CONSTRUCTION DETAILS OF A MEDIUM-SIZED TESLA COIL DESIGNED FOR HIGH VOLTAGE EXPERIMENTS AND PERFORMANCE ART APPLICATIONS

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Since this is the Author's first attempt at constructing a Tesla Resonant Transformer in the kW range, the approach of this paper is mostly descriptive rather than prescriptive. Suggestions and criticisms regarding this coil design are encouraged, especially when accompanied by supporting data. I would like to thank Harry Goldman for providing such a rich venue of information on Tesla Coils, the TCBA News. I also want to bring some criticism to bear on certain "experts" of resonant transformer theory in Massachusetts and Southern California who consider their knowledge to be "proprietary", and their time too precious to be spent talking with amateurs. Such attitudes are more in line with Wall Street than with the scientific community.

The Tesla Coil presented in this paper is of the single stage resonant type, consisting of a tuned primary circuit that is loosely coupled to the base of a quarter-wave helical resonator, which stands vertically and is terminated on the top with a toroidal head electrode. The coil system is comprised of five parts:

- The three-phase power source
- Power distribution and control console
- High voltage DC power supply
- Primary drive circuit
- Resonant transformer structure with head electrode

The three-phase power source consists of an Oldsmobile 455 cu in V8 engine coupled to a 480V, three-phase generator through a 2.5:1 speed reducer. The synchronous generator is of the 6 pole, salient wound type, and is designed to produce 93 kilowatts of power at 1200 RPM and at 0.8 power factor. A standard cruise control is employed for frequency regulation, and a solid state circuit adjusts the exciter drive for output voltage stabilization.

The control console transforms and distributes power to the 120V utility outlets, the various instrumentation systems, and regulates the 480V three-phase power that is delivered to the HVDC power supply. The instrument panel contains a number of gauges that monitor the vital statistics of the Tesla Coil, and the Personnel and Machine Interlocks are summarized in the lower right-hand corner. These interlocks provide protection against incorrect speed or nitrogen pressure on the rotary gap, against open HV access panels, and against personnel coming within the "Kill Radius" during operation by monitoring the continuity of a He-Ne Laser beam which encircles the striking range of the coil.

The power delivered to the HVDC power supply is regulated by a motor-driven three-phase variac, operating as a variable series reactor. Three current transformers measure the mains current to the supply, while a fourth monitors the neutral to detect power imbalances or ground faults.

The HVDC power supply cabinet contains the three-phase step-up transformer set, the three-phase full-wave rectifier stacks, plus a HV divider and return current shunt for diagnostic purposes. A magnetic reed switch coupled to the DC return line will cause the main contactor to trip if the DC output current should suddenly rise above a given setpoint. The HVDC supply output is connected to the primary circuit through a 1.5 inch diameter high voltage coaxial cable of the type used for underground HVAC power transmission. The wiring diagram for the supply is shown in Figure I. For simplicity, the instrumentation and control circuits have been omitted. The three power transformers are identical and have the following ratings:

PRIMARY (RMS)-	480 Volts	34 Amperes
SECONDARY (RMS)-	10000 Volts	1.5 Amperes

Since the secondary windings are star connected, the maximum continous output rating of the DC supply after full-wave rectification is:

$$10000V(RMS) \times \sqrt{3}\ (3\phi) \times \sqrt{2}\ (PEAK) \times \sin 60^\circ (ripple) = 21213\ Volts$$

$$1.5A(RMS) \times \sqrt{3}\ (3\phi) = 2.60\ Amperes$$

The maximum power available to the Tesla Coil primary circuit is therefore 21213V x 2.60A = 55154 Watts. During normal operation however, the supply is usually not taxed beyond 45000 Watts.

The arrangement of the primary circuit and charging reactors is shown schematically in Figure I. The charging reactors CHR1 and CHR2 have nominal values of 5 Henry at 3 Amperes each, and are

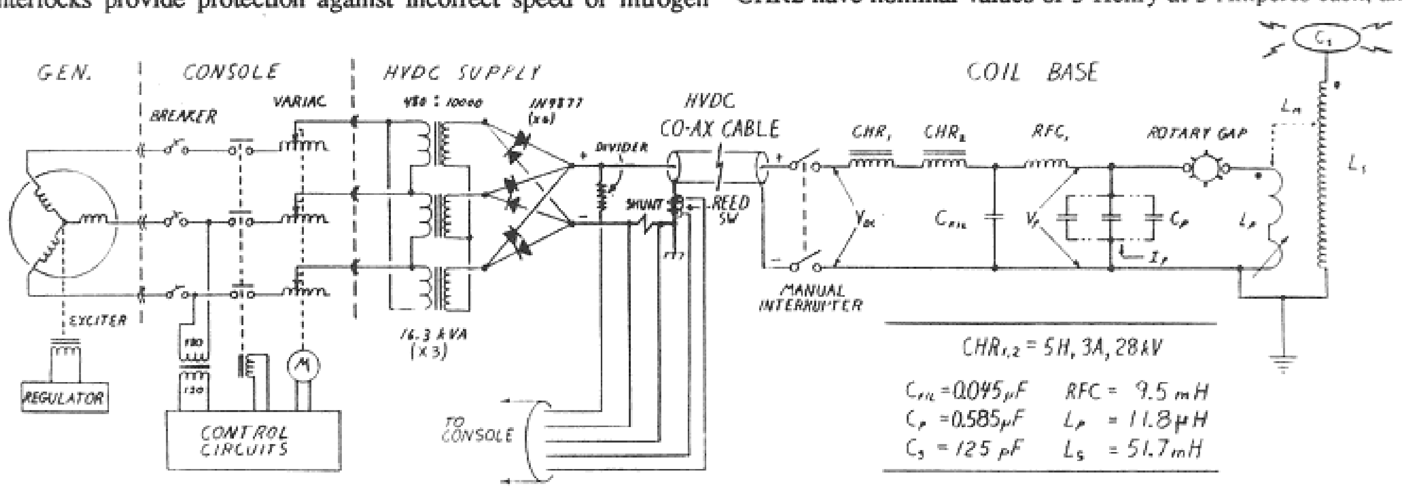

Figure I. Schematic Diagram.

made variable by adjusting the gap distance in the magnetic cores. These reactors provide the charging current to the primary capacitor bank, and act to match the effective impedance of the operating Tesla Coil to the source impedance of the HVDC supply. This match is essential to provide the maximum possible continuous power transfer.

A necessary consequence of using reactors in this way is the overcharging of the primary capacitor bank due to resonant rise. This occurs because the reactors exhibit a "flywheel" action that continues to push charge into the capacitor bank, even after the full DC supply voltage has been reached. This effect is often used to advantage in high power klystron pulse-forming networks, such as those used on linear accelerators, and for this coil design a resonant rise of about 40% brings the peak primary capacitor voltage to 26 kV.

The amount of resonant rise in a circuit such as in Figure I can be closely approximated by the equation:

$$V_{p(MAX)} = V_{dc} - \left(V_{dc} \times \cos\left(\frac{1}{\sqrt{L_{chr} \times C_p}} \times T_{gap} \right)\right)$$

where Tgap is the time between rotary gap discharges.

An interesting feature of this circuit is that the inductance of the charging reactors can be set so that the primary voltage Vp(MAX) increases or decreases as the rotary gap speed is increased. That is:

If Tgap is between	then Vp(MAX) will
$(0^\circ \text{ and } 90^\circ) \times \sqrt{L_{chr} C_p}$	decrease
$(90^\circ \text{ and } 180^\circ) \times \sqrt{L_{chr} C_p}$	increase

as the rotary gap speed is increased.

The radio frequency choke (RFC) is 560 turns of #24 wire wound on a 4.5 inch diameter PVC form. It acts with the filter capacitor to block RF currents from flowing back into the DC power supply.

The primary capacitor bank consists of 14 capacitors, arranged in two banks of seven, on either side of the coil base. Each capacitor is a 0.045µF, 50000V pulse capacitor of the oil-immersed foil / film type, with an ESR of about 3mΩ. This low ESR becomes negligible when divided by the number of capacitors employed. The capacitors are connected in parallel by 2.5 inch wide copper busbars which are arranged so that the currents through them counter-rotate, as in Figure II. This counter-rotation cancels the effect of stray inductances on the busbars, since no net magnetic field can be generated by currents through the busbars. Two coarse tuning links are provided which

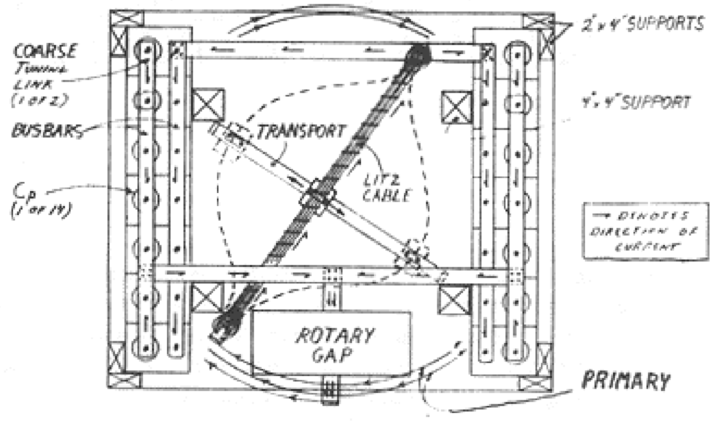

Figure II. Plan View of Base.

allow 12, 13, or 14 capacitors to be connected.

Fine tuning is accomplished by means of a flexible Litz cable which can effectively add or subtract one half turn from the primary as shown in Figure II. This cable, which consists of eighteen #8 gauge wires in parallel, is physically moved underneath the primary turns by a linear transport mechanism until the proper tuning is established. This mechanism is operated from the safety of the control console, of course, and is equipped with a position sensor which provides feedback to the operator.

The peak current that circulates in the primary when the spark gap closes can be calculated as follows:

$$I_{p(MAX)} = V_p \times \sqrt{C_p / L_p} \quad \text{for Loaded Q's} >> 1.$$

Since the Loaded Q for this Coil is approximately 10, the peak curren in the primary circuit is about 3600 Amperes.

The primary circuit is switched by a multi-stage, rotary quench gap, which is detailed in Figure III. This gap system is actually four gaps in series, two on either side of the rotors. In his lecture to the IEE in 1892, Tesla discussed the advantage of multiple gaps, how they could hold off higher voltages and offer a lower total impedance. Quench times also improve in a multiple gap scheme. The quenching action is further enhanced by the use of a heavily heat sunk electrode whose high thermal conductivity prevents the formation of cathode spots on the metal surface.

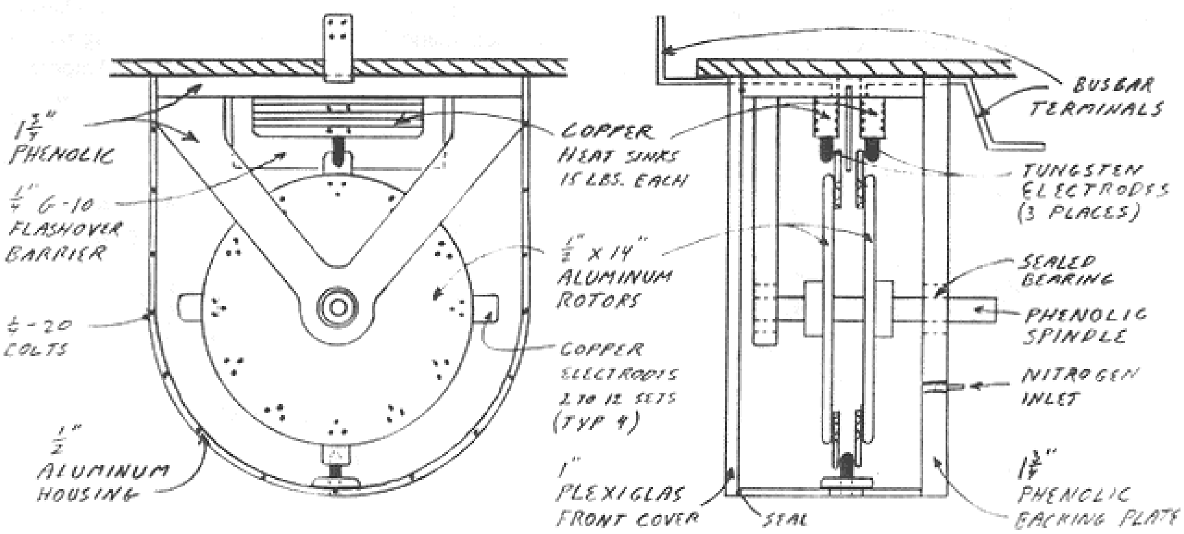

Figure III. Rotary Gap.

The stationary electrodes are made of pure tungsten, and are mounted into large copper heatsinks. The rotating electrodes are made from burnished oxygen-free copper plate and are bolted in place on the rotors. The two rotors are both 0.5 inch thick discs of aluminum that are 14 inches in diameter, and can each carry 2 to 12 electrodes. The dwell period of the gap is adjusted by changing the relative phase of one rotor to the other. Provisions for this have been designed into the rotor hubs.

The gap enclosure is made airtight, and is charged to 3 PSI above atmosphere with dry, zero-grade nitrogen. Although Sulfur Hexaflouride (SF6) has superior properties as an insulating gas, its proper use is restricted to applications such as in waveguides, switchgear, and power transmission cables, where the SF6 is not exposed to repetitive flames or arcs. If it were to be used in a rotary gap, great quantities of sulfur and fluorine compounds would be liberated in the in the intense heat of the arc, and the exposed metal components of the gap would be attacked in short order. Fluorine gas is also extremely poisonous, and has no odor. This is why smoking is not permitted in areas that contain SF6 or S2F10. Nitrogen however, does not react with copper, and re-combines into diatomic nitrogen after de-ionizing. Nitrogen is also inexpensive and readily available.

The rotary gap is spun at rates of up to 4500 RPM by a 1HP permanent magnet DC motor whose speed is controlled by a variac. A small sensing motor is mounted on the main motor shaft to inform the operator of the gap speed.

Dimensions of the Resonant Transformer Structure are given in the cutaway view of Figure IV. The primary consists of two turns of finely burnished, oxygen-free copper busbar, 5 inches wide by 0.25 inches thick. The primary winding is an Archemedian spiral which has an average winding diameter of 51 inches, and weighs approximately 200 pounds. The sectional view in Figure IV shows the arrangement of supporting structures for the secondary coilform. Each of the vertical supports is made from kiln-dried redwood, and treated liberally with Thompson's Water Seal. Under test conditions, this brand of water sealant has demonstrated a dielectric strength of greater than 100kV per inch. The supports are notched to accept the secondary windings and are fastened to the central fiberglass drum with half-inch wide nylon cable ties. The end plates of the coilform are made from 1.25 inch thick plywood , and are also fastened to the supports with cable ties. One-half inch dowel pins locate the vertical supports to the end plates.

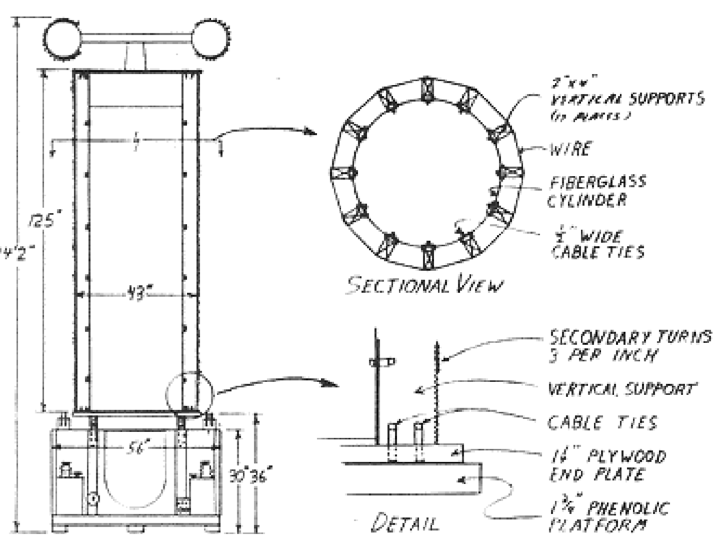

Figure IV. Elevation View.

The secondary is wound with 375 turns of #8 guage stranded wire, spaced at exactly 3 turns per inch. This leaves an inter-turn spacing (from wire to wire) of 0.19 inches, 57% of which is made up of the wire insulation. The average winding diameter is 43 inches, and the winding height is 125 inches. The completed secondary form contains approximately 4250 feet of #8 gauge wire and weighs 470 pounds, 215 pounds of which is copper.

