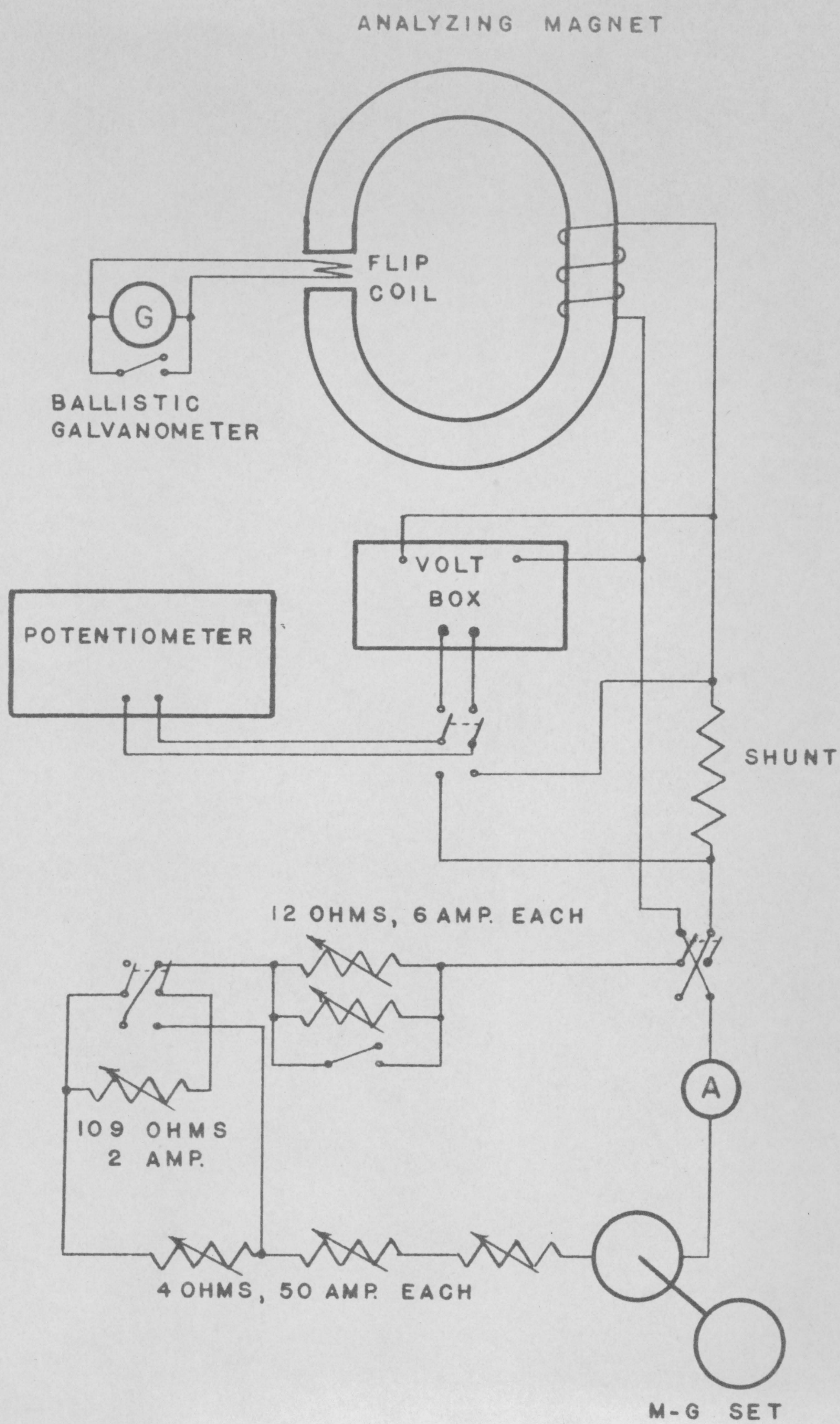
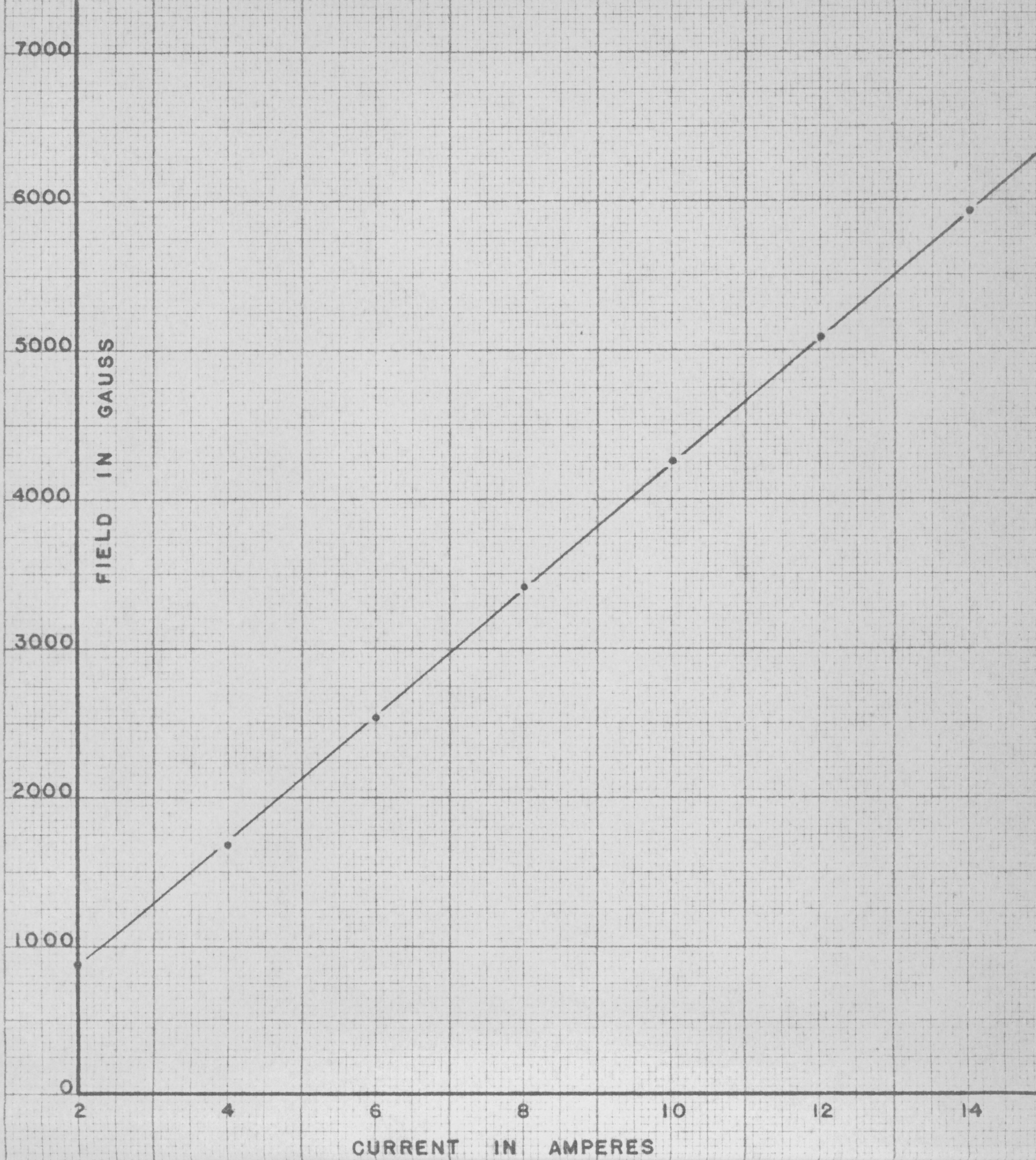


FIG. 10 FIELD MEASUREMENT CIRCUIT

FIG. II MAGNETIZATION CURVE



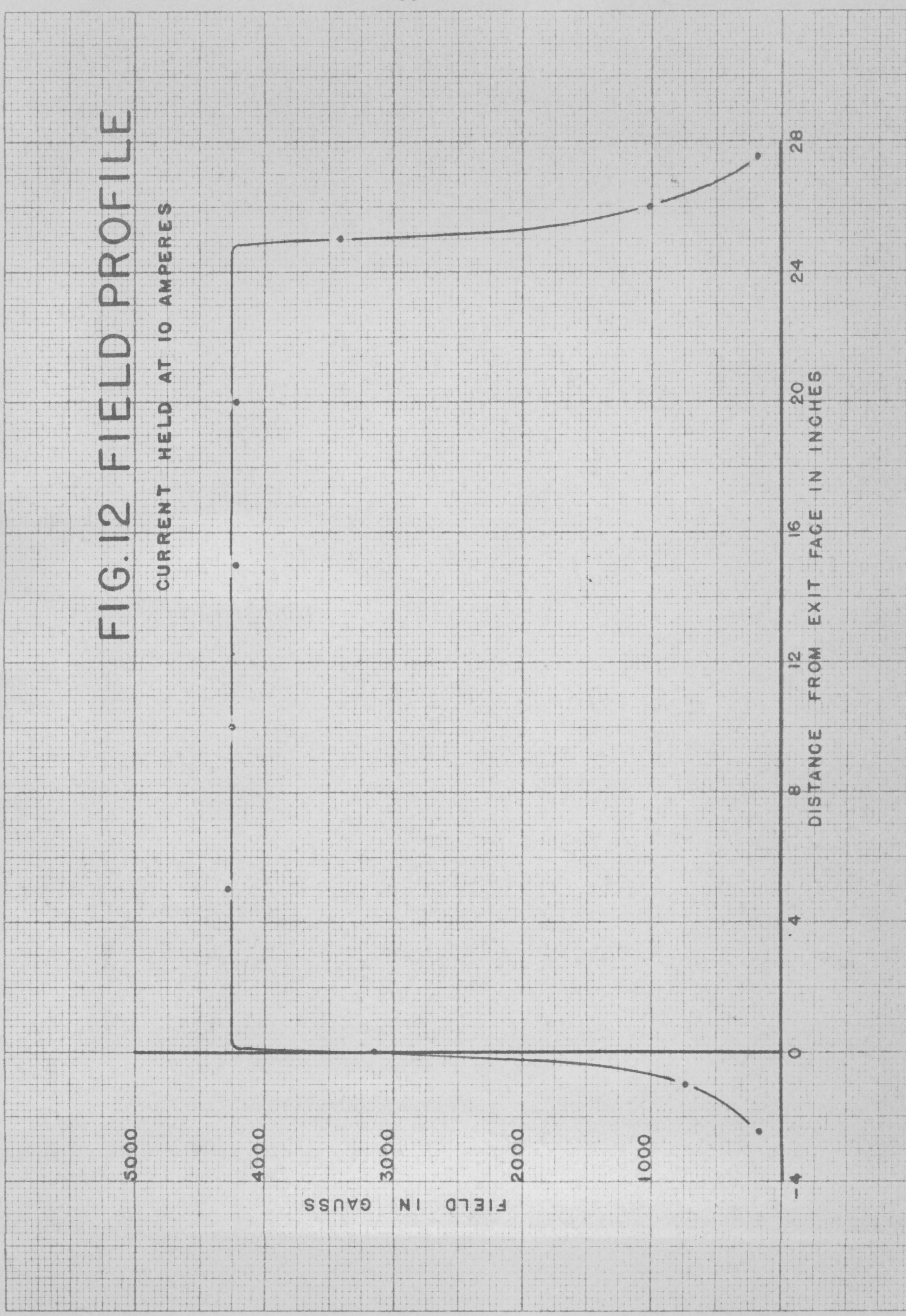


FIG. 12 FIELD PROFILE

Table 3

Flip Coil Calibration Data

Magnetron Magnet I #18651   4850 Gauss

Galvanometer Deflection

Zero	Maximum	Total
0.15 cm	13.40 cm	13.25 cm
0.15 cm	13.40 cm	13.25 cm
0.15 cm	13.30 cm	13.15 cm
0.15 cm	13.20 cm	13.05 cm
		13.18 cm av.

Magnetron Magnet C #2293   4850 Gauss

Galvanometer Deflection

Zero	Maximum	Total
0.15 cm	-13.1 cm	-13.25 cm
0.15 cm	-13.1 cm	-13.25 cm
0.15 cm	-13.1 cm	-13.25 cm
0.15 cm	-13.1 cm	-13.25 cm
		-13.25 cm av.

Average deflection 13.22 cm

Calibration constant 366.9 gauss per cm

Table 4

Shunt Calibration Data

$X = \frac{ND}{P}$ (All corrections given in parts per million)

X (ohms)	Tx	N (ohms)	Tn	P (ohms)	D (ohms)	I (amp)
W #6506 0.01 ≁958	24°C	W #6507 0.001 ≁578	22°C	50 ≁1200	500.313 ≁1586	25
L ≁ N #5685 0.01 ≁4591		W #6570 0.001 ≁578	22°C	50 ≁1200	502.130 ≁5222	10
L ≁ N #5684 0.01 ≁4559		W #6507 0.001 ≁586	23°C	50 ≁1200	502.110 ≁5182	25
L ≁ N #5684 0.01 ≁3746		W #6507 0.001 ≁614	29°C	50 ≁1200	501.688 ≁4340	75
L ≁ N #5684 0.01 ≁2666		W #6507 0.001 ≁612	28°C	50 ≁1200	501.150 ≁3262	100
W #6507 0.001 ≁593	24°C	W #6510 0.0001 ≁456	24°C	50 ≁1200	500.190 ≁1340	20
L ≁ N #8573 0.001 ≁893		W #6510 0.0001 ≁456	24°C	50 ≁1200	500.340 ≁1640	20

Table 5

Magnetization Curve Data

Field (gauss)	Position* (inches)	Current (amps)	Shunt L/N#8573	Ballistic Galvanometer Zero	Maximum	Total
842	15	2	2.0018 mv	-0.10 cm	2.20 cm	2.30 cm
				-0.10 cm	2.18 cm	2.28 cm
				-0.10 cm	2.20 cm	2.30 cm
				-0.10 cm	2.20 cm	2.30 cm
						2.30 cm av
1690	15	4	4.0036 mv	-0.10 cm	4.50 cm	4.60 cm
				-0.10 cm	4.50 cm	4.60 cm
				-0.10 cm	4.50 cm	4.60 cm
				-0.10 cm	4.50 cm	4.60 cm
						4.60 cm av
2540	15	6	6.0054 mv	-0.10 cm	6.80 cm	6.90 cm
				-0.10 cm	6.82 cm	6.92 cm
				-0.10 cm	6.83 cm	6.93 cm
				-0.10 cm	6.83 cm	6.93 cm
						6.92 cm av
3410	15	8	8.0072 mv	-0.10 cm	9.20 cm	9.30 cm
				-0.10 cm	9.20 cm	9.30 cm
				-0.10 cm	9.20 cm	9.30 cm
				-0.10 cm	9.20 cm	9.30 cm
						9.30 cm av
4260	15	10	10.009 mv	-0.10 cm	11.50 cm	11.60 cm
				-0.10 cm	11.50 cm	11.60 cm
				-0.10 cm	11.50 cm	11.60 cm
				-0.10 cm	11.50 cm	11.60 cm
						11.60 cm av

Table 5 (con't)

Field (gauss)	Position* (inches)	Current (amps)	Shunt L/N#8573	Ballistic Galvanometer Zero	Maximum	Total
5100	15	12	12.010 mv	-0.10 cm	13.80 cm	13.90 cm
				-0.10 cm	13.80 cm	13.90 cm
				-0.10 cm	13.80 cm	13.90 cm
				-0.10 cm	13.80 cm	13.90 cm
						13.90 cm av
5940	15	14	14.013 mv	-0.10 cm	16.10 cm	16.20 cm
				-0.10 cm	16.10 cm	16.20 cm
						16.20 cm av
6420	15	15	15.014 mv	0.00 cm	17.50 cm	17.50 cm
				0.00 cm	17.50 cm	17.50 cm
						17.50 cm av.

* The position of the flip coil is measured from the exit face of the magnet.

Table 6

Field Profile Data

Field (gauss)	Position* (inches)	Current (amps)	Shunt L/N#8573	Volt Box 750/1.5	Ballistic Galvanometer Total
176	-2.5	10	10.009 mv	82.45 mv	0.48 cm 0.49 cm 0.47 cm 0.48 cm av.
748	-1.0	10	10.009 mv	82.45 mv	2.00 cm 2.08 cm 2.04 cm 2.04 cm av.
3150	0	10	10.009 mv	82.45 mv	8.65 cm 8.62 cm 8.50 cm 8.59 cm av.
4300	5	10	10.009 mv		11.70 cm 11.70 cm 11.72 cm 11.71 cm av.
4250	10	10	10.009 mv		11.60 cm 11.58 cm 11.58 cm 11.59 cm av.
4220	15	10	10.009 mv		11.50 cm 11.50 cm 11.50 cm 11.50 cm av.

Table 6 (con't)

Field (gauss)	Position* (inches)	Current (amps)	Shunt L/N#8573	Volt Box 750/1.5	Ballistic Galvanometer Total
4220	20	10	10.009 mv		11.50 cm 11.52 cm 11.52 cm 11.51 cm av.
3420	25	10	10.009 mv		9.22 cm 9.40 cm 9.38 cm 9.33 cm av.
1030	26	10	10.009 mv		2.80 cm 2.82 cm 2.80 cm 2.81 cm av.
183	27.5	10	10.009 mv		0.50 cm 0.50 cm 0.50 cm 0.50 cm av.

Resistance of Winding: 4.12 ohms

* The position of the flip coil is measured from the exit face of the magnet.

Table 7

Magnet Characteristics

Magnet type:	Double focusing, 90° wedge, $\frac{1}{r^{\frac{1}{2}}}$ field
Focal length:	16 inches
Radius:	16 inches
Air gap:	3/4 inch
Total turns:	640
Number of coils:	16
Number of coil assemblies:	8
Wire size:	0.044 inches x 0.156 inches
Resistance at ten amperes:	4.12 ohms
Inductance:	32 millihenries
Number of cooling plates:	8

FIELD STABILIZATION AND FIELD MEASUREMENT

The Physics Department has obtained and is awaiting delivery of a 6.5 kilowatt, 125 volt motor generator set for the power supply of the magnet. The unit consists of a General Electric CD 284 D.C. generator, shunt wound for separate 125 volt excitation; a ten horsepower, three phase, 60 cycle, 208 volt induction motor, type K, frame 256U; and a model 5AM 79AB334 motor-amplydine with an electronic amplifier. Magnetic full voltage starters and start-stop push button stations are provided for the amplydine motor and the 10 horsepower motor.

The magnet current must be held constant to prevent fluctuations in accelerator voltage. A number of different control methods have been successfully employed, all of which maintain constant field by reference to a stable standard or standards, such as, voltage, resistance, time, or magnetic field. Van der Walt[39] has used the field of a permanent magnet as reference to attain a stability of 0.004 per cent. Sommers, Weiss, and Halpern[31] have achieved stabilization to one part per million, using high gain voltage feedback of an error signal obtained by comparing the potential across a standard resistor carrying the magnetizing current with a reference voltage. Packard[25] employed a field regulator which utilized nuclear magnetic resonance of protons for both field control and field measurement. His method has the advantages of inherent high sensitivity and of using actual air gap conditions for obtaining both the error signal and the field measurement signal.

Until nuclear magnetic resonance equipment is obtainable, the V.P.I. magnetic analyzer will be stabilized with voltage feedback, since this method is readily applicable to the amplydine and amplifier. Field control to a few parts in 10,000 is required in order to insure accelerator voltage stability of one part per thousand.

Voltage Feedback System

The operation of the voltage feedback system with an amplydine excited generator may be understood from the block diagram of Figure 13. The amplifier supplies the amplydine control coils so that an increase in signal from the amplifier causes an increase in amplydine output. Feedback of a portion of the amplydine output to the amplifier stabilizes amplydine output. The current level control applies a voltage directly to the amplifier, setting amplydine output, generator output, and excitation current. A reference resistor and a precision shunt are connected in series with the generator and the magnet. After setting current, the potential across the reference resistor is balanced with the reference voltage so that no signal is sent to the amplifier and amplydine via the feedback network. Any variation in magnetizing current changes the potential across the reference resistor and causes the error signal, due to the difference between reference voltage and reference resistor potential to enter the amplifier and amplydine. The amplydine responds by changing the current until the error signal disappears and the current is restored to its original value.

Sufficient loop gain for current control to 0.02 per cent can be attained by using a small reference resistor, 0.01 ohms, perhaps, and additional electronic amplification in the feedback network. The difficulties of operation of a D.C. amplifier can be avoided by using a large reference resistor, one to eight ohms, which will provide the gain needed at the expense of generator efficiency. Because of the simplicity of a large reference resistor and the large generator capacity available, the second method of attaining gain is chosen, using a reference voltage of 60 volts.

