2XII-B PULSE COIL DESIGN

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Abstract

The design of the 2XII-B pulse coil system is presented. Development of the coil geometry is given as well as the results of magnetic field calculations. A discussion of the forces developed by this high energy coil set and the electrical stress on the magnet insulation is presented. The results of materials selection for both the coil insulation and structure is included and also a description of the fabrication procedure.

Introduction

The 2XII is a pulsed experiment designed to study plasma confinement in open ended geometry. The machine is currently being modified by the installation of a new pulse magnet set into the existing apparatus. The new arrangement is designated 2XII-B. Several changes in the magnet design have been incorporated to improve both the operation and reliability of the system as well as its performance as a plasma compression and containment device. The coil set is part of an overall machine which includes: a non-conducting high vacuum chamber, end tanks and associated vacuum pumps, cryogenic liners and sublimators; large neutral beam sources; and the energy distribution/supply network and diagnostic apparatus.

The previous machine has been described[1] and is shown in Figure 1. The 2XII-B layout is given in Figure 2 which shows the four active components: dc guide field solenoids, Yin-Yang[2] plasma compression coil pair, slow gate barrier magnet, and the fast gate magnet. This coil system first forms a guide field for a warm plasma then sequentially traps the plasma and compresses it as neutral ions are injected. The major design changes have been made to the compression coil pair which form the heart of the machine. The most obvious improvement is the enlargement of the transverse apertures yielding about 4.5 times the area available for neutral beam injection. Large sources are now being designed for intensities up to 600 amperes compared to the 10 ampere source presently used with 2XII.

The compression coils are constructed with 2-1/2 turn windings which has increased the inductance over 6 times from the single turn 2XII coils. This will enhance longer plasma containment times as the intrinsic L/R time has increased up to 60 ms. Many design improvements have been made that reduce mechanical and electrical stresses. The compression coils are wound 4-filar so that the current may be split up into four leads per winding, reducing lead stresses by a factor of 12. The gate magnets are constructed with less conductor, much simpler to fabricate, and with reduced coupling to the main coils to minimize induced potential. All of the pulse coils are wound with .814 inch square hollow copper conductor. Much effort has been made in materials selection, especially with regard to electrical insulation and the structural material. The bulk of the magnet construction effort for the project goes into the magnet reinforcement so that particular attention was given to fabrication methods in an attempt to reduce construction time and simultaneously build a stronger, more reliable magnet system. The nature of the 2X coil set is such that failures are nearly impossible to repair making reliability a key requirement.

Magnet Geometry

The geometry of the compression coils was determined by making magnetic field calculations for a range of geometric parameters. These were further iterated to account for various conductor sizes and alterations in the number of turns and filars in the winding. The geometric model used in the calculations is shown in Figure 3. The principle concern was what effect varying the minor radius had on the mirror ratio and field line shape. Field calculations were made using MAFCO[3] which represents finite conductors with filamentary currents. Generally a 2 x 2 cm region of a winding is approximated by a single filament. In all, fields have been computed for over 50 different configurations and the mirror ratios, well depths and flux tube shapes compared. All calculations were made with a 2 kG solenoidal base field and 1 MA in each of the compression set pairs. The 2XII geometry was used as a basis for comparison which has $R_2 = 65$ cm and $R_1 = h = 23$ cm. Figure 4 is a plot of the mirror ratio as a function of the minor radius for two cases ($R_2 = 65$ and $R_2 = 70$ cm). The mirror ratio is a fairly weak function of the minor radius but increases in both directions from a minimum value. As the minor radius becomes large the mirror ratio increases because the point of maximum field is shifted farther from the center of the magnet. The well depth is a strong function of the minor radius as shown in Figure 5. The field line shape remained convex toward the plasma (hydromagnetically stable) for all cases considered. The effect of increasing the minor radius is to spread out the "fan" more, but only by a small amount.

These calculations showed that the minor radius could be greatly increased and still maintain, and even improve, the plasma confining field. The geometry is in fact limited by other considerations such as intereference of the windings or excessive forces in the region where the windings become close. The geometry selected has a major radius of 70 cm and a minor radius of 42 cm, which greatly improves the usable volume of the magnet. This configuration allows for increasing the base field from 2 to 3 kG while maintaining a mirror ratio of about 2. When account is made of the inter-turn insulation the current density is reduced slightly so that the final coil parameters compared to 2XII are:

		2XII-B	2XII
major radius	R_2	70.00 cm	65.00 cm
minor radius	R_1	42.00	23.00
lobe separation	h	26.18	23.00
half aperture	a	22.54	22.36
coil width	w	23.50	20.32
coil thickness	t	2.35	1.27
lobe angle	θ	12.26°	–

When operated at 1 MA per winding with a 3 kG base the calculated field values are:

$B_0 = 9.12$ kG
$B_{max} = 17.60$ kG
mirror ratio = 1.93
well depth = 34% at the vacuum wall

A plot of the field lines and |B| contours is shown in Figure 6 for the vertical plane. The coil cross-sections and limiting vacuum wall are also included. The dotted line represents the mirror or reflection points along the field lines.

The gate magnets are simple coils of rectangular aperture but curved to conform to the shape of the main compression magnets. The slow gate is a single turn coil and the fast gate is a 1/4 turn magnet to reduce inductance producing a short rise time. These magnets have a half aperture of 26.7 cm and are curved

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*Work performed under the auspices of the U.S. Atomic Energy Commission on a 104 cm radius. The field produced by the gates is about 14 G/kA and they will typically peak at 5.6 kG. The current decay for both of the gates is relatively fast so that their field components are negligible by the time the main compression magnets have peaked. The geometric input used for field calculations is given in Figure 7 to show the relative sizes and locations of the coils. The compression magnets and fast gate coil are connected to feed rings which are required to minimize lead inductance and evenly distribute the current flowing from the capacitor banks. This arrangement is shown in Figure 8 for the compression coils. The new pulse coil assembly is somewhat larger in diameter so two new 9 ft I.D. solenoids have been designed to supplement the existing 6 ft I.D. coils for operation at 3 kG.

Magnetic Forces

Associated with the high current required in the pulse magnets are large magnetic forces which constitute the primary mechanical design and fabrication problem for 2X. A total of 6.7 MJ is dumped into these coils of which 82% goes into the compression magnets. The coils must be restrained by a nonconducting structure that can absorb the shock of each pulse and limit deflections to a tolerable amount. The structure must have mechanical properties to withstand a load that is applied in a few microseconds and sustained for several milliseconds, or static loading.

The main coil set has, at any section through the winding, 10 conductors in close proximity and each carrying about 100 kA. Any forces trying to cause a conductor to "jump-over" its neighbor must be restrained.

Calculations have been made using FORCE[4] comparing the forces on 2XII-B to the previous set on an equivalent current basis. The forces of course vary at any location around the coil, but in total magnitude are less than those in 2XII. This is due to the increase in both major and minor radii resulting in lower energy density.