The 2.9 to 1 Aspect Ratio of the secondary is intentionally slightly higher than optimum, since the ion cloud which forms around the head electrode can raise the terminal capacitance by as much as 10%.

The Coefficent of Coupling between the primary and secondary coils was initially set at 0.118, and was then adjusted for optimum performance by means of an adjustable mechanism that can raise or lower the secondary coilform inside the primary. The coefficent of coupling was determined from the equations shown below, using measurments obtained from the test setup in Figure V.

f — frequency of the measurment signal (60 Hz for this case)
Lp — determined empirically with inductance bridge

$L_s = E_s / 2\pi f I_s$ $\qquad L_m = E_p / 2\pi f I_s$

$k = L_m / \sqrt{L_p L_s}$

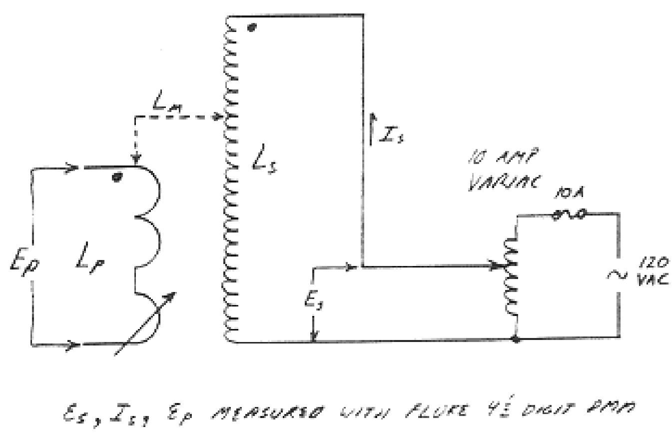

Figure V. Lm Test Setup.

The toroidal head electrode measures 13 by 65 inches and uses a finite element construction technique, similiar to the corona shields that are installed on high tension transmission lines. This method of construction was chosen over metal spinning because a toroid of this size requires highly skilled labor, and could not be provided by AWF, a supplier of conventional toroids.

The toroid frame is built out of 0.035 wall, half-inch diameter aluminum tubing, which is bent into concentric circles and welded onto aluminum supports as in Figure VI. The continuity of the toroid is broken in two places by sheets of 0.25 inch phenolic, which prevent the toroid from acting as a shorted turn. The height of the toroid is adjustable in order to optimize the electric field distribution at the top of the coilform. The total height of the completed Tesla Coil is 14 feet, 2 inches.

During operation, the spark discharges propagate outward from the head electrode approximately 20 to 25 feet, often striking the ground. In an isolated incident, the streamers connected with a nearby lighting tower, which was placed at a clearance of 31 feet from the coil. Hearing protection is generally not required if the rotary gap cover is in place, since the heavy cover silences the percussive gap action. The long streamers produce a continuous hissing and crackling sound that is quite comfortable to the unshielded ear.

Plans for future experiments with this Tesla Coil include a qualitative study of the creation and maintenence of ball and bead lightning phenomena. The arrangment of the test apparatus for this experiment has been inspired by the fascinating results and conclusions obtained by Kenneth and James Corum in their paper on <u>Tesla's production of electric fireballs</u> (TCBA Vol. 8, #3, pp 13-18). The proposed setup is illustrated in Figure VII. In this scheme the Marx Generator is positioned within striking range of the coil, and when so struck is forced to suddenly release its energy into the discharge path. A Marx Generator was chosen for this experiment rather than an additional helical resonator because although a Tesla Coil can store up to several hundred joules of energy in its head capacitance, this Marx Generator will store 33600 Joules, and can deliver this energy non-repetitively at a peak power of several hundred megawatts. The electrode on the Marx Generator should have a pointed carbon tip, which will serve to increase the local electric field and power density at the point of the fireball origin. Any arguments pertaining to the feasibility of this approach are encouraged.

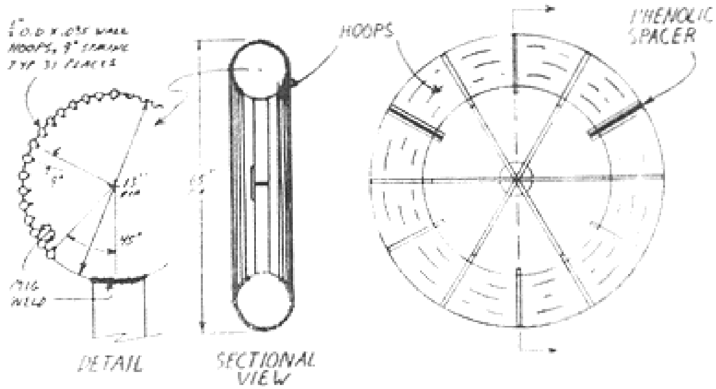

Figure VI. Toroid.

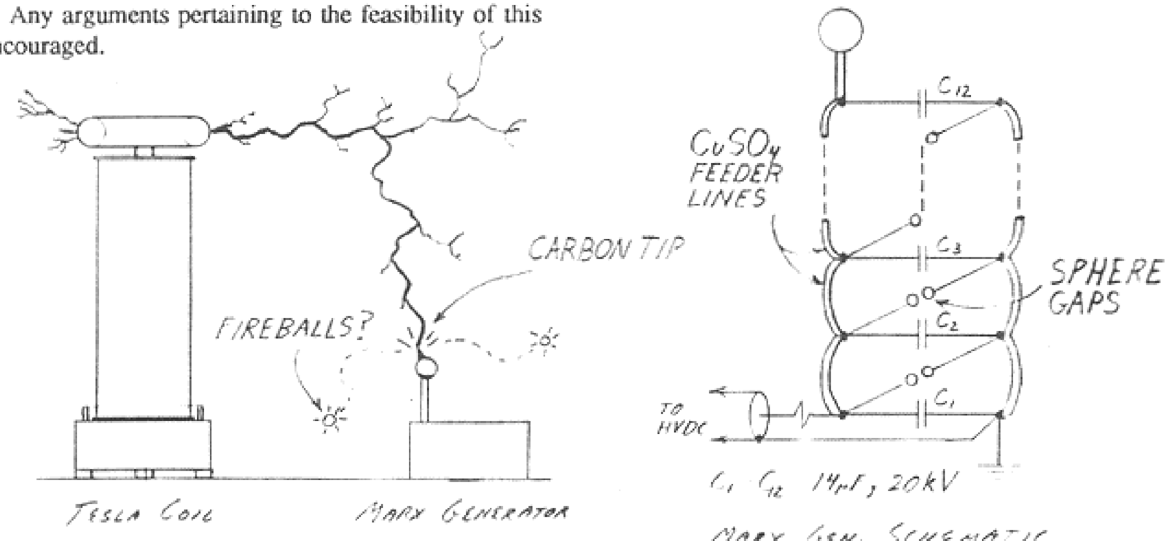

Figure VII.

Special thanks to:
- Bill Holzapfel (TCBA Vol. 7, #2, p 15), for his ideas, patience, and "slave labor"
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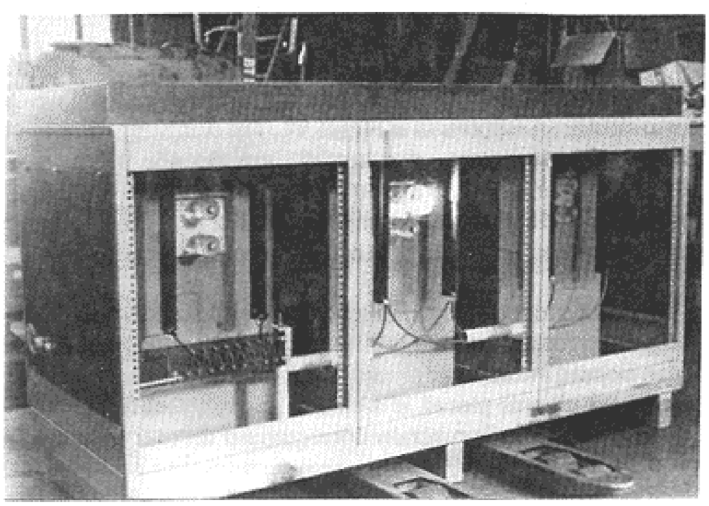
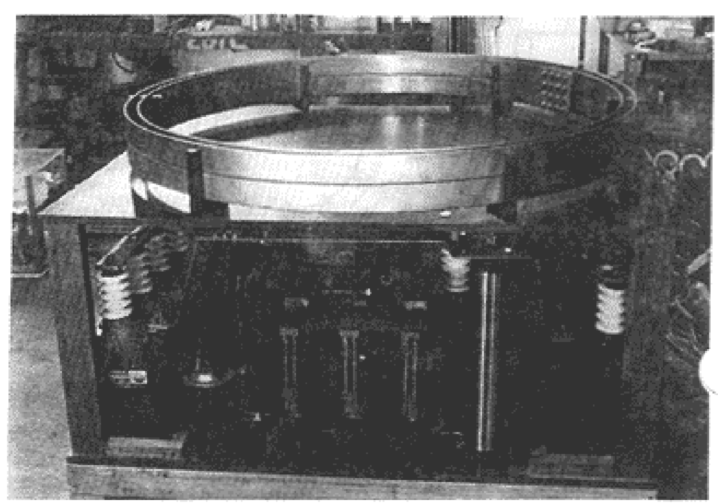
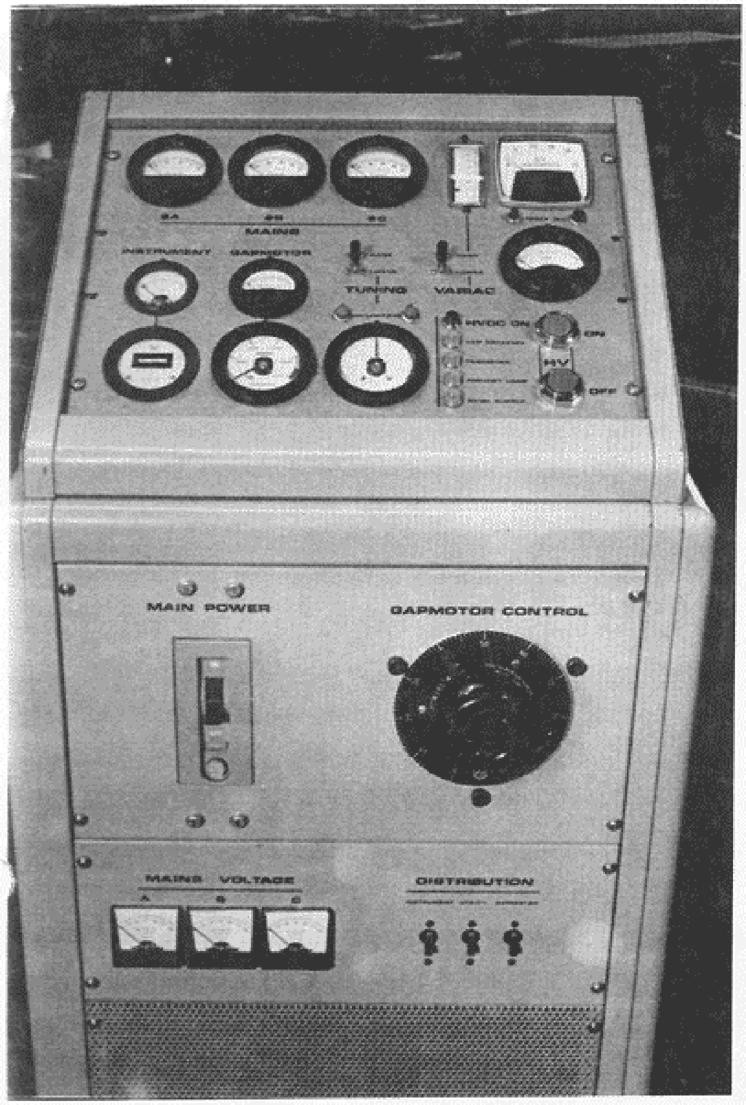
- Tim Lindholm and Curry for their assistance in the final construction phases
- Mark Pauline and Survival Research Laboratories, for providing the necessary "serendipity" essential to the success of this project.



HVDC Supply.



Coil Base, Rear View.



Control Console. ↑

Tesla Coil in Operation. ↓ →