A suggested feedback circuit is shown in Figure 14. The circuit design and the values of circuit elements are based on the work of Shelton, Howard, and Karn[28] at the University of Kentucky. A six kilowatt, water cooled, reference resistor provides at least 60 volts for each of the current ranges: 8-12 amp., 11-15 amp., 14-21 amp., 20-27 amp., 26-36 amp., 35-47 amp., and 46-60 amp. These current ranges are chosen to keep the reference resistor voltage between 60 volts and 95 volts. The 10K potentiometer balances the reference resistor voltage against the reference voltage when setting current. A 60 volt mercury cell stack serves as the reference voltage and a dual range microammeter indicates the balanced or unbalanced condition of the circuit. The error signal is coupled to the feedback network through a 130K potentiometer. A voltage divider, an integrator, and a differentiator, made up of linear elements, give the feedback network a response which is dependent upon the magnitude of the error signal, the rate of change of error, and the duration of the error. The elements of the University of Kentucky feedback network had the following values: $C_1 = 1$ mfd., $C_2 = 0.25$ mfd., $C_3 = 0.50$ mfd., $R_1 = 1$ megohm, $R_2 = 1$ megohm.

The field in the magnet air gap is made a repeatable function of the magnetizing current by following a demagnetizing routine before each run with the accelerator. The particle energy can then be calibrated

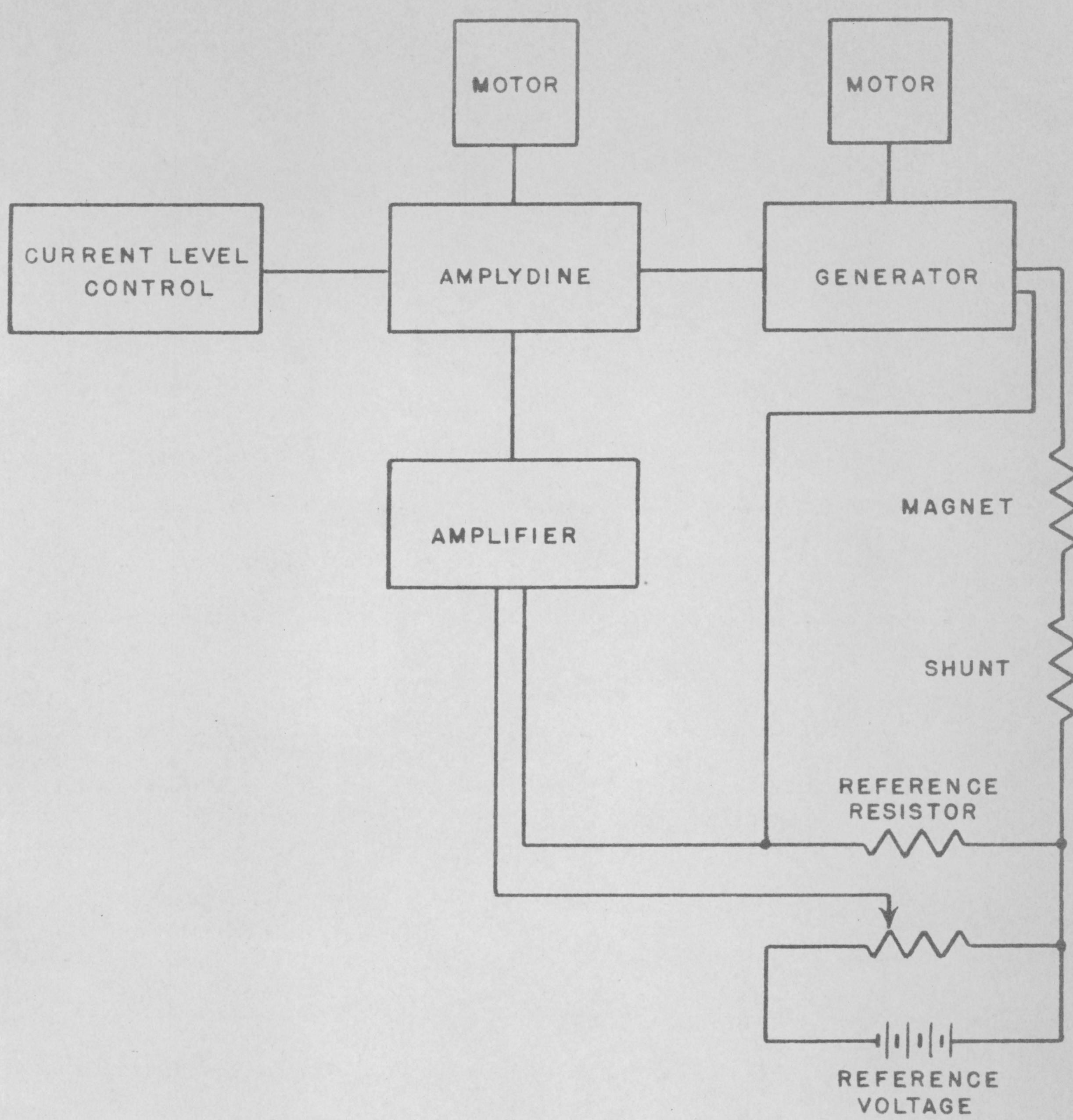


FIG. 13 VOLTAGE FEEDBACK BLOCK DIAGRAM

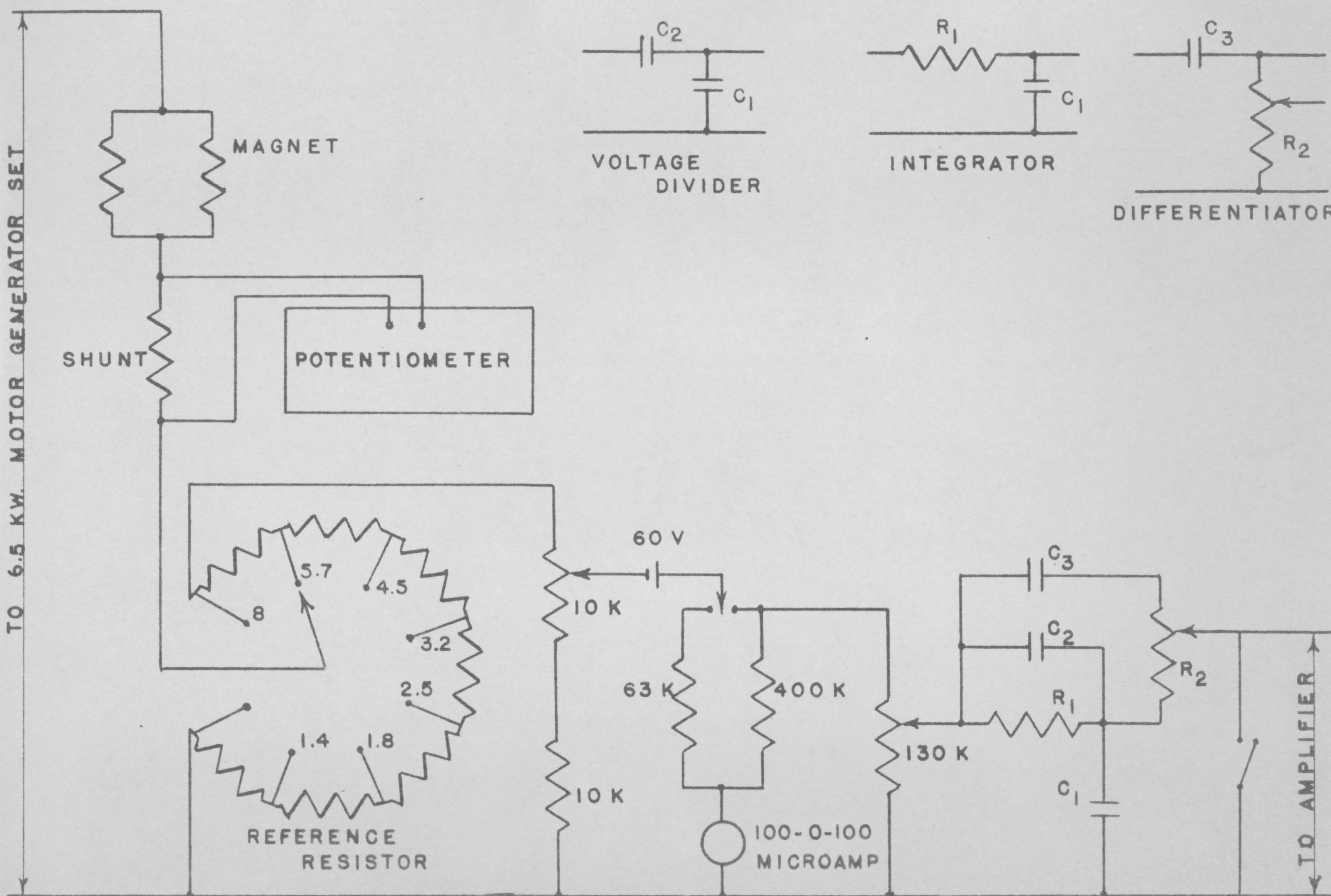


FIG. 14 VOLTAGE FEEDBACK CIRCUIT

against the potential drop across the precision shunt in the magnet circuit, using known nuclear resonances.

Nuclear Magnetic Resonance System

In 1900 Larmor showed that a gyromagnetic system with colinear angular momentum and magnetic moment will precess in a constant magnetic field about the direction of the field. The angular velocity of precession is equal to the product of the gyromagnetic ratio of the system and the applied field. Nuclear particles have inherent colinear magnetic moment and angular momentum, but are space quantized in a magnetic field. In fields of usual laboratory magnitude, the Larmor frequency of such particles is in the R.F. range. As shown by Bloch,[3, 4] application of an RF magnetic field at right angles to the constant magnetic field causes transitions in the quantized energy states of precession. By induction, these transitions can be detected directly with an RF receiving coil placed at right angles to both the constant magnetic field and the RF transmitting coil.

A diagram of a nuclear magnetic resonance probe is shown in Figure 15(a). For proton resonance, a sample such as mineral oil is placed in the sample bottle S. A magnet, M-M'supplies a uniform field B_o about which precession occurs. The RF transmitting coil and the receiving coil are shown at "X" and at "Y". A third coil "Z" is placed with its axis parallel to B_o and is used to introduce an audio perturbation on B_o. At a fixed RF transmitting frequency the induced RF signal varies with B_o as shown in Figure 15(b). With the field B_o at point A in Figure 15(b), application of an audio signal to coil "Z" causes a large audio modulation of the RF signal induced in the RF receiver. With B_o at point B, the resonant field value, audio modulation of the received RF signal will be a minimum because the resonance curve is horizontal at this point. At point C, a modulation will be obtained equal in magnitude to that at point B, but with 180 degree phase shift. Detection of the envelope of the received RF signal will produce an audio signal which varies with B_o as shown in Figure 15(c). This audio signal is easily amplified, and provides the positive-negative form needed for voltage stabilization with an amplydine controlled generator.

Application of the amplified audio pulse to the amplydine locks the magnetic field to the RF oscillator frequency. Stability of the field is dependent upon the stabilization of the oscillator, a technique well advanced. In addition, the RF oscillator frequency is a direct measure of the magnetic field so that particle energy can be found directly from oscillator frequency after calibration of the accelerator. A block diagram of a proton magnetic resonance system is given in Figure 16. The accuracy of field measurement and the degree of field stabilization are dependent upon the sharpness of the resonance. A Field nonuniformity of 5 per cent broadens the resonance sufficiently to make the method inapplicable. Since the field in the air gap is made nonuniform for vertical plane focusing, it cannot be used for probe insertion. However, a small cylindrical hole can be drilled into the side of the magnet to produce a uniform field and to accept the probe. The problem of a cylindrical hole in a uniformly magnetized material of permeability μ_1 has a simple solution.[35]

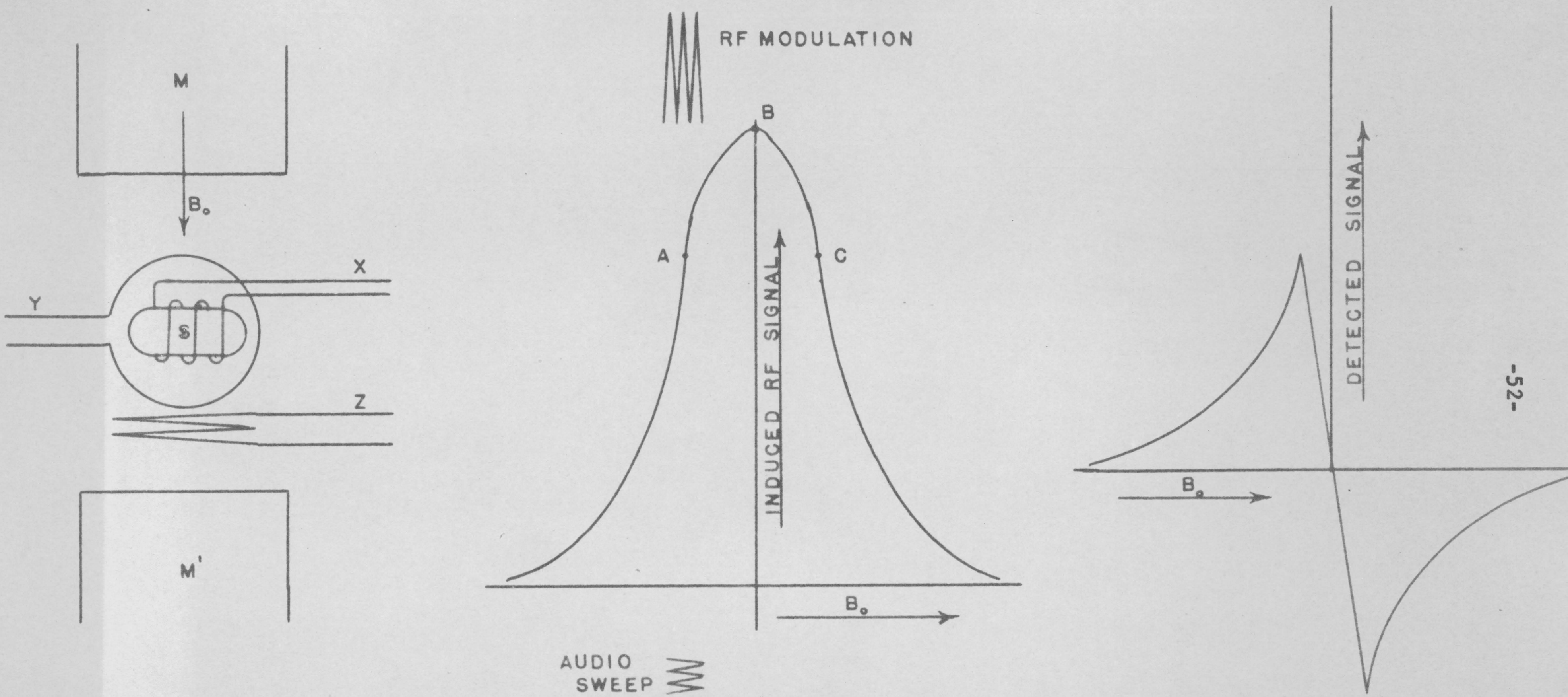
$$B = \frac{2\mu_0 B_0}{\mu_1 + \mu_0}$$

where: B is the magnetic induction at any point in the hole

B_0 is the magnetic induction in the magnetic material at a great distance from the hole

μ_1 is the permeability of the magnetic material

μ_0 is the permeability within the cavity



A– NUCLEAR MAGNETIC RESONANCE PROBE

B– VARIATION OF RF SIGNAL WITH MAGNETIC INDUCTION

C– VARIATION OF DETECTED SIGNAL WITH MAGNETIC INDUCTION

FIG. 15

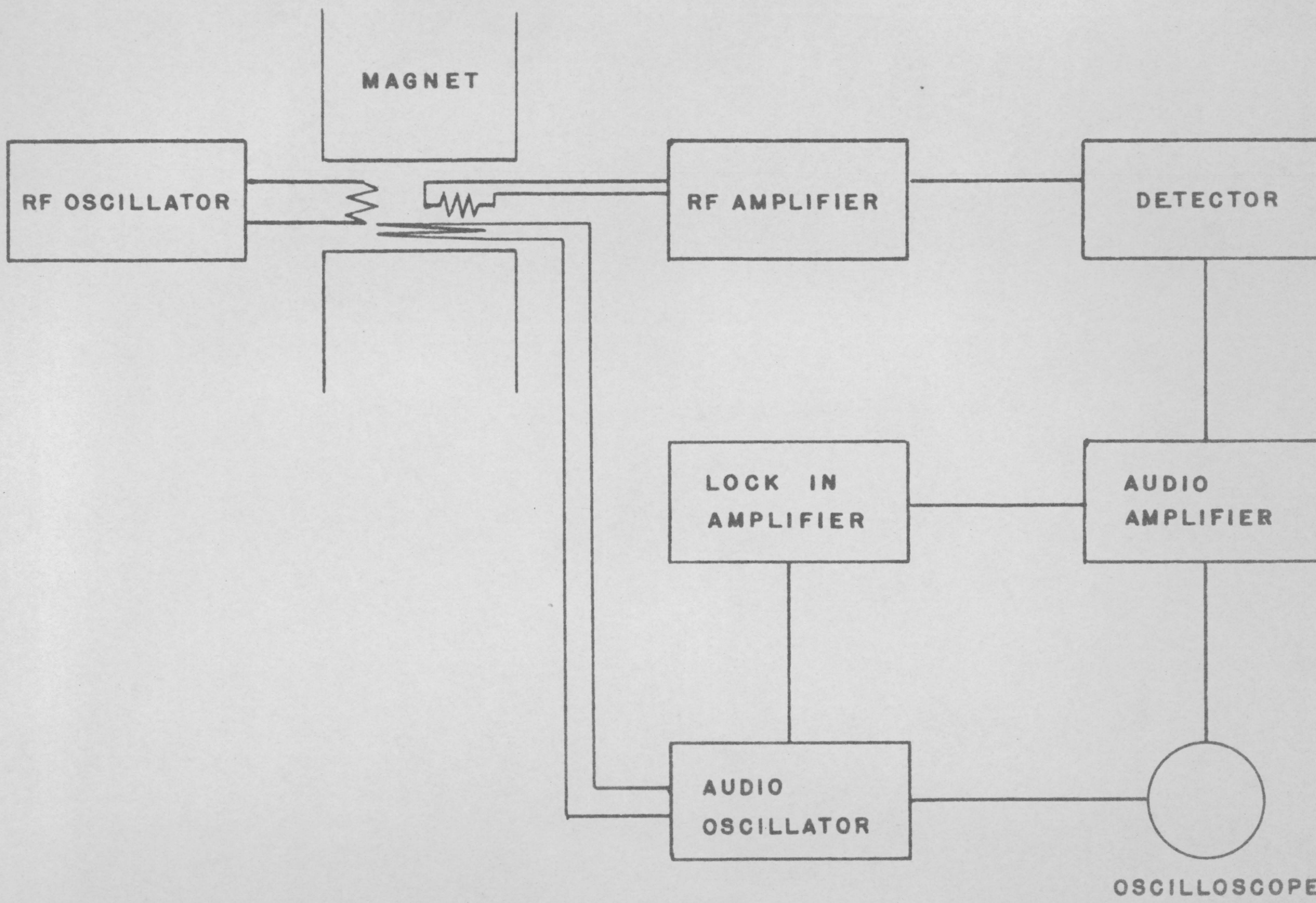


FIG. 16 NUCLEAR MAGNETIC RESONANCE CIRCUIT BLOCK DIAGRAM

SUMMARY

A magnetic analyzer capable of bending the four million electron volt beam of the Virginia Polytechnic Institute electrostatic accelerator has been constructed. The magnet is the circumferential yoke, double focusing type. Tests show its field to be uniform within one per cent along its 16 inch radius, its magnetization curve to agree with the design requirements, and its cooling system to be more than adequate.

A motor-generator set and a motor amplydine have been obtained for the magnet power supply, delivery now awaited. A voltage feedback system has been designed for field stabilization, and the considerations in applying nuclear magnetic resonance equipment to field stabilization have been examined.

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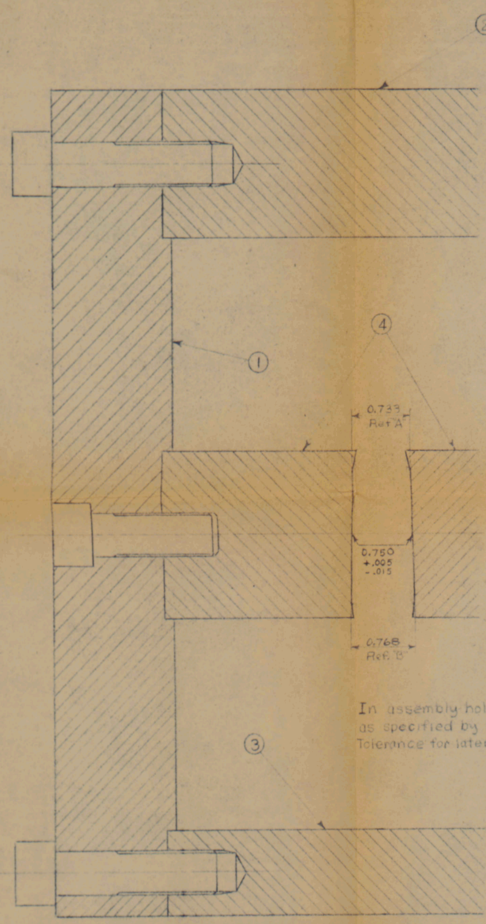
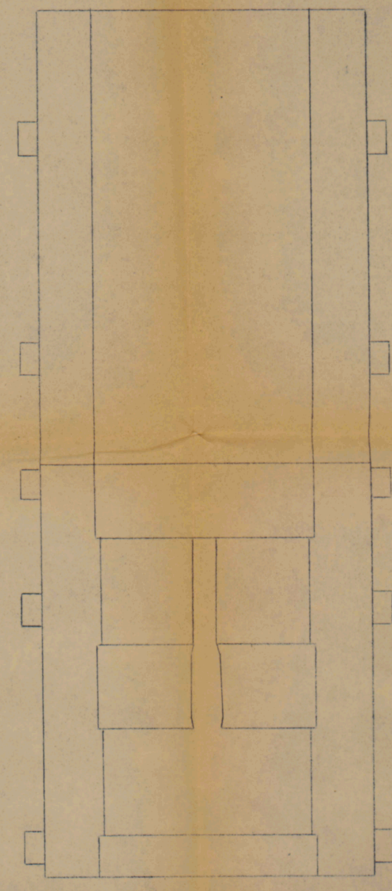


In assembly hold angle between pole faces as specified by ref. dimensions "A" and "B". Tolerance for lateral separation of pole faces $^{+.005}_{-.015}$

Section of Assembly

Full size

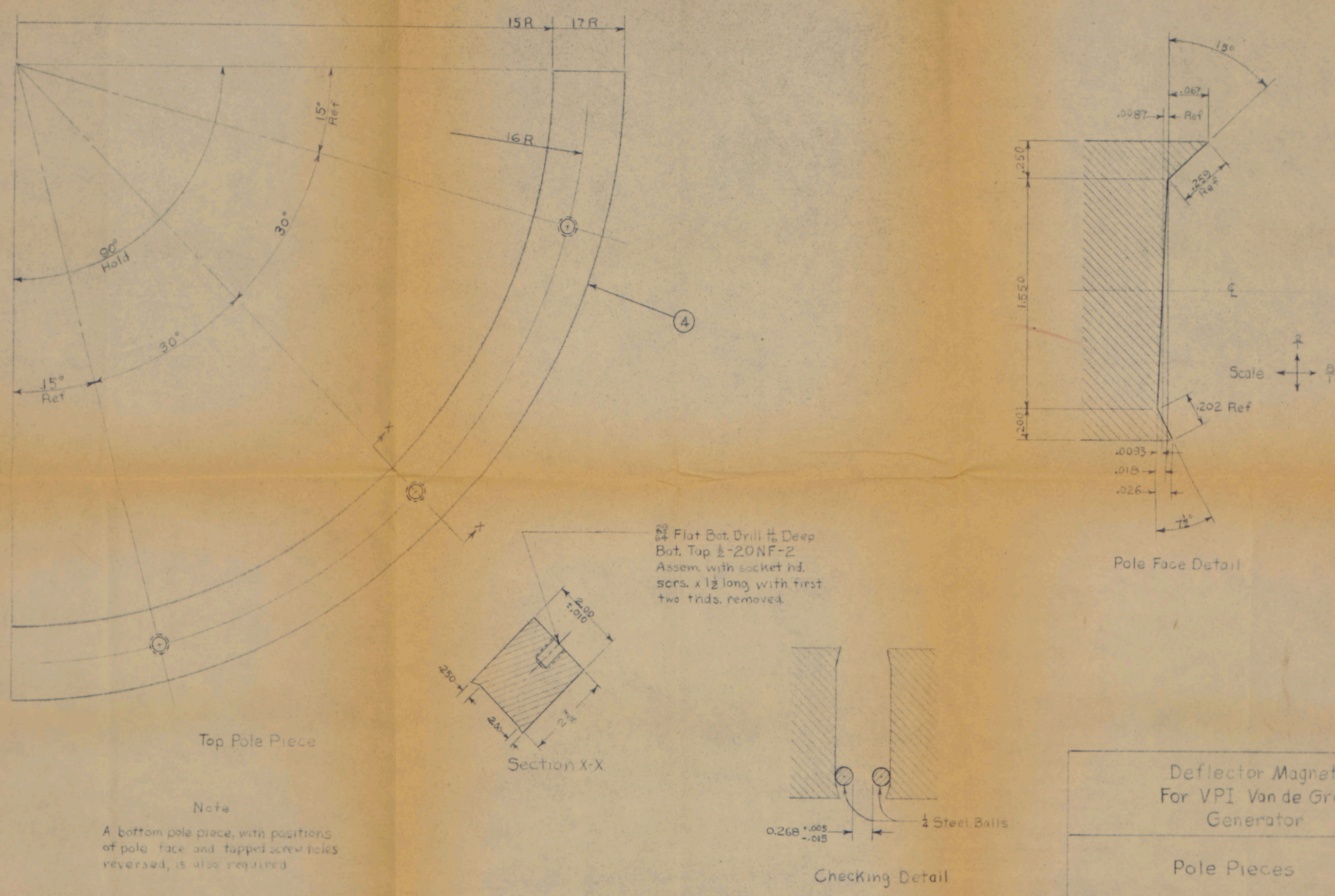


End Elevation Assembly

Half size

Deflector Magnet
For VPI Van de Graff
Generator

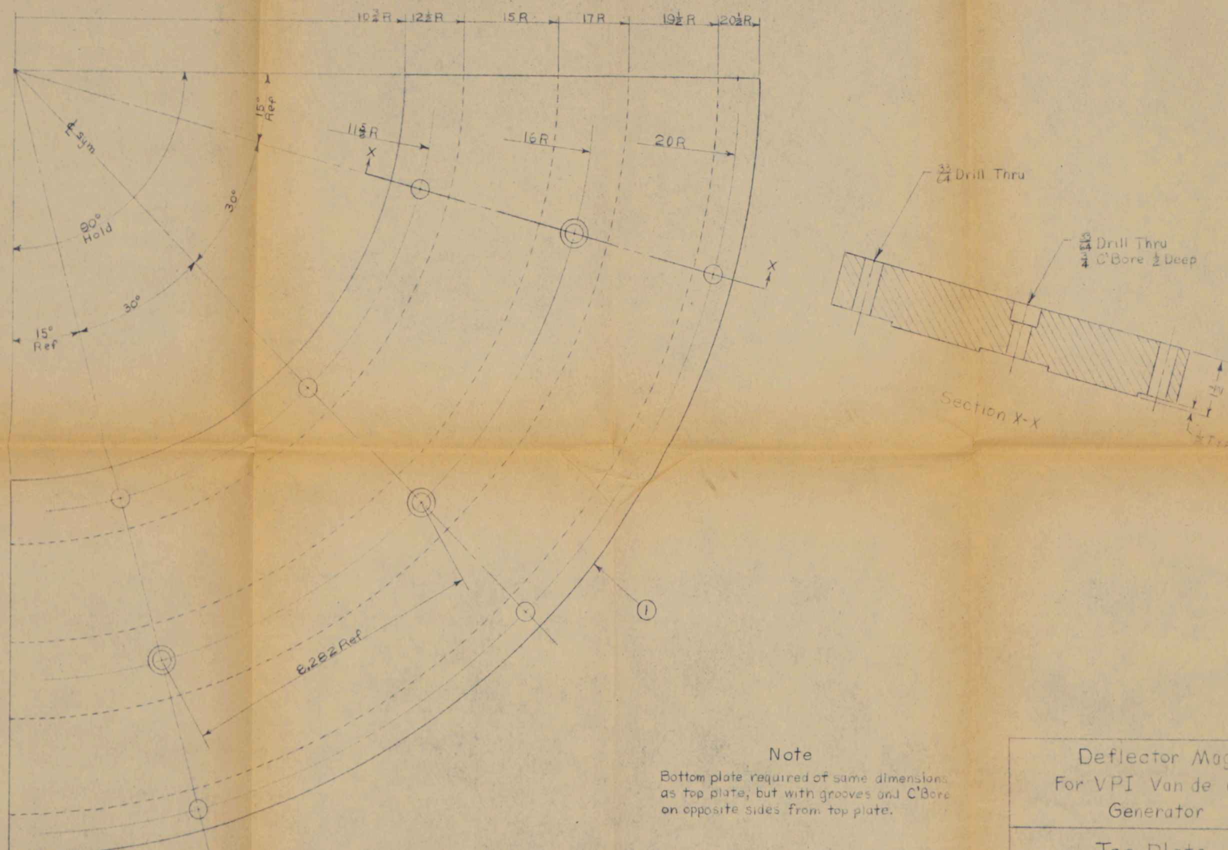
Total weight 375.# EST



Note

A bottom pole piece, with positions of pole face and tapped screw holes reversed, is also required

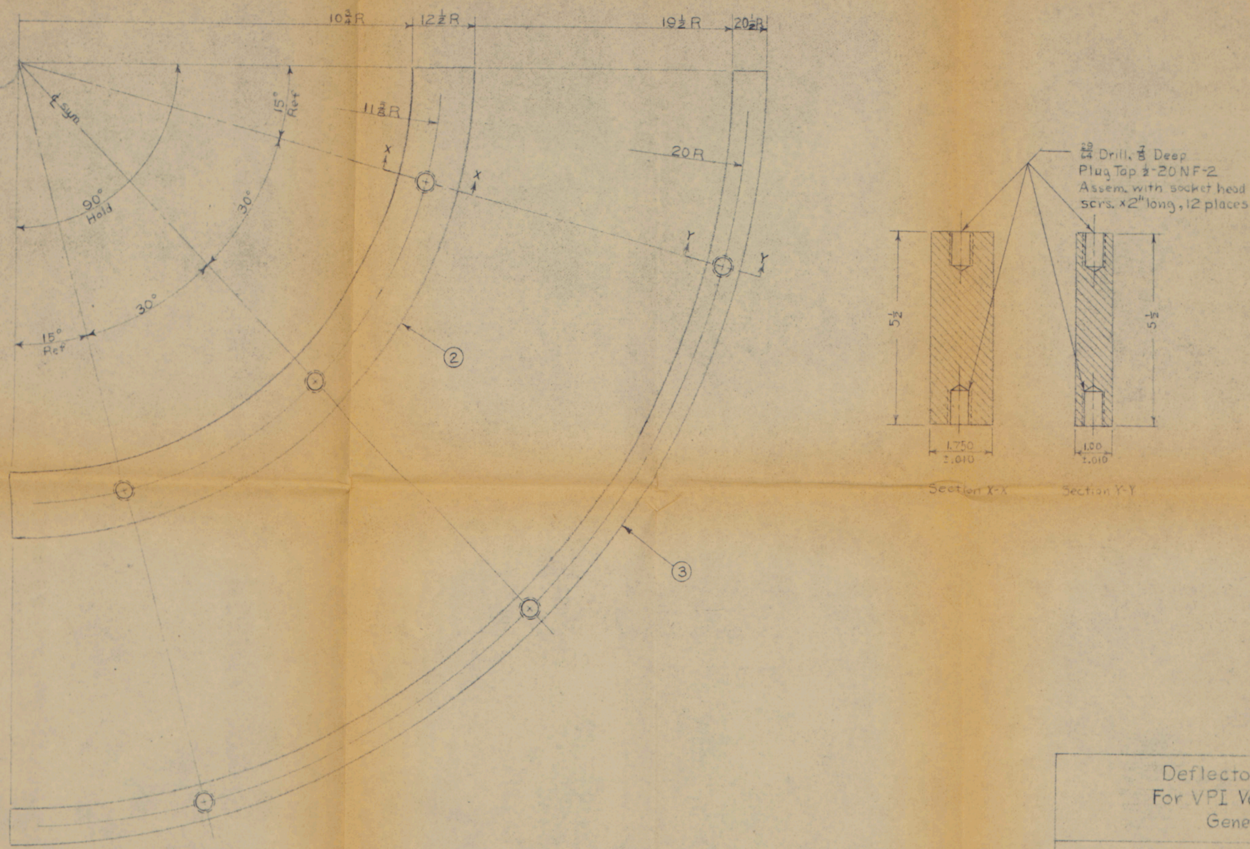
Deflector Magnet For VPI Van de Graff Generator					
Pole Pieces					
Drawn	DWO	Check	TMH	Scale	Half size
Material	Magnet iron or Mild steel				
No. Required	one top and one bottom pole piece				



Note

Bottom plate required of same dimensions as top plate, but with grooves and C'Bore on opposite sides from top plate.

Deflector Magnet For VPI Van de Graff Generator					
Top Plate					
Drawn	DWO.	Checked	TMH	Scale	Half size
Material	Magnet iron or mild steel				
No. Required	one top plate and one bottom plate				



Deflector Magnet
For VPI Van de Graff
Generator

Side Plates

Drawn	DWO	Check	TMH	Scale	Half size
Material	Magnet iron or Mild steel				
No. Required	one ② and one ③				