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THE TOKAPOLE II DEVICE

J. C. SPROTT

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J. C. Sprott
University of Wisconsin
Madison, Wisc. 53706

I. INTRODUCTION

When the first of the internal ring devices began operation in 1963, it created quite a stir of excitement. It was an era of pessimism. Toroidal pinches were plagued by MHD instabilities. Stellarators were stuck with Bohm diffusion.

But here was a device that was stable, with a confinement time clearly in excess of the predictions of Bohm scaling. Soon, every major fusion laboratory had an internal ring machine. There followed several years of rapid growth in the understanding of toroidally confined plasmas. Unfortunately, everyone assumed you can't make a reactor with internal rings. The engineering problems were too great. Not only that, but internal ring devices tended to have cold, low-density plasmas -- not so much out of necessity, but simply because no one had tried to push them to their limits. Everyone was too busy doing physics.

Then along came tokamaks -- stable, dense, hot, and well confined. One by one, the internal ring machines were shut down, until there were only four left -- two at Wisconsin, one at General Atomic, and one at Culham, in England.

Recently two developments have spurred a renewed interest in these devices. The first is the realization that tokamaks will probably require some form of divertor, and a divertor is, after all, an internal ring. The second is that, although a tokamak reactor might work with a fuel of deuterium and tritium, an internal ring device is much better suited for burning the advanced fuels that would be used in later generation reactors.

Consequently, we, at Wisconsin, began about a year ago the construction of a new internal ring machine aimed at confining a state-of-the-art plasma in a toroidal octupole field. It incorporated our fifteen years of experience with internal ring devices as well as the large body of lore that has built up around tokamaks. We call the device a tokapole, since it combines the strong, toroidal ohmic heating of a tokamak with the good stability and confinement properties of a multipole. It is called Tokapole II because, during its last year of operation, the original Wisconsin toroidal octupole was operated in a tokapole mode with quite impressive parameters. The Tokapole II device began operation on March 29, 1978. A drawing of the device as it appeared shortly after completion is shown in figure 1, and a summary of its design parameters is given in Table I. This paper will discuss its design and initial operation.

II. PHYSICS CONSIDERATIONS

The starting point for the design of Tokapole II was to use as much of the equipment left over from the original toroidal octupole as possible in order to keep the cost to a minimum. This included a 0.15 volt-second iron core, 108 kJ

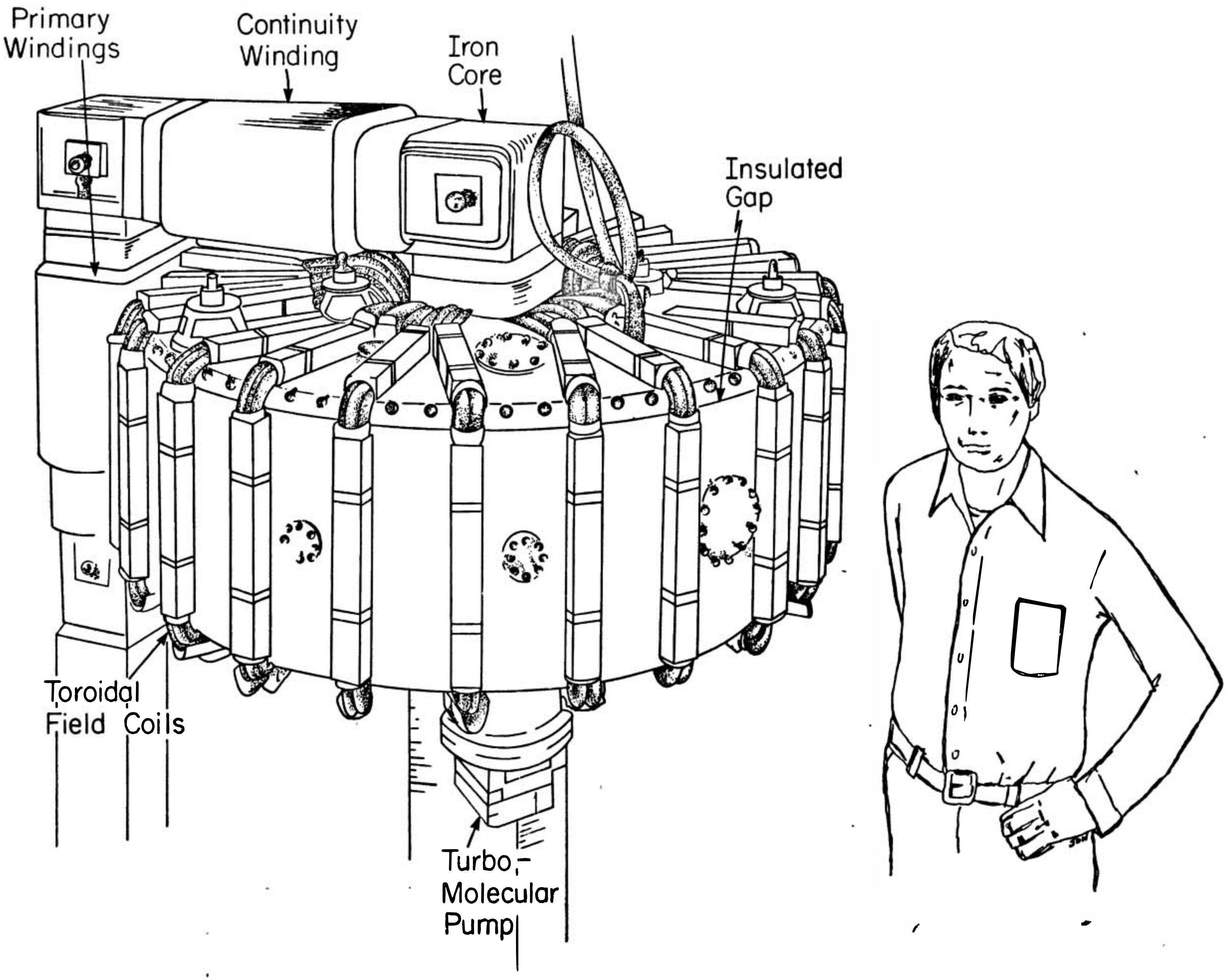

Primary Windings
Continuity Winding
Iron Core
Insulated Gap
Toroidal Field Coils
Turbo-Molecular Pump

Figure 1.

TABLE I.

PARAMETERS OF TOKAPOLE II

Major Radius: 50 cm

Minor Cross Section: 44 cm x 44 cm square

Toroid Walls: Aluminum, 3.0 cm thick with poloidal and toroidal insultated gaps

Vacuum Volume: 600 liters

Vacuum surface area: 6 square meters

Number of internal rings: 4 (copper, 5 cm dia., supported at 3 points)

Ports: 2-7.5" dia., 5-4.5" dia., 22-1.5" dia., 13-0.25" dia.

B_T on axis: 4.4 kG (extendable to 10 kG by the acquisition of additional capacitors)

L/R time of B_T: 20 msec.

Available OH voltage: 125 volts

Poloidal Flux: 0.15 webers

Available Energy (Poloidal + Toroidal Fields): 219 kJ (73-240 μF, 5 kV capacitors)

Base Vacuum: 1×10^{-8} torr

Pumping System: 1500 ℓ/sec turbomolecular pump, 1000 ℓ/sec 10° K Cryopump, Titanium getter pump.

Bakeout Temperature: 150° C., quick cool to <50° C. in 15 min.

Preionization: 5 kW, 2.45 GHz; 10 kW, 9 GHz; 10 kW, 16 GHz ECRH of 5 kV capacitors, control circuits, and diagnostics.

Conventional wisdom holds that tokamak densities scale as $n \propto B_T/R_o$ where B_T is the toroidal magnetic field and R_o is the major radius, and that energy confinement times scale as $\tau \propto na^2$, where a is the minor radius. The product $n\tau$ is therefore proportional to $(B_T a/R_o)^2$, so that large toroidal fields and low aspect ratios (R_o/a) are desired. The existing iron core with a 10-inch square cross-section and a 28-inch square window was sufficient to allow a toroid with $R_o = 50$ cm and a 44 cm square cross-section.

The toroidal field was designed for 10 kG, since that would allow it to run conservatively at 5 kG with capacitors on hand and facilitate future upgrades by adding more capacitors. A 20 msec L/R time was chosen for the toroidal field to insure that the discharge could last for several energy confinement times.

Special attention was paid to magnetic field symmetry and vacuum cleanliness. Field symmetry, especially in the vicinity of the octupole null, is very important in a tokapole, because the plasma current is in competition with the internal ring currents. A clean vacuum wall is crucial because the energy confinement time of small tokamaks is typically limited by impurity radiation. Configurations with less than three rings are deemed unsatisfactory for toroidal ohmic heating because small toroidal plasma currents are incapable of altering the field topology near the null. A configuration with four rings makes the most effective use of the square cross section, and so an octupole field was chosen. Since the device is primarily dedicated to heating studies rather than to confinement, no attempt was made to levitate the rings, but the size of the supports was kept to a minimum.

III. THE VACUUM VESSEL

A basic decision in any pulsed device is whether to make the vessel walls transparent or opaque to the confining magnetic fields. Conducting walls were chosen for a number of reasons: (1) The short pulse times allowed it. (2) Magnetic field errors, especially the harmful types which result from field lines intersecting the wall, can be minimized. (3) Less magnetic energy is wasted. (4) Conducting walls may suppress plasma instabilities. (5) The outside of the machine is kept relatively free of windings so that access is improved. For these reasons, the vessel was made of 3 cm thick type 6061-T6 aluminum, as a reasonable compromise of yield strength (40,000 psi) and conductivity (45% IACS). The 3 cm thickness allows an L/R time of $\sim$15 msec.

One disadvantage of a conducting wall is that insulated gaps are required for both the toroidal and poloidal magnetic fields. These gaps were made with ¼" viton sheet squeezed to a thickness of 0.180" for electrical insulation and vacuum seal. The vessel was made with two cylinders welded to an aluminum bottom plate. The lid is bolted to the rest of the tank with an insulated gap at the outer wall and a conducting joint at the inner wall. A total of 42 ports were laid out along radials at 30^o intervals so that the channels which hold the toroidal field windings in place could be as straight and as short as possible. Note that since the wall is conducting, toroidal field symmetry is assured if the toroidal field windings cross the gap at evenly spaced intervals, and this was done with considerable care. A top view of the machine is shown in figure 2.

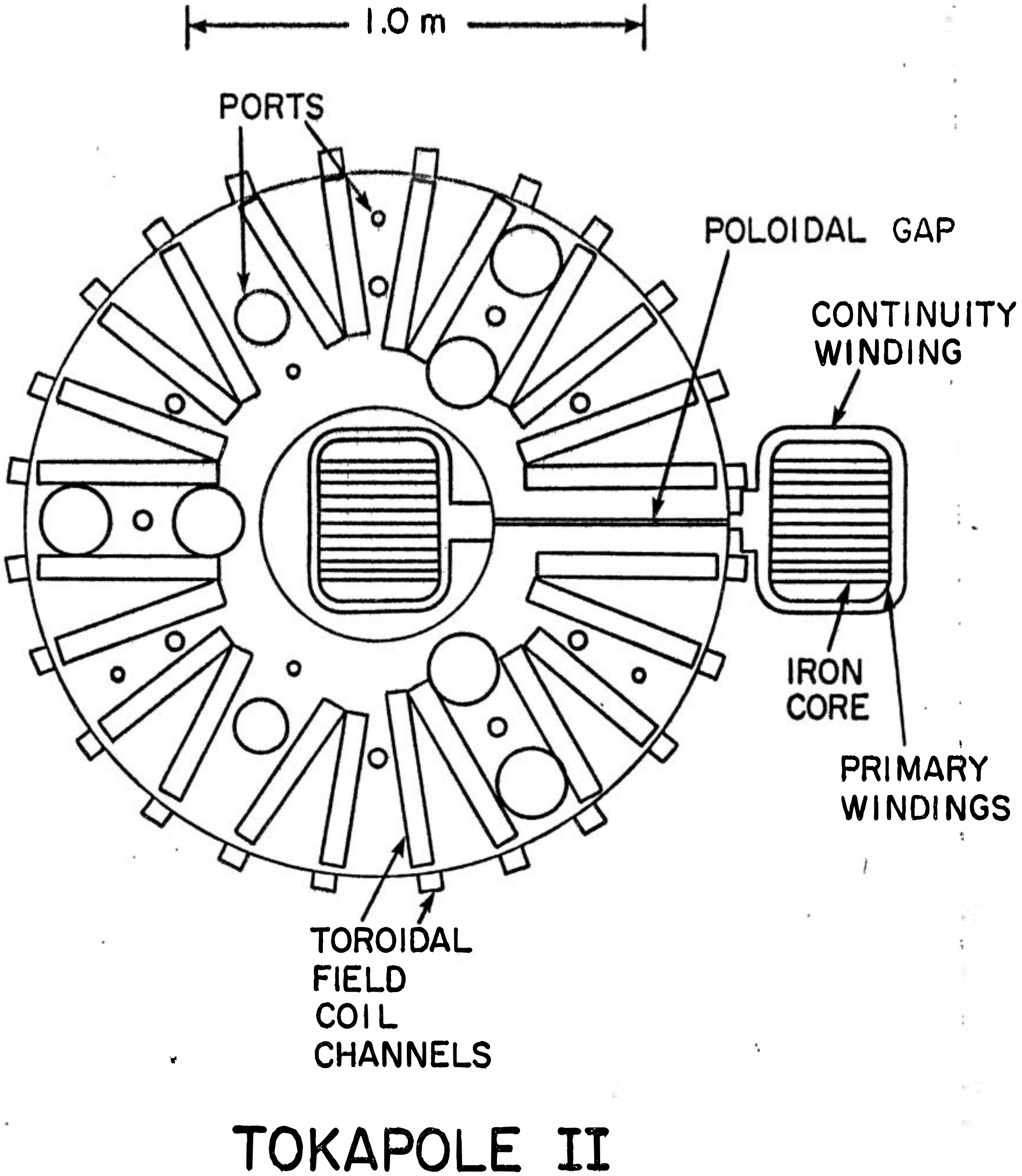

1.0 m
PORTS
POLOIDAL GAP
CONTINUITY WINDING
IRON CORE
PRIMARY WINDINGS
TOROIDAL FIELD COIL CHANNELS
TOKAPOLE II

Figure 2.

Whenever possible, symmetry about the horizontal midplane was preserved by arranging ports in pairs on the top and bottom. All tolerances were specified to ±0.020" (0.5 mm) with particular attention paid to axisymmetry. The interior surface was machined to a high degree of smoothness ($\sim$63 μinches) to reduce the effective surface area, but it was not polished for fear of trapping air pockets which would produce virtual leaks.

IV. POLOIDAL FIELD

In an internal ring device, the poloidal field is produced by a combination of ring currents and plasma currents. The starting point is a multipole field with a closely degenerate field null in the absence of plasma so that a negligibly small plasma current will produce closed flux surfaces surrounding the plasma. Consideration was given to making rings with multiturn imbedded conductors which could be driven independently of the ohmic heating transformer. The idea was rejected because of the difficulty of construction, because the optimum design would have put unacceptably large stresses in the rings, and because careful programming of the currents would have been required to maintain a degenerate field null in the presence of plasma currents and field soak-in. The proportion of current flowing in the rings and plasma can be adjusted over a wide range by varying the toroidal field, gas pressure, and preionization, and so the additional flexibility of having independently driven rings was deemed unnecessary.

A computer code was used to calculate poloidal magnetic flux plots and other quantities of interest for four perfectly conducting rings of arbitrary size and position within the square cross section previously chosen. The vacuum flux plot chosen is shown in figure 3, and the surfaces of constant B in the absence of plasma currents are shown in figure 4.

In the presence of a toroidal plasma current, equilibrium calculations predict a poloidal flux plot as shown in figure 5. This calculation assumes a plasma current one-fourth of the total ring current. Note that no additional vertical field, other than that produced by the rings themselves, is required for equilibrium. The ring supports are attached to the lid and bottom with bellows, allowing a ±0.5 cm adjustment which permits equilibria of both the inside dee and outside dee types.

Some of the most detailed design of Tokapole II went into eliminating the field errors that invariably accompany a voltage gap in a conducting wall. The toroidal image currents which flow in the walls are returned around the transformer core in copper sheets called continuity windings. Their resistivity was tailored to vary inversely with the wall current density, which is proportional to the magnetic field strength at the wall. The primary windings were placed very close to the continuity windings to reduce flux leakage, and the primary was wound with a non-uniform turn spacing to reduce poloidal currents at the gap. An 80-turn primary was used which could be connected in either a 40:1 or

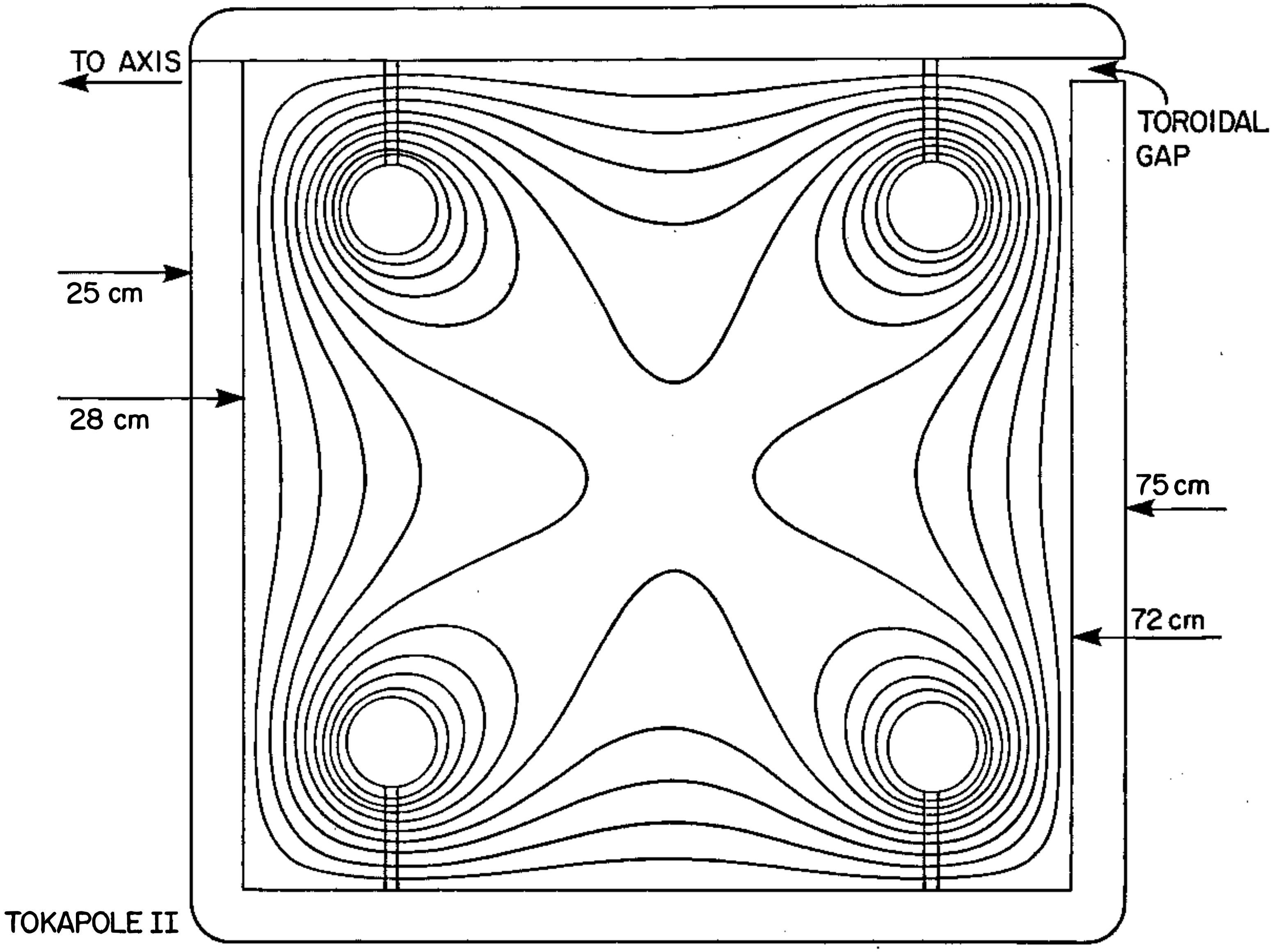


Figure 3.

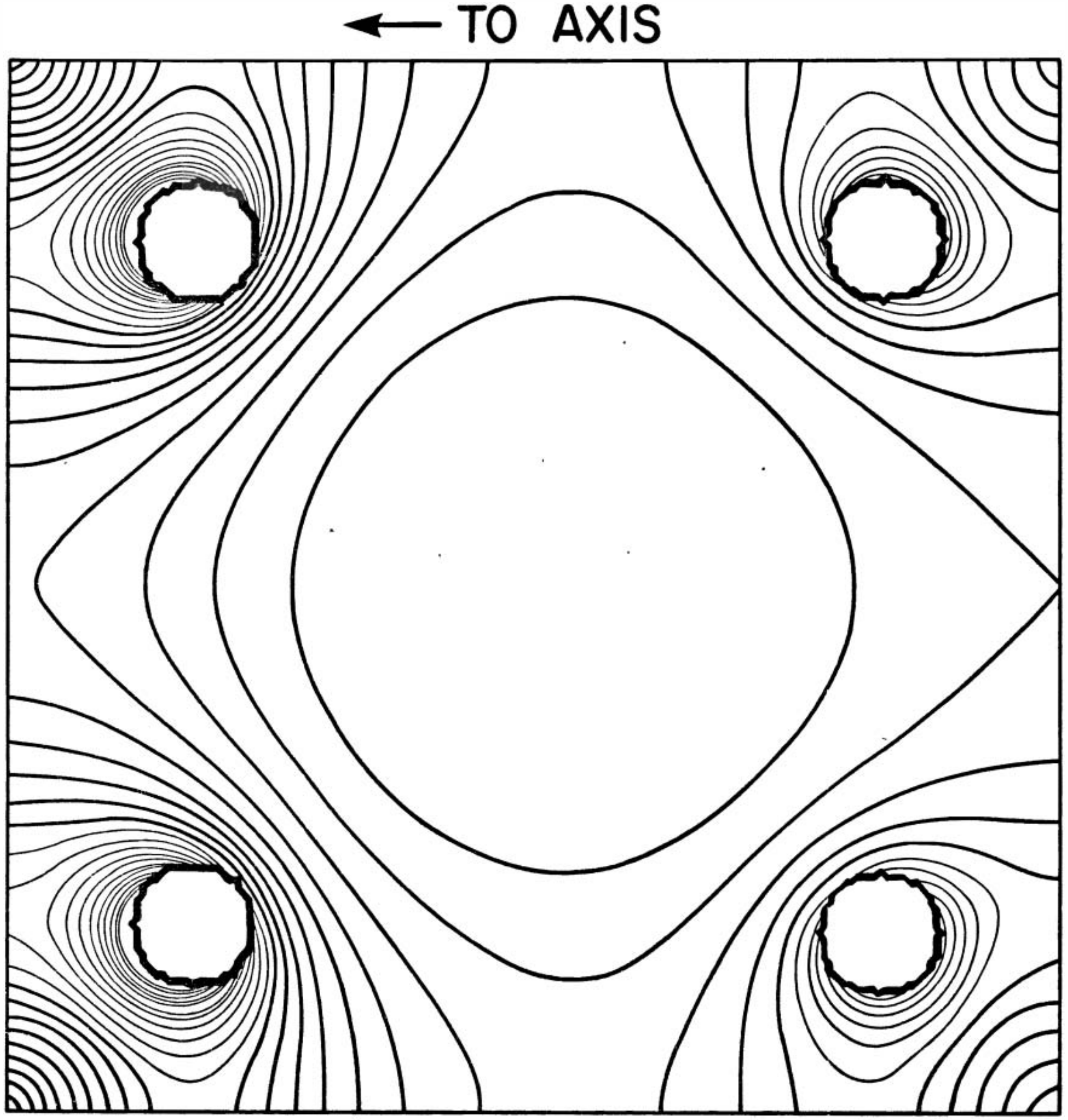


Figure 4.

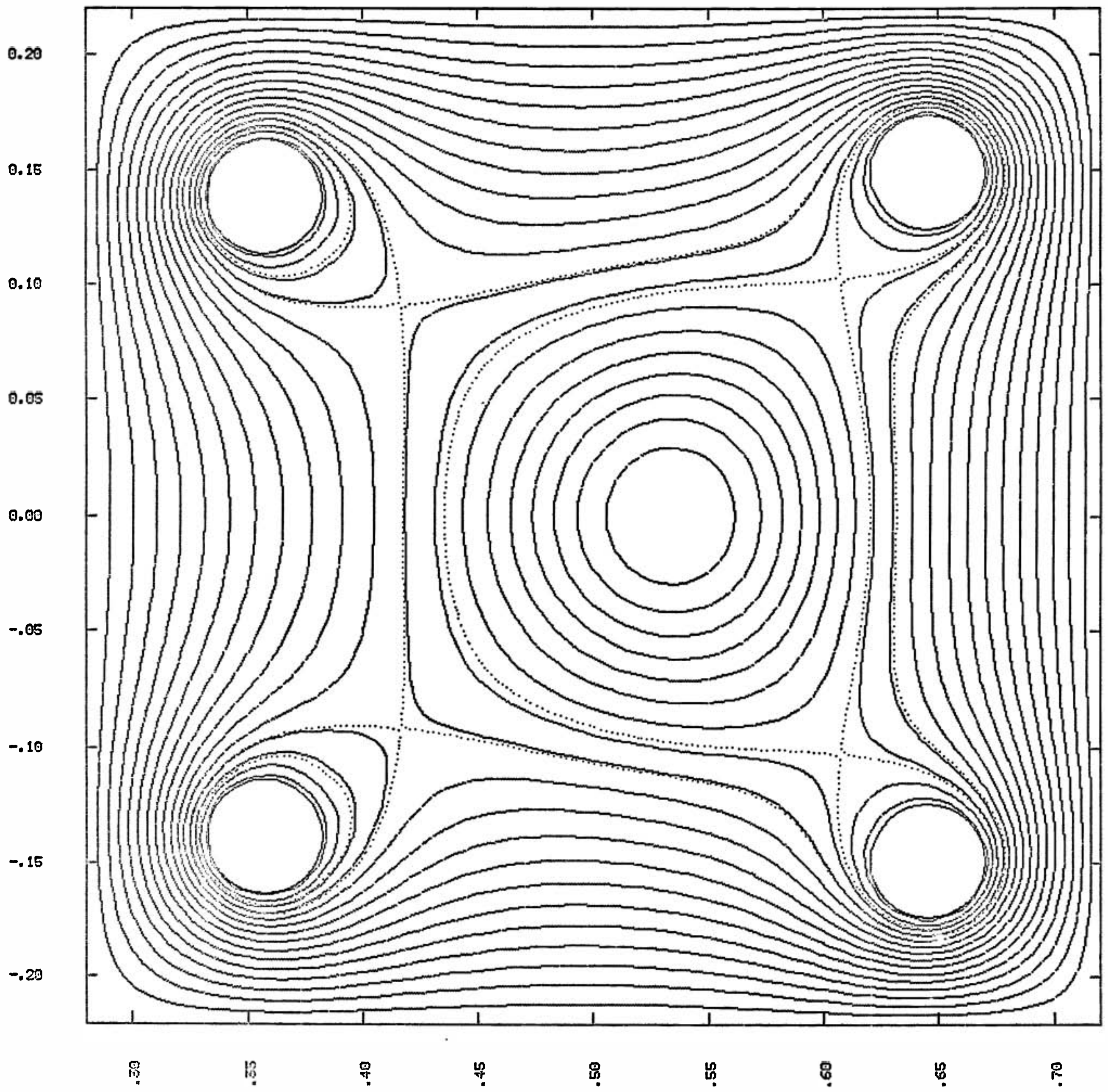


Figure 5.

80:1 turns ratio, allowing single turn loop voltage of up to 125 volts. Note that the plasma links only half the poloidal flux, and so it sees only half the poloidal gap voltage.

The energy losses in the transmission line, primary windings, continuity windings, walls, and rings were calculated in detail. With 90 kJ of energy stored in the capacitors, 63 kJ appears as energy in the poloidal field at the peak of a 5.5 msec half-sine wave, and 27 kJ is lost.

V. RING AND SUPPORT DESIGN

The Tokapole II rings are subjected to a peak magnetic force of ∿12,500 lb for each inner ring and ∿8000 lb for each outer ring. A compromise of strength and conductivity dictated a choice of a chromium-copper alloy (Ampcoloy 97) for the 5 cm diameter rings (yield strength of 43,000 psi, conductivity of 78% IACS). The rings were forged in a form where they could be machined to the final dimensions without the necessity of welding or bending operations which could destroy the axisymmetry. The rings were machined to a tolerance of 0.005" (0.13 mm) and highly polished.

The supports were designed using a Beryllium-copper alloy (Berylco 25 HT) with a 165,000 psi yield strength after heat treating. This allowed a total support area exposed to the plasma of 133 cm^2 with a comfortable safety margin. The supports are circular and are threaded into the rings. Careful attention was given to reducing stress risers throughout the ring-support system. The rings are electrically insulated from the vacuum chamber and are capable of being biased to 10 kV.

VI. TOROIDAL FIELD

The 30^o port spacing allows a toroidal field coil of 24 segments. A total of 96 turns was desired to give a reasonable half-period (12 msec) with the available capacitors, so that each channel contains four windings. The largest channels that could conveniently fit between ports would accomodate four turns of AWG 4/0 wire. The wire chosen was fine-stranded (2100 strands of AWG #30), high temperature welding cable. The energy losses in the transmission line, primary windings, walls, and rings were calculated in detail. The L/R time of the toroidal field system is about 20 msec. The square cross section of the machine, and the conducting walls make it necessary to secure the windings to the tank walls with 2 × 1 3/4 × 1/8", 6063-T52 aluminum channels. The mechanical strength is sufficient to permit toroidal fields of 10 kG.

VII. VACUUM SYSTEM

The vacuum pumping system consists of a 1500 ℓ/sec turbomolecular pump (Sargent Welch model 3133) and a 1200 ℓ/sec, 10° K Ultek cryopump. The field errors produced by the 6" ASA ports will eventually be minimized by installing 55% transparent copper plugs which have an average resistivity equal to that of 6061 aluminum. All vacuum seals are viton. An ultimate base pressure of 1×10^{-8} torr is expected.

Provisions have been incorporated for baking the entire machine to 150° C by circulating hot oil through a set of coils bolted to the machine between the toroidal field coils. The same system will allow cool-down to <50° C in 15 minutes.

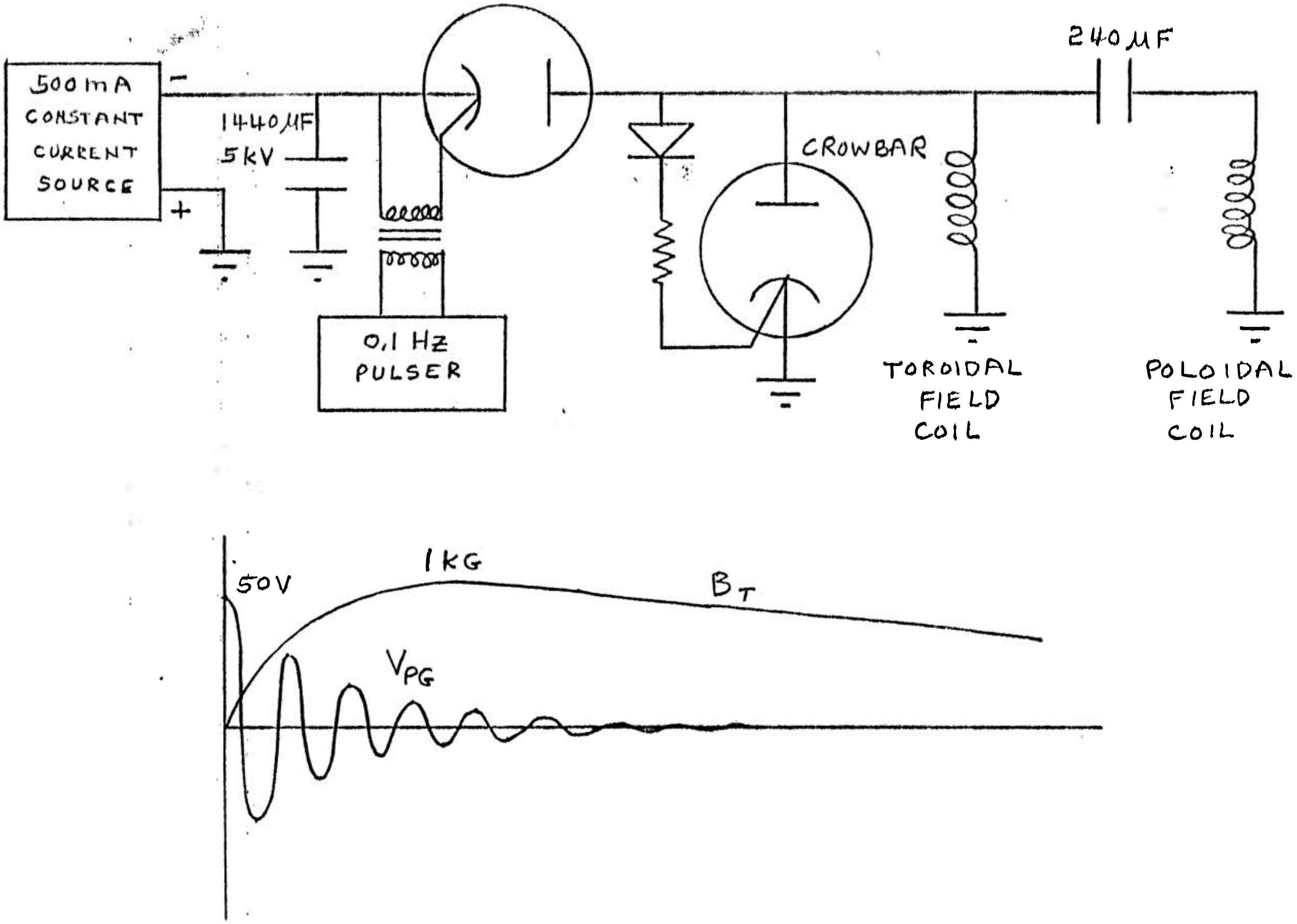
Discharge cleaning is accomplished by pulsing the toroidal field to ∿1 kG every ten seconds and ringing the poloidal gap with a decaying sine wave with an initial voltage of ∿50 volts and a frequency of ∿600 Hz. A diagram of the discharge cleaning system and a sketch of the waveforms of the toroidal field and poloidal gap voltage are shown in figure 6.

VIII. INITIAL RESULTS

Normal operation involves puffing in a burst of H_2 from a Veeco PV-10 piezoelectric valve to raise the machine pressure to $\sim 2 \times 10^{-4}$ torr in ∿2 msec. The toroidal field is then pulsed, reaching its peak value in ∿4 msec, and crowbarred. Just before application of the ohmic heating pulse, a 10 kW, 1 msec pulse of 9.0 GHz ECRH is applied for preionization. This makes a plasma of density $\sim 10^{10}$ cm^{-3} with a profile peaked sharply in major radius at the lo[illegible] of the cyclotron resonance zone. Such preionization helps to form the discharge near the minor axis. The ohmic heating voltage is then applied, and the toroidal plasma current builds to a value of ∿50 kA in ∿500μsec and then decays in ∿1 msec as the internal ring currents build up and pinch off the discharge channel. The time dependence of the various quantities is shown in figure 7. Densities are $\sim 1 \times 10^{13}$ cm^{-3} and electron temperatures are $\lesssim 50$ eV. Higher electron temperatures and longer discharge times are expected once the machine is adequately discharge cleaned, and the ring positions have been optimized.

IX. FUTURE PLANS

The Tokapole II was built as an extremely versatile basic research device to explore a wide variety of problems relevant to the fusion program. It can be operated as a pure octupole with no toroidal field and no ohmic heating, or as a tokamak with a four node poloidal divertor, or anywhere in between. The initial research program will concentrate on four main areas:



DISCHARGE CLEANING SYSTEM

Figure 6.

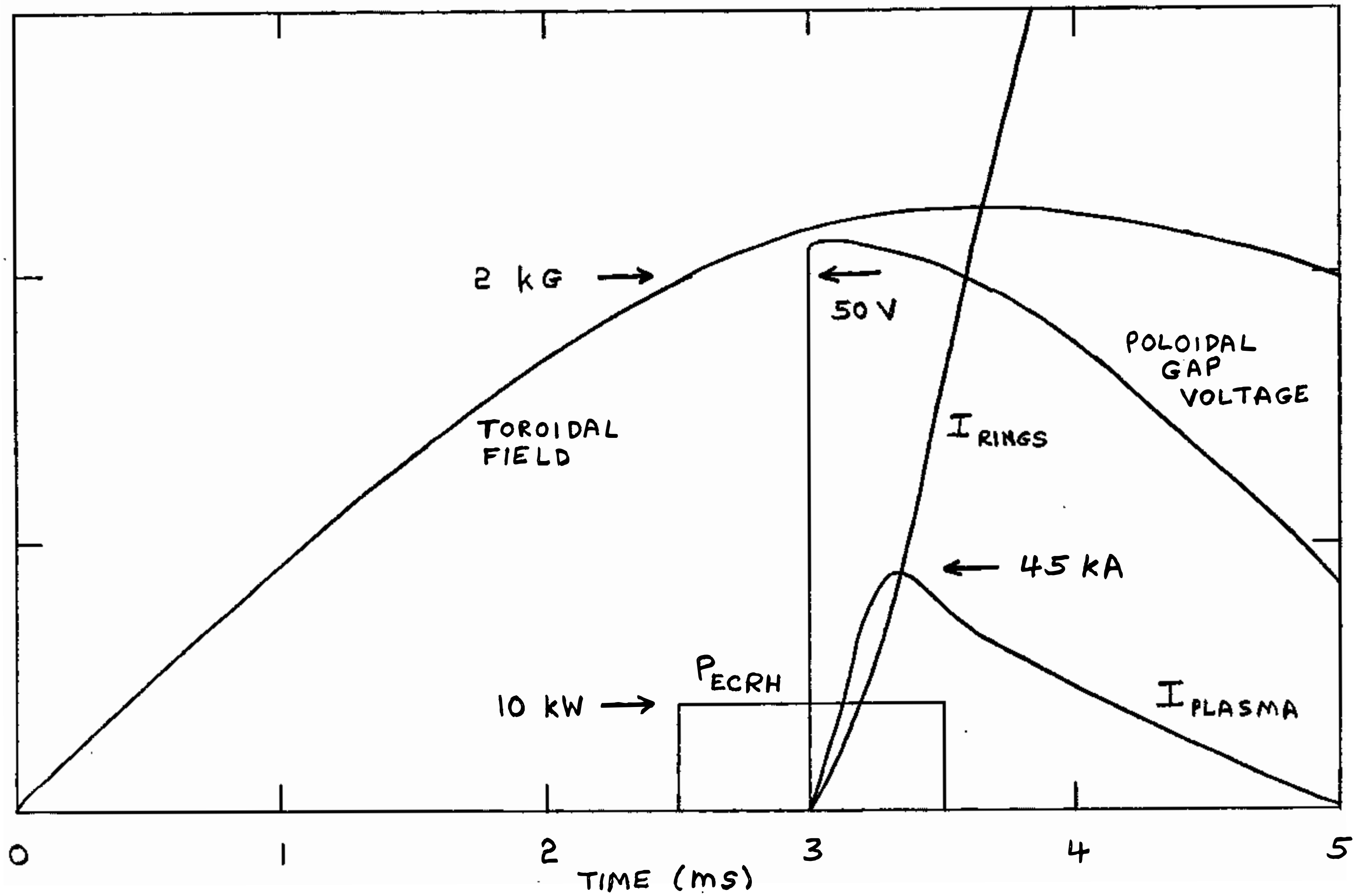

2 kG
50 V
POLOIDAL GAP VOLTAGE
TOROIDAL FIELD
I RINGS
45 kA
P ECRH
10 kW
I PLASMA
0
1
2
3
4
5
TIME (ms)

Figure 7.

1. Equilibrium and stability of poloidal divertor configurations,
2. Plasma/wall interactions and impurity studies,
3. Electron cyclotron coupling and breakdown,
4. Toroidal eigenmodes and ion cyclotron heating.

One of the earliest experiments will be a comparison of the square, inside dee, and outside dee divertor configurations. Quantitative spectroscopic measurements of VUV impurity line radiation is already under way, and the effects of various types of discharge cleaning on the impurity content will be studied. The coupling of waves near the electron cyclotron frequency to critically- and over-dense plasmas will be studied, as well as the use of ECRH for controlled discharge initiation. The toroidal eigenmode spectrum near the ion cyclotron frequency is being studied, and a 2 MW ICRH source is ready for installation as soon as an appropriate antenna is designed.

X. ACKNOWLEDGEMENTS

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