Turn-to-turn forces will exist in 2XII-B which are not present in 2XII. These must be determined accurately because excessive stresses could damage the turn-to-turn insulation causing voltage breakdown and subsequent coil failure. These forces have been calculated for every location on the magnet and the cummulative compressive stress on the insulation is found to range from 4600 to 5700 psi. The magnetic pressure on the face of the winding is an order of magnitude lower with a maximum value of 760 psi. In general, the forces in each of the 10 conductors is very similar to those of a single layer solenoid: an outward (radial) pressure trying to enlarge the magnet aperture and strong attractive (axial) forces within the winding bundle. Figure 9 is a comparison of the force vectors on a single layer, 42 cm radius solenoid with those of 2XII-B at the center of the minor radius bend.

The stresses in the coil structure for both the compression and gate magnets is difficult to analyze accurately because of the complex geometry and nonuniform loading. All of the pulse coils are embedded in a common "sea" of reinforced epoxy which makes stress analysis indeterminate in nature. However, simplyfying the geometry and loading to a more tractable but conservative case shows that stresses are not severe and that reducing deflection is the key requirement of the coil structure. The force on each lobe of the compression coils is about 550,000 lb. The core of the compression coil structure is a "beam" of composite material built up between each of the Yin-Yang pairs. The forces acting on this beam per unit length are approximately constant and approximately radially outwards, from the center of the sphere, as pointed out by Last and Skellet[5]. The lobe deflection (change in half aperture) has been measured for the 2XII coil to be .09 inch. This deformation is expected to be reduced with 2XII-B due to improvements in the coil structure.

Magnet Insulation

The multi-turn/multi-filar construction of the compression coils is used to achieve sufficient thermal mass and inductance but of course allows for both electrical and mechanical stresses on the turn-to-turn dielectric. The compression coils nominally operate at a potential of 60 kV making turn-to-turn voltages 6 kV. This value is further increased due to coupling with the fast gate magnet. The gates are constructed so that electrical stresses exist only at the leads.

A testing program was initiated involving: dielectric samples stressed mechanically and electrically, measurement of mechanical properties of resin systems, and test coils cycled on a high energy capacitor bank for several thousand shots. The results of these tests were conclusive and the following insulation system has been selected.

1. each conductor is covered with three woven dacron sleeves
2. polyester film/web composite strip is inserted between turns
3. the bundle is double wrapped with fiberglass tape
4. the dry winding is vacuum impregnated with epoxy per LBL specification M20[6]

Dacron sleeving is used because it is a rugged material permitting the conductor to be bent around mandrels or otherwise formed. Three sleeves build so that there is approximately .10 inch between turns. A strip of polyester composite, commonly called DMD (Dacron-Mylar-Dacron) is placed between the turns. This added dielectric will permit some imperfections in the casting without destroying its electrical integrity. Wrapping the winding with fiberglass tape adds an outer thickness of material for protecting the insulation during subsequent operations such as sanding or grinding on the magnet. The resin formulation designated in specification M20 provides a low viscosity (150 centapoise), long pot life (over 4 hr), tough epoxy system.

In arriving at the above insulation system a total of about 40 individual samples were made and tested. Preliminary tests on parallel conductors yielded a wide range of breakdown voltages. Conductors covered with three dacron sleeves and impregnated with epoxy by a hand wet-lay-up technique brokedown at 16-17 kV. A 35 kV breakdown was measured for a vacuum impregnated sample with the same sleeving. Subsequent dielectric strength tests on larger, more complicated samples resulted in breakdowns ranging from 5 to 105 kV. This lack of uniformity prompted an extensive series of sample testing involving two epoxy systems and several types of film and fibrous materials. A fatigue test described here involved preparing specimens of parallel copper conductors (.814 inch square) and insulated in a manner applicable to the pulse coils. The samples were stressed electrically with a high voltage power supply throughout a mechanical loading cycle which compresses the insulation material to 80, 100, 150 then 200% of the working level in the compression magnets for several thousand cycles.

As samples were tested, improvements in materials and techniques were made so that we were finally able to achieve good uniformity in the specimen performance. A significant improvement was achieved by agitating the resin during deaeration prior to impregnation as discussed by Hill[7]. This test gave only a qualitative indication of the overall sample performance.

The inclusion of DMD increased the breakdown strength an average of 40% for three specimens. Measurements of the breakdown voltage for the M20 epoxy using the parallel conductor samples showed that the pure resin has a dielectric strength greater than 1200 volts/mil. When used in conjunction with dacron sleeving and DMD the dielectric strength is about 1000 volts/mil. After the severe fatigue loading samples breakdown at stresses from 720 to 910 volts/mil.

Mechanical strength properties of the M20 epoxy system have been measured. This epoxy has a tensile strength of 10,040 psi and an elongation of 5% at maximum stress (10.6% at failure). The initial or tangent modulus is .44 x 10^6 psi. Its compressive properties have been determined for both static and high rate impact loading. Static compressive properties are: 14,200 psi maximum stress at 6% deformation and a modulus of .51 x 10^6 psi. The impact stress-strain characteristics were determined using the Hopkinson Split-Bar Facility[9] at LLL, and data reduced by the method presented by Wesley[10]. At an average strain rate of 1000 sec^{-1} (μs loading) the M20 epoxy has a maximum compressive stress of 33,200 psi with 7.8% deformation and a modulus of .89 x 10^6 psi. Thus the area under the stress strain curve for this material is about 3 times greater at high rate impact than its static value. These strength values are significantly higher than those of the epoxy system previously used at LLL for magnet impregnation.

As a final test of the insulation materials a small solenoid test was developed. A coil was designed so that the loading, in terms of mechanical and electrical stresses, match those of the full size compression magnets. To evaluate the proposed materials two test coils were fabricated, one with and one without DMD. Techniques that would be used on the full size coils were used so far as practical. The coils were wound bifilar so that a dc high pot could be made, corona onset voltages measured and high turn-to-turn voltages developed when on the bank. These coils have a 12 inch diameter and are wound with .340 inch square copper conductor. Figure 10 is a photograph of one of the test coils.

The coil without DMD completed 100 shots at the 150% stress level then breakdown at 15 kV turn-to-turn (250 volts/mil) with a dc high pot. The coil with DMD passed the dc high pot at the same level and received 2060 more shots at 150% energy and 600 shots at 200% energy. At this point it breakdown turn-to-turn at 18 kV. Thus, DMD proved to be valuable in prolonging breakdown after the coil was subjected to a rather severe test before failing at a factor of 2 in mechanical stress and a factor of 5 in electrical stress.

Structural Material

The pulse magnet set must be strengthened with a non-conducting structure. Glass fiber reinforced epoxy is a suitable material but due to the enormous size of the coil and the lack of rotational symmetry the job of building the structure is quite difficult and time consuming. The previous coil used a room temperature curing epoxy system that has respectable mechanical properties but is difficult to work with due to its short pot life (few minutes) and toxicity. A development program was initiated to achieve two general goals: improve the epoxy system with regard to its handling characteristics and improve the cured properties of the composite. Candidate materials were tested using the standard ASTM methods for plastics with tensile, compressive and flexural properties being determined. The Hopkinson Split-Bar test was also conducted for impact measurements.

Glass reinforcement was thus chosen for the pulse coil set. The bulk of the magnet is built up with a plain weave 19.5 oz fabric with 745 warp/230 fill tensile strengths. Small amounts of boat tape are used also. A new product being produced by Kaiser Glass Fiber* is a roving tape constructed by weaving 9 strands per inch of roving with Dacron thread to form a 22.5 oz tape. This material is available in 4 inch widths. It is useful where unidirectional binding is required and applies at a fast rate of build.

Preliminary testing was done on several epoxy curing agents with a pure DGEBA (diglycidyl ether of bis-phenol A) resin in an effort to find an optimum hardener. No great differences existed between room temperature curing agents with respect to mechanical properties. A particular polyether triamine was selected based on experience by Chiao and Moore[13]. A typical commercial product is Jefferson Chemical Co. agent Jeffamine T-403. When mixed with a pure DGEBA epoxy resin the working life for a 500 gm batch is over 15 hr without violent exotherm developing. Moderate temperature can be used to accelerate the cure.

Due to the pulse nature of the loading we were interested in imparting toughness to the epoxy formulation and also an ability to inhibit crack propagation. Siebert, et al[11] summarize work in this area using liquid polymers to toughen epoxy resins. B.F. Goodrich Co's. Hycar CTBN (carboxyl terminated butadiene-acrylonitrile copolymer) gave the best toughening improvement among the materials investigated. CTBN is used at relatively low levels, 5-10 phr (parts hardener to resin) to achieve in-situ formation of small rubbery particles (0.2-3μ) dispersed in the glassy matrix. It is known that the bonding of the dispersed particles to the matrix is essential to optimize the toughening effect and the terminal carboxyl groups on the liquid rubber are important to toughen an amine cured epoxy system. B.F. Goodrich suggests[12] several methods for the proper reaction of CTBN in particular resins, however, experience at LLL suggests that the proper reaction is difficult to accomplish except under laboratory conditions. Fortunately this problem has been attacked commercially and the Dow Chemical Co. has recently (July 1973) placed a complete modified resin on the market tentatively called XD7575.02. This epoxy is an improved version of the earlier resin XD7575.01. However, the only significant difference between the two is the viscosity which is 12,000 cP (centapoise) for the 02 material and about 20,000 for the 01 resin. The current shortage of petrochemicals has delayed production of the newer version so the XD7575.01 resin was selected for use with the pulse magnets. When mixed with T-403 (36 phr) the viscosity of the system is 3200 cP at room temperature.

Mechanical properties have been measured for the resin system using the 19.5 oz fabric and are summarized here and compared to values measured for the materials of the previous coil.

	2X11-B	2X11
tensile strength----------------	46,700 psi	11,500 psi
tensile modulus, 1% strain-------	2.7 x 10^6	1.7 x 10^6
flexural strength----------------	53,200	---
flexural modulus-----------------	2.8 x 10^6	---
compressive strength-------------	30,700	16,000
compressive modulus, 1% strain--	2.1 x 10^6	1.3 x 10^6
compressive strength transverse to the fibers---------------	46,100	35,000
compressive modulus transverse to the fibers, 1% strain---	1.17 x 10^6	.55 x 10^6

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*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

The fiber contents for the 2XII-B samples averaged 65% fiber by wt., whereas for the 2XII samples the fiber content is about 50% by wt. Compressive properties measured at high rate impact by the Hopkinson Split-Bar technique are 51,500 psi strength, 2.5 x 10^6 psi modulus when the load is aligned with the fibers and 75,000 psi strength and 1.4 x 10^6 psi modulus when the load is applied transversely to the fabric.

In addition to changing the resin system, a new technique has been developed for the impregnation of the glass cloth and roving. The glass is preimpregnated with the epoxy system, including curing agent, by *a local firm (Hexcel Corp.) and shipped to LLL on dry* ice so that the prepreg remains non-reactive in the A-stage. The material is stored at the use point in a liquid nitrogen cooled trailer at 0°F. When material is required, a roll is removed from the trailer and the cloth quickly warms up to room temperature when unrolled. The prepreg is sandwiched between polyethylene films which keep out condensed water vapor and allow for easily cutting the material with a razor blade or scissors. A technician can then strip the plastic film off and lay-up the cloth. Laminating rollers of grooved aluminum on a paint roller type handle are used to work out trapped air and compress the saturated cloth. The epoxy system remains tacky for over 8 hr so that grinding off a glazed surface is not required frequently. This method of impregnation has several advantages. The fiber content is well controlled and mixing large quantities of resin is not required. The total volume of material necessary is about 130 cu ft which will weigh about 7 tons. The prepreg eliminates much of the discomfort to the technicians that exists with the usual wet lay-up method. The total cost of materials, refrigeration and the processing is $2.05 per pound or $227 per cu ft of prepreg. Quality control tests are made from random samples of this material before it is used.

Coil Fabrication

Each of the compression magnet pairs are wound individually on a multi-axis winding mandrel. Prior to winding, the .814 inch conductor is drawn through straightening rollers then passed through a sand blaster to remove surface oxides and enhance bonding to the epoxy. This is followed by a three section annealing furnace with an argon atmosphere and a water quench. Measurements were made to determine both *spring back and keystoning* of the annealed conductor on an inside radius bend of 15 inches. Spring back of 7/16 inch and keystoning of .020 inch were observed with 300 lb tension on the conductors. A minimum radius of 3 inches was selected for the bends in the leads and keystoning is removed by a hydraulic press. Prior to bending, the conductor is triple sleeved with Dacron. The conductor is wound with minimum tension and over bent. One of the windings is shown in Figure 11.

The completed windings are then transferred to a holding structure to maintain dimensions and the internal mandrel collapses and is removed. At this point the winding is wrapped with fiberglass tape, 2 layers 1/2 lapped. Slotted polyethylene sheets for decreasing pumping resistance are attached to the coil surface and then the vacuum jacket is added. It consists of 1/8 inch aluminum sheet and thicker bars for the edge seal. The jacket is sealed with RTV silastic. The coil is evacuated and baked out for several hours and continually checked for leaks. Baking is accomplished by circulating heated water through the conductor, which is also the heat source for curing the epoxy. Resin feed is regulated so that the impregnation consumes approximately 2 hr. Sight glasses are located in the jacket to monitor the resin level. The jacketed winding is shown in Figure 12.

The cured coils are next transfered to a large mandrel and aligned as shown in Figure 13. At this point a styrofoam form is built up in the region between the coil pairs to shape the inner surface of the beam. The prepreg lay-up is then started as shown in Figure 14. When the beam is built out to its final shape it is bound with roving tape which is partially shown in Figure 15. Beams of prepreg are also constructed for the gate coils. The fast gate magnet at this stage is shown in Figure 16. When the coil subunits are completed they are all assembled on the large mandrel and the final structural build-up is made.

Summary

The 2XII-B pulse coil set has an improved geometry for accepting high current neutral beams. The coil design has decreased mechanical and electrical stresses specifically on the magnet leads. A method of insulation has been developed to improve the reliability of the coil. The materials and the method of fabrication employed will greatly reduce deformation of the coils during operation.

Acknowledgements

The work reported here is the product of a rather large group guided by F. H. Coensgen, Project Physicist, aided by W. C. Nexsen, Jr. and the rest of the Physics staff. C. J. Anderson and G. E. Vogtlin have contributed immensly in the materials testing and selection program. They are reporting on additional topics at this conference. M. O. Calderon has been responsible for most of the layout and design work required for the magnet system. H. C. Saulter assisted by K. L. Gillespie supervise the magnet construction and associated equipment. T. T. Chiao and C. M. Walkup of the Chemistry and Materials Science Department at LLL have made many valuable contributions improving the magnet materials and fabrication techniques.

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12. Mr. P. C. Cramer, B.F. Goodrich Chemical Co., Los Angeles, California, Private Communication.

Captions

1. 2XII Device
2. 2XII-B Device
3. Geometric model of compression coils
4. Mirror ratio as a function of minor radius
5. Well depth as a function of minor radius
6. 2XII-B field lines and |B| contours at NI = 1 MA and B_{dc} = 3 kG
7. Geometric computer input
8. Compression coils showing feed rings
9. Comparison of force vectors on the compression coil winding to those of a single layer solenoid
10. 12 inch test solenoid
11. Compression magnet on the winder
12. Compression magnet ready for vacuum impregnation with epoxy
13. Both compression coils on the assembly mandrel
14. Partially completed prepreg beam
15. Completed beam is partially bound with roving tape
16. Fast gate magnet with beam nearly complete

2 X II

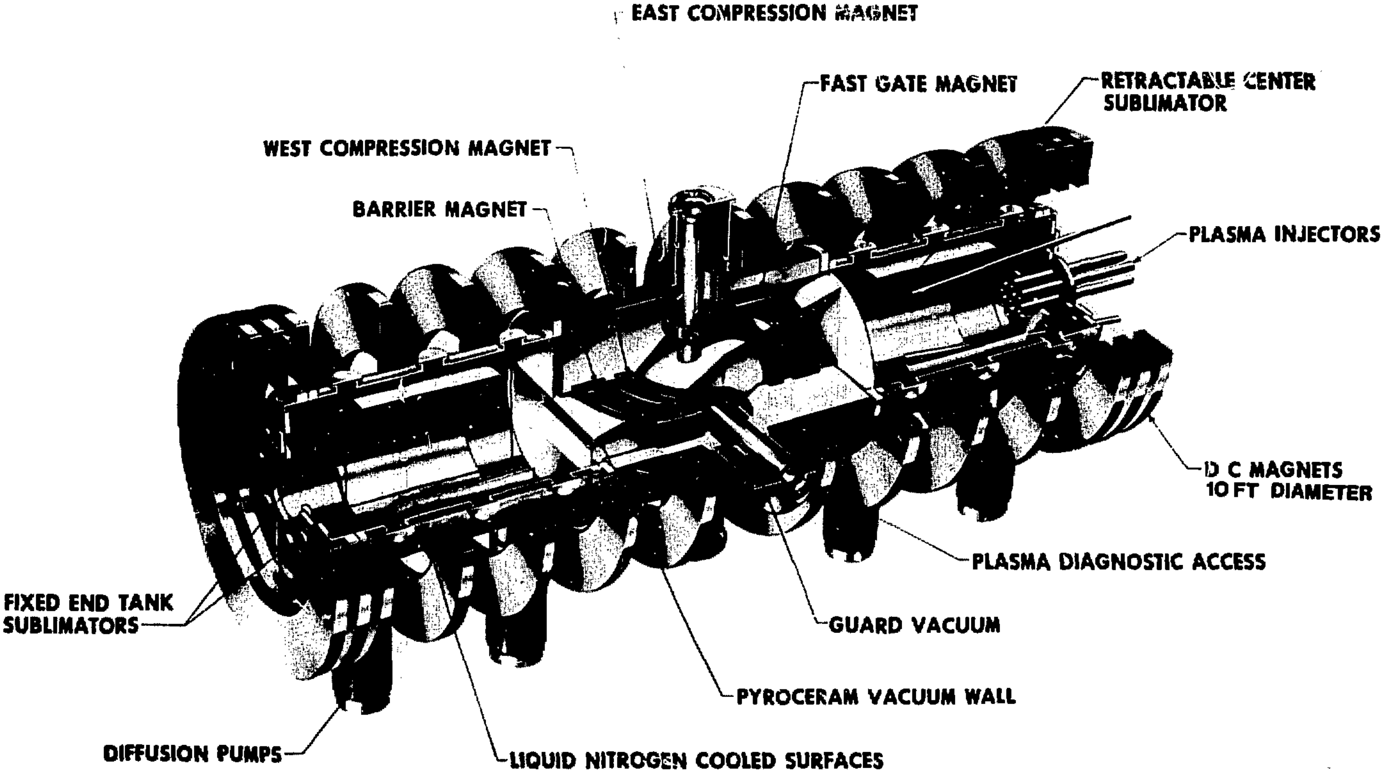
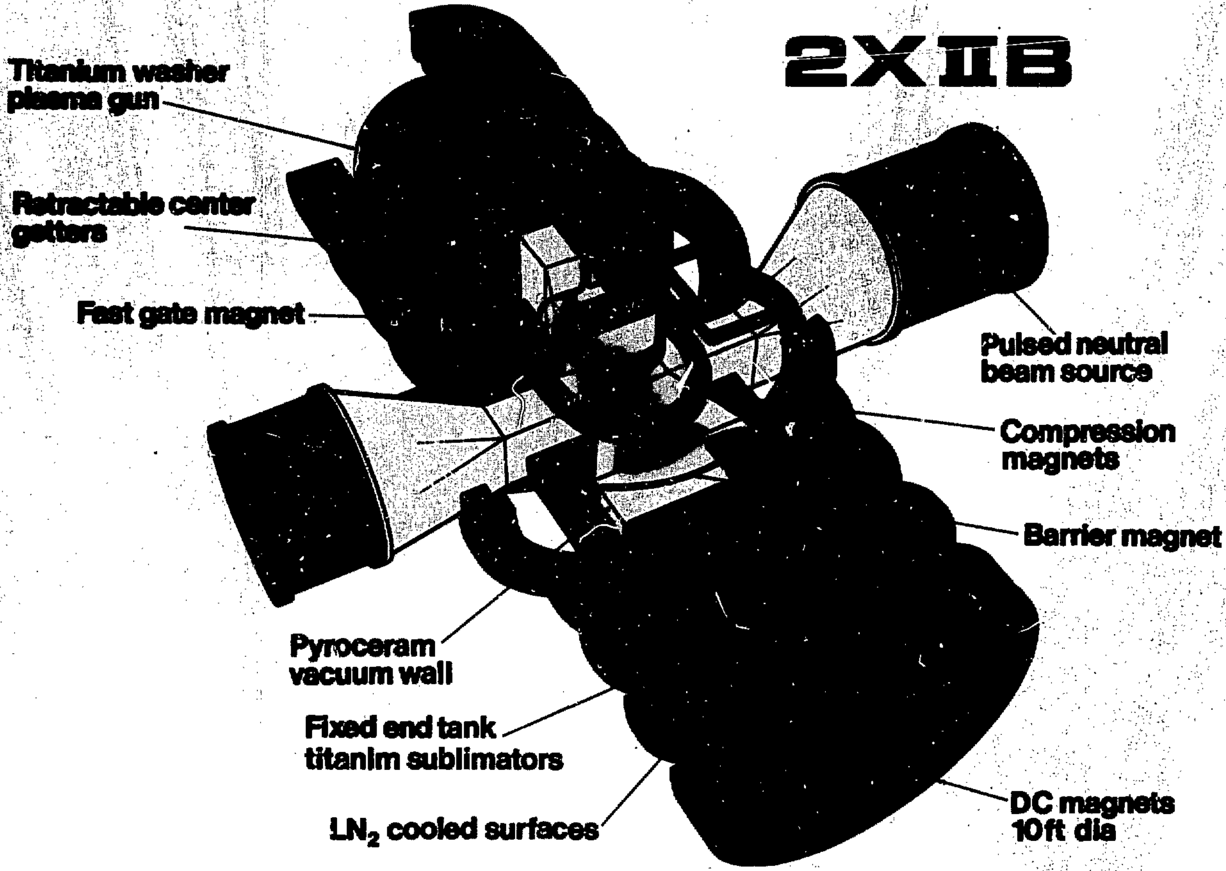


FIGURE 1


2XIIB
Titanium washer plasma gun
Retractable center getters
Fast gate magnet
Pulsed neutral beam source
Compression magnets
Barrier magnet
Pyroceram vacuum wall
Fixed end tank titanim sublimators
LN_2 cooled surfaces
DC magnets 10ft dia

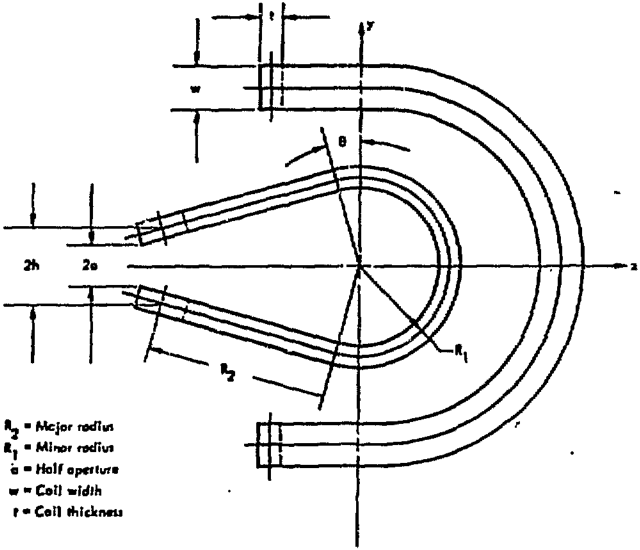

t
y
w
θ
2h
2a
x
R₁
R₂
R₂ = Major radius
R₁ = Minor radius
a = Half aperture
w = Coil width
t = Coil thickness

FIGURE 3

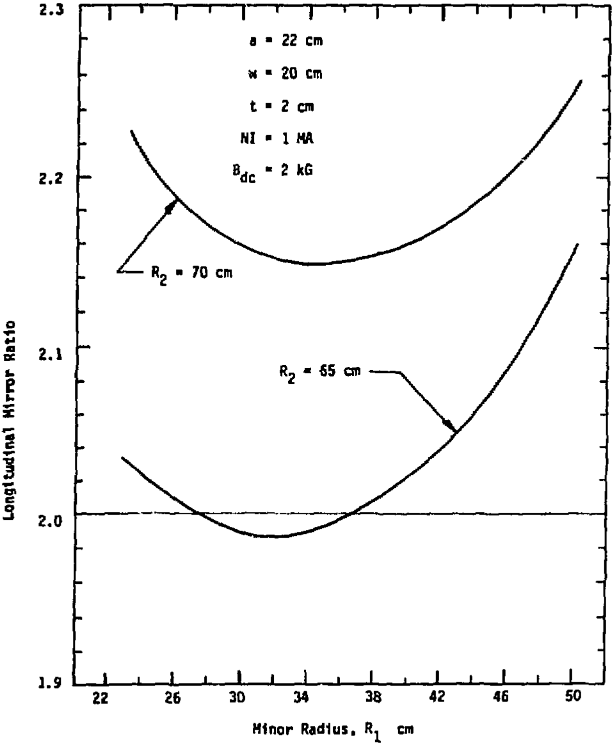

a = 22 cm
w = 20 cm
t = 2 cm
NI = 1 MA
B_{dc} = 2 kG
R_2 = 70 cm
R_2 = 65 cm
Longitudinal Mirror Ratio
2.3
2.2
2.1
2.0
1.9
22
26
30
34
38
42
46
50
Minor Radius, R_1 cm

FIGURE [illegible]

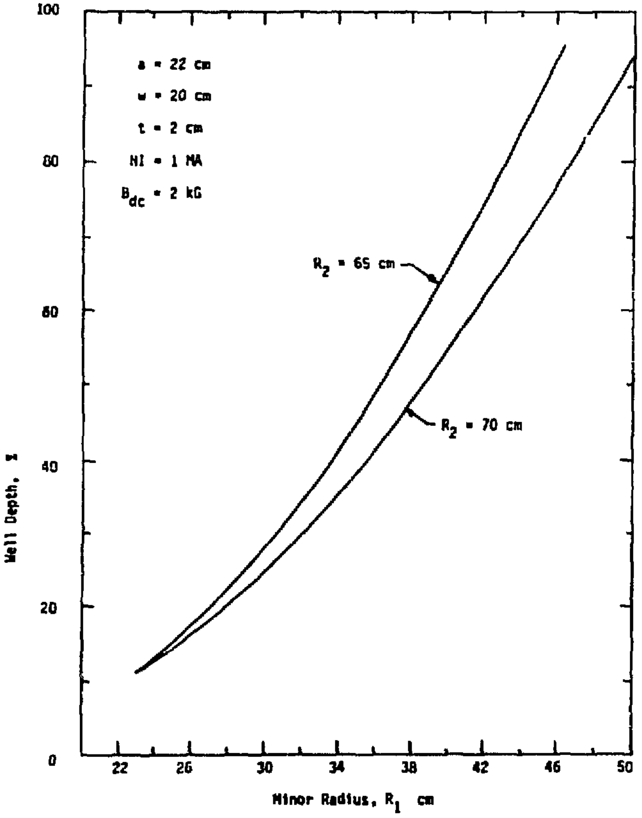

a = 22 cm
w = 20 cm
t = 2 cm
NI = 1 MA
B_{dc} = 2 kG
R_2 = 65 cm
R_2 = 70 cm
Well Depth, %
0
20
40
60
80
100
22
26
30
34
38
42
46
50
Minor Radius, R_1 cm

FIGURE [illegible]

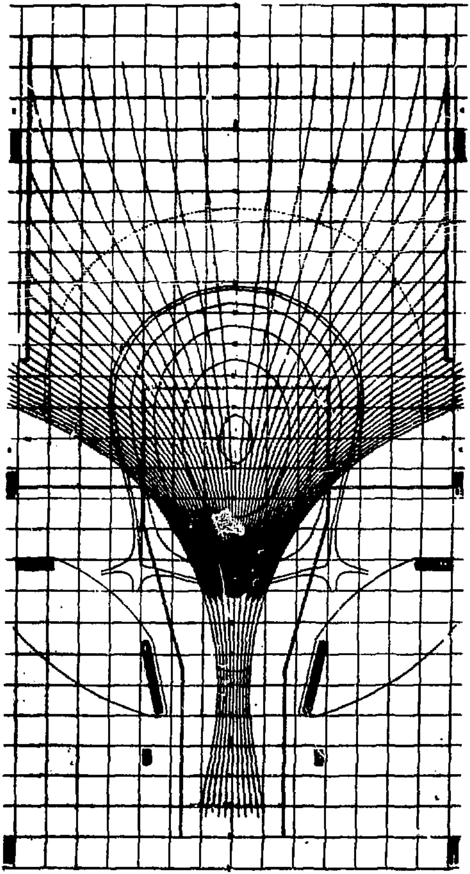


FIGURE 6.

top

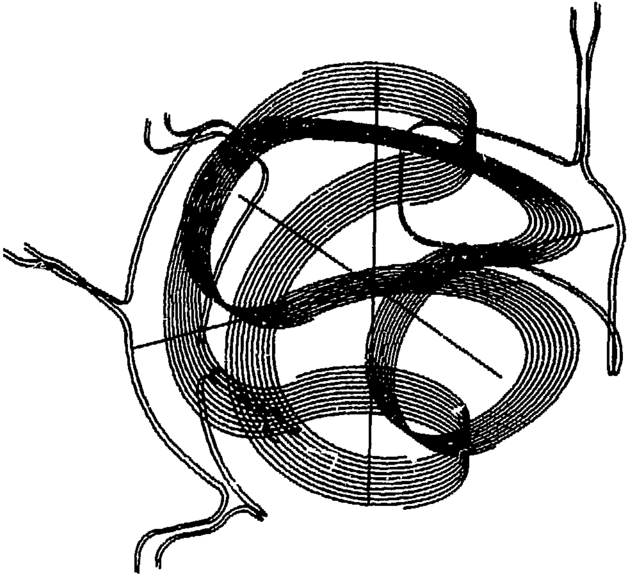


FIGURE 7

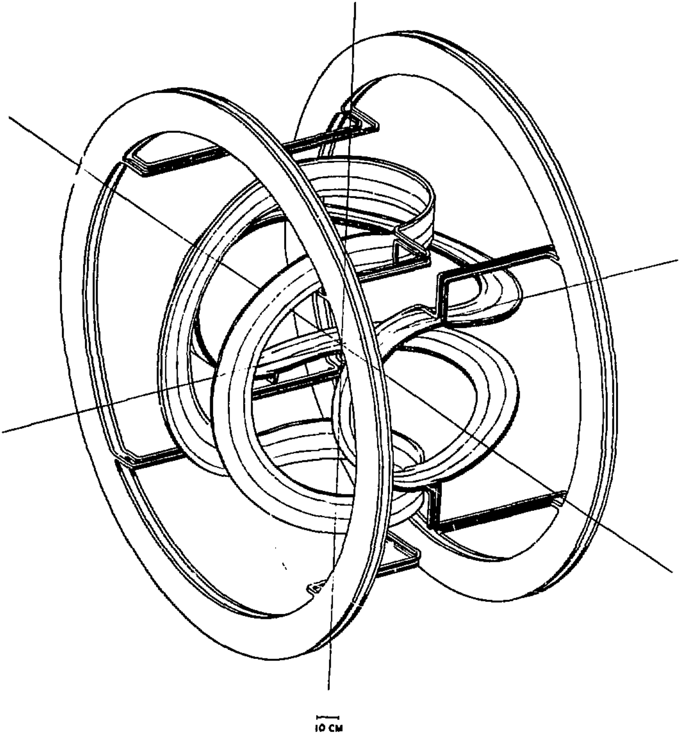
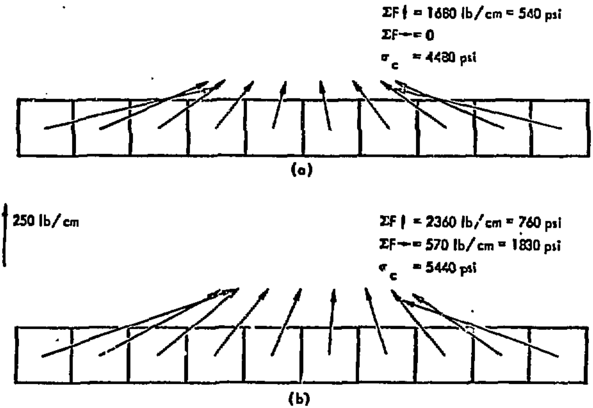


FIGURE 8



[illegible] Comparison of the force vectors on (a) a single layer 42-cm radius solenoid with (b) the forces at the center of the minor radius bend on 2XIIB.

FIGURE 9

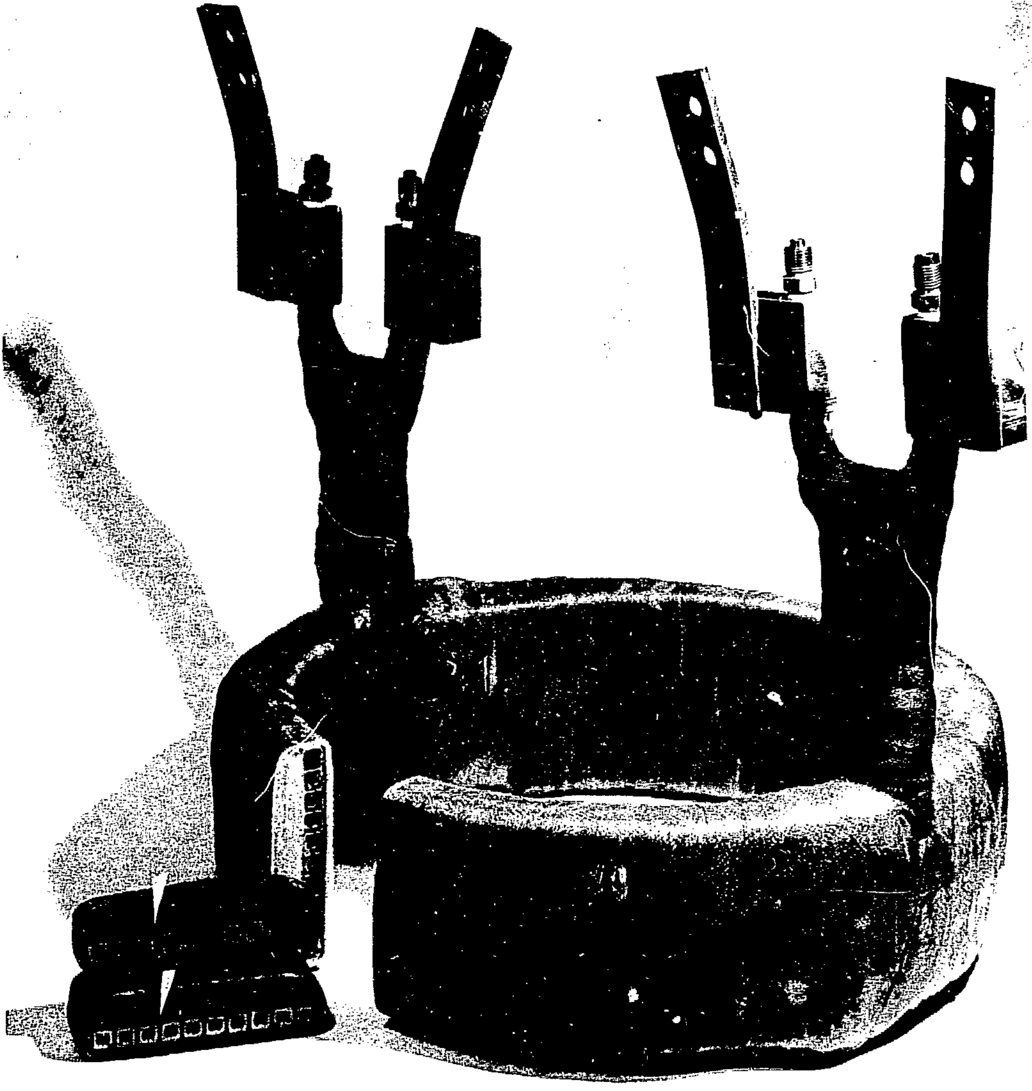


FIGURE 10

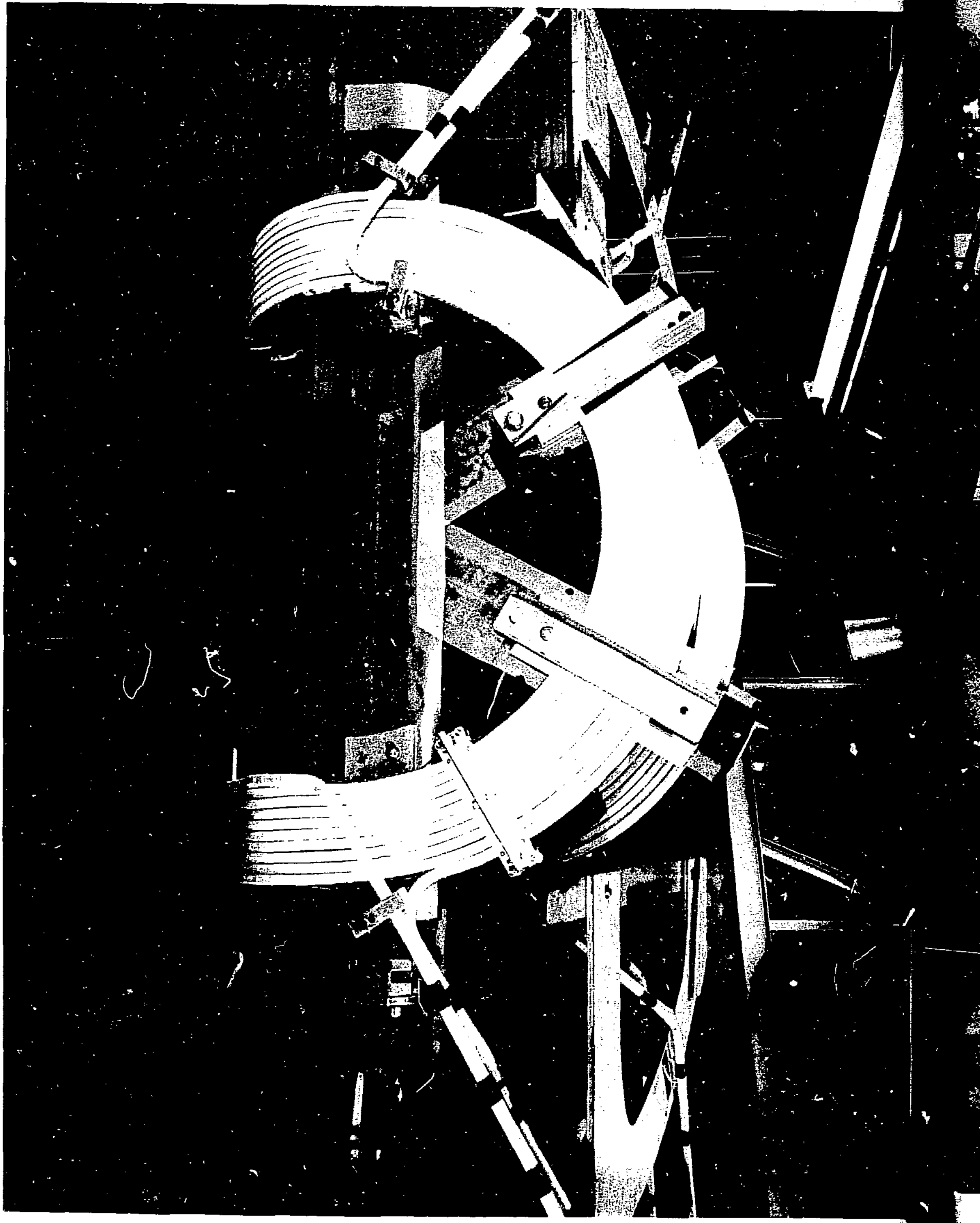


FIGURE 11

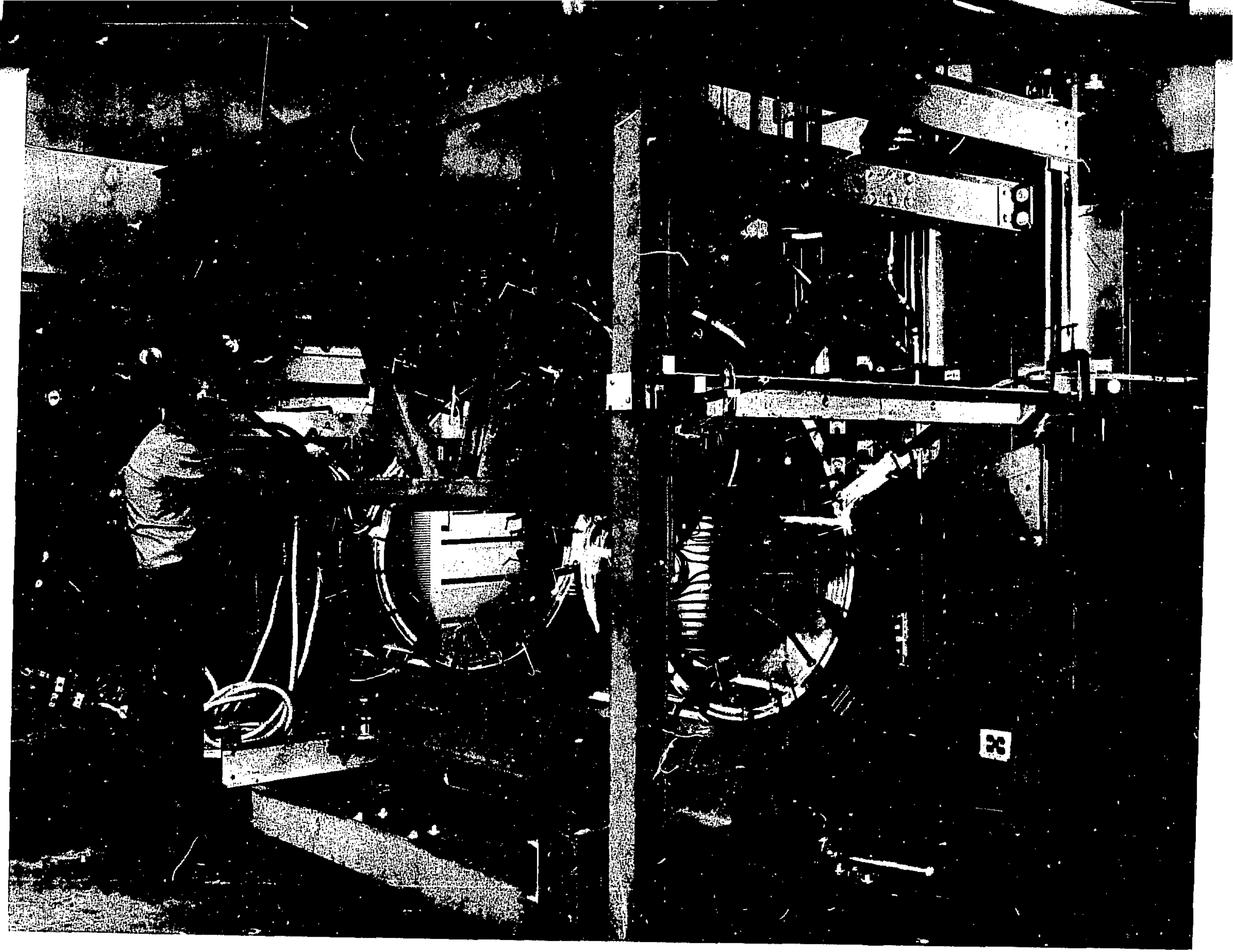


FIGURE 12

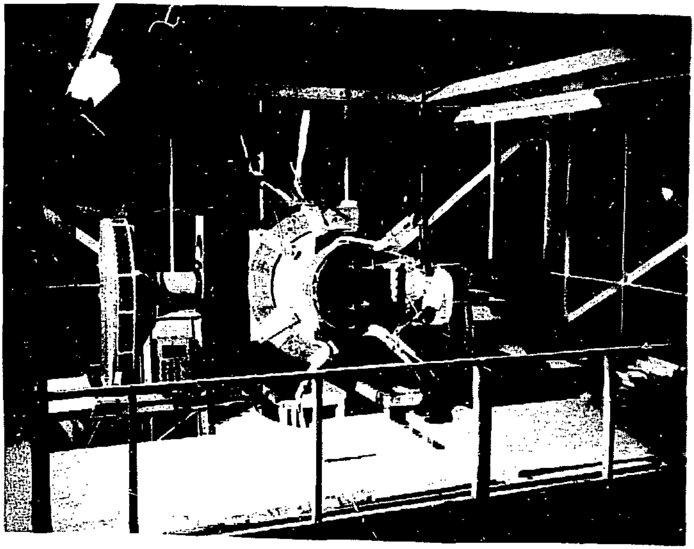


FIGURE 13

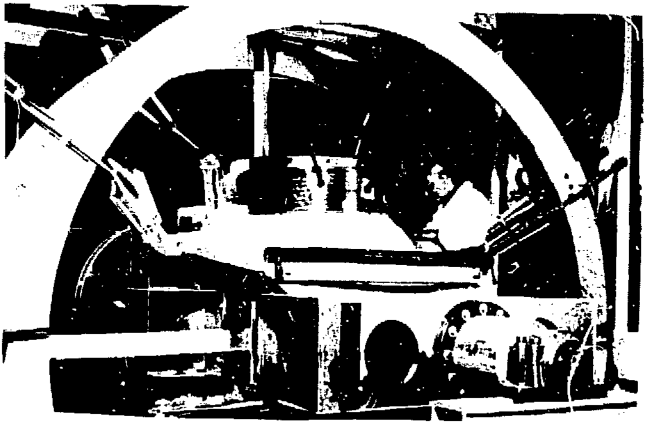


FIGURE 14

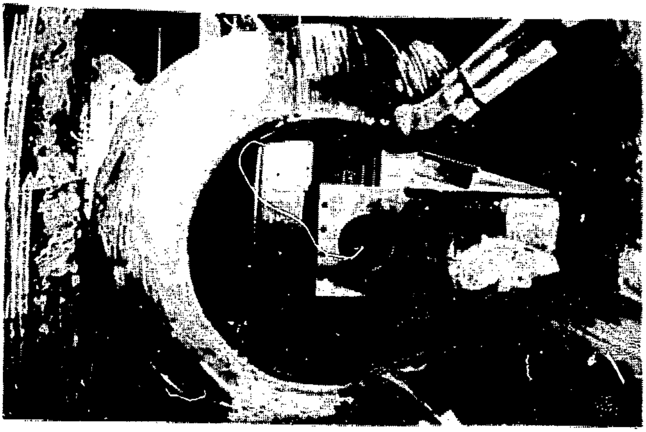


FIGURE 15

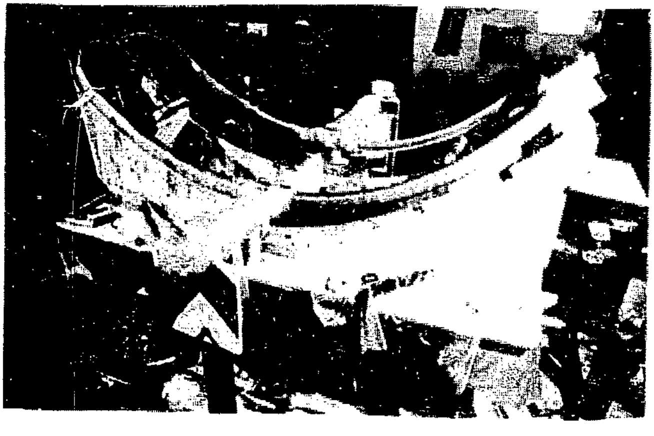


FIGURE 16