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# Proposal for a Shock-Heated Toroidal Z-Pinch Experiment

by

James A. Phillips

PROPOSAL FOR A SHOCK-HEATED TOROIDAL Z-PINCH EXPERIMENT

by

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ABSTRACT

A shock-heated toroidal z-pinch experiment is proposed in which a plasma temperature of ~ 1 keV is anticipated. The fast rising z-current is driven by a magnetic energy storage system similar to that successfully used in a linear experiment.

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## I. INTRODUCTION

It is proposed that a fast toroidal z-pinch device be constructed. Encouraging results from our fast linear z-pinch experiment[1] indicate that a stable plasma with a peak temperature (~ 1 keV) has been produced by shock heating. Toroidal geometry eliminates end effects, end losses, and cooling by electrodes. The experiment verifies certain symmetry hypotheses for the stability of toroidal confinement programs that claim advantages for z-pinch configurations. To our knowledge, there is no other experimental device available that permits a high beta pure z-pinch in toroidal geometry capable of making this verification.

## II. EXPERIMENT

The toroidal z-pinch device has the design parameters shown in Table I.

The main confinement magnetic field is the $B_\theta$ magnetic pressure of a high (~ 300 kA) axial

TABLE I

DESIGN PARAMETERS FOR TOROIDAL Z-PINCH DEVICE

| | | |
|---|---|---|
| 1. | Major diameter | ~ 76.5 cm |
| 2. | Minor diameter | ~ 11.3 cm |
| 3. | Aspect ratio | ~ 6.8 |
| 4. | Rate of rise of plasma current | ~ 3 x $10^{12}$ A/sec |
| 5. | Initial $\dot{B}_\theta$ | ~ 12 x $10^{10}$ G/sec |
| 6. | Peak plasma current | ~ 300 kA |
| 7. | Number of voltage feed points | ~ 4 |
| | Maximum voltage per feed point | ~ 80 kV |
| 8. | Energy storage | ~ Magnetic |
| 9. | Capacitor bank required | ~ 2500 μF at ~ 20 kV |
| 10. | Longitudinal bias $B_z$ field | $\lesssim$ 6 kG |
| 11. | Deuterium gas filling pressure | $\lesssim$ 10 μHg |

current. The $B_z$ field internal to the pinch encourages m = 0 stability while the $B_z$ field external to the pinch is small or zero.

The main heating mechanism, a strong shock, requires a high initial sheath acceleration. With a snowplow model, the initial acceleration in both the z- and $\theta$-pinch can be shown proportional to the initial $\dot{B}/\sqrt{\rho}$, where B is the magnetic field on the surface of the plasma and $\rho$ is the mass density. An energy source of high voltage (> 50 kV) and low inductance (< 20 nH) giving rates of rise of current $\gtrsim 10^{12}$ A/sec is required. When these conditions have been obtained, a hot z-pinch should be achieved.

## III. RESULTS OF THE FAST LINEAR Z-PINCH EXPERIMENT

The experiment[1] is designed to produce shock heating of a plasma in a linear z-pinch configuration. The present operating specifications are presented in Table II and in Fig. 1.

TABLE II

OPERATING SPECIFICATIONS

| | | |
|---|---|---|
| 1. | Length of z-pinch | 30 cm |
| 2. | Inside diameter of return conductor | 11.5 cm |
| 3. | Inside diameter of discharge tube | 10.6 cm |
| 4. | Rate of rise of discharge current | $2 \times 10^{12}$ A/sec |
| 5. | Initial $\dot{B}$ | $8 \times 10^{10}$ G/sec |
| 6. | Peak current | 200 kA |
| 7. | Voltage across z-pinch | ~ 60 kV |
| 8. | Primary capacitor bank | 450 μF at 12.5 kV |
| 9. | Magnetic energy storage inductance | 35 nH |
| 10. | Bias $B_z$ field | 0-10 kG |
| 11. | $D_2$ gas filling pressure | 10-200 μHg |

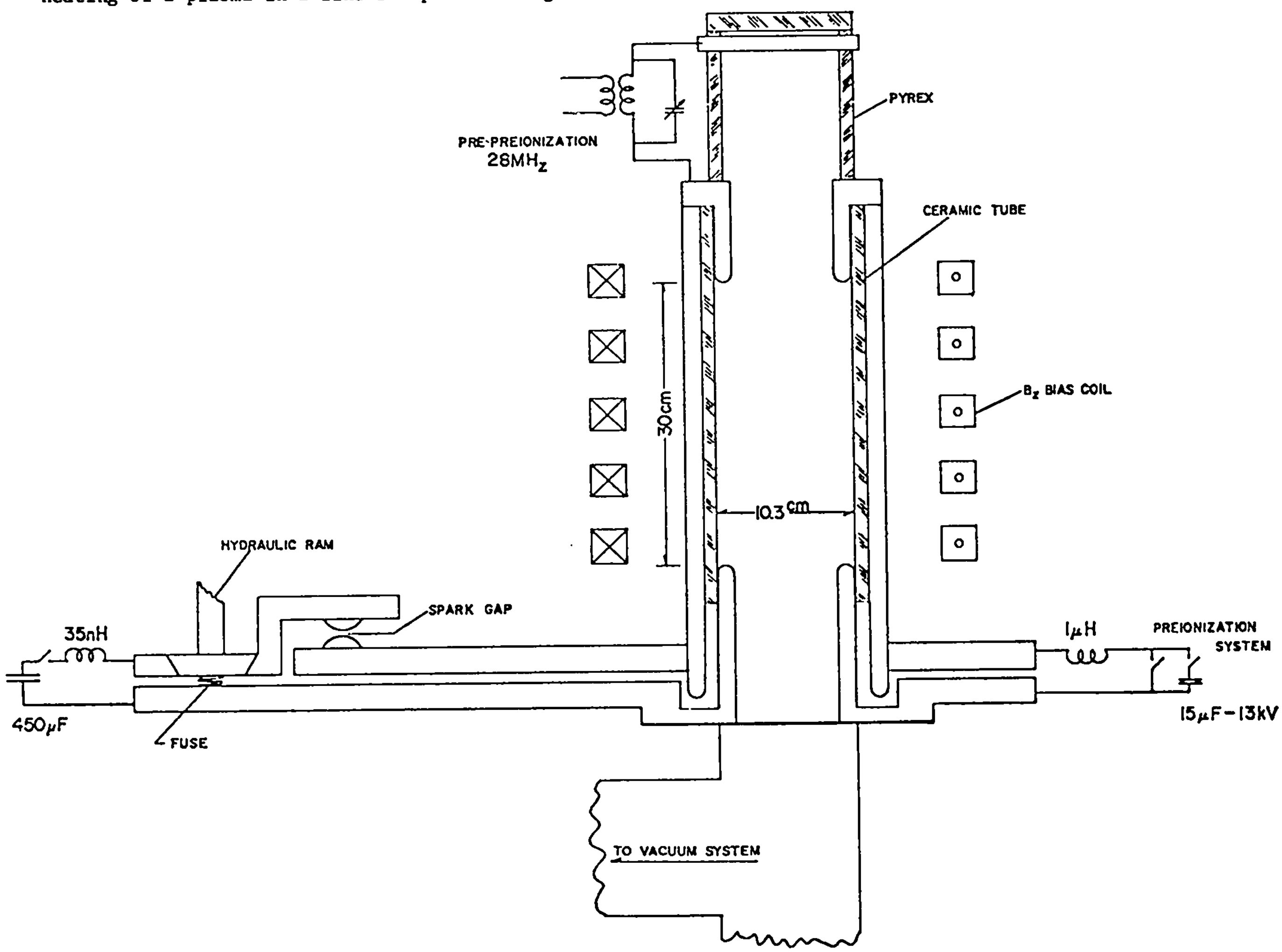


Fig. 1. Schematic diagram of the shock-heated linear z-pinch showing the technique of coupling a magnetic energy storage system to the z-pinch.

The very rapid rise of current, which is essential to the experiment, is accomplished with a magnetic energy storage system. The basic operational characteristics are shown in Fig. 2. Current that is flowing in circuit A is interrupted by opening switch $S_2$. The resulting voltage across resistance $R_s$ is allowed to increase to some predetermined value and then is applied to the z-pinch (circuit B) by means of the spark gap-transfer switch. Current interruption is accomplished by means of a copper foil that vaporizes and becomes a relatively large resistance. The advantage offered by the system is that the current interrupter switch can be located close to the z-pinch reducing the inductance $L_2$.

The experimental observations follow.

1. Discharge currents with $\dot{I} \sim 2 \times 10^{12}$ A/sec and $\dot{B} \sim 8 \times 10^{10}$ G/sec have been achieved. This $\dot{B}$ is about the same or greater than that achieved in hot (keV) $\theta$-pinch experiments.
2. Magnetic probe measurements indicate that the current detaches from the wall of the discharge tube even at the highest value of $\dot{B}$ so far obtained.
3. Radial velocities of $\sim 4 \times 10^7$ cm/sec (10 μHg $D_2$) are measured by streak photography. With a bias magnetic field of 3 kG, this velocity corresponds to an Alfven Mach number of 3. Using hydromagnetic shock theory, a resulting plasma ion temperature of 1 keV is predicted.
4. At low bias field (~ 800 G), loss of axial symmetry is observed in times of the order of 1 μsec.
5. At high-bias field (3200 G) and 30 μHg filling pressure:
   a. $B_\theta$ and $B_z$ probes indicate current symmetry for times ~ 8 μsec.
   b. Axial streak photographs show a cylindrical plasma column for times of the order of 5 μsec. The observation is then limited by light released from the electrodes.
   c. A rather thin (1 cm) plasma current sheath is measured by $B_z$ and $B_\theta$ probes. This sheath expands to a thickness ~ 2 to 3 cm in times ~ 3 to 4 μsec.
   d. Pressure balance, as determined from the radial dependence of the magnetic fields, yields a plasma temperature ($T_i + T_e$) of 0.75 keV in agreement with that predicted from hydromagnetic shock theory.

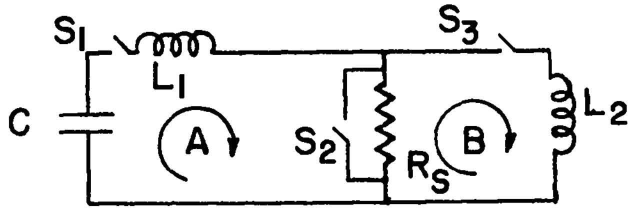


Fig. 2. Idealized circuit diagram of the magnetic energy storage system.

$$I_B = \frac{L_1}{L_1 + L_2} \; I_{A_o} \left[ 1 - \exp - \frac{R_s t}{L_3} \right]$$

$$\dot{I}_B = \frac{V_s}{L_2} \left[ \exp - \frac{R_s t}{L_3} \right]$$

where

$$L_3 = \frac{L_1 L_2}{L_1 + L_2}$$

6. When the filling pressure is increased by a factor of six (200 μHg), the plasma is colder (~160 eV is predicted). The $B_\theta$ and $B_z$ probes indicate the onset of instability in times of the order of 5 to 6 μsec.

From these data we postulate,

1. A high temperature (~ 1 keV) plasma is produced by shock heating in the fast linear z-pinch.
2. The current channel forms into a cylindrical shell of thickness ~ 1 cm and radius about one half the wall radius. The resulting plasma is stable in agreement with the thin sheath stability predictions of Tayler-Kruskal.[2,3]
3. When the plasma temperature is reduced by the introduction of impurities from the electrodes, the plasma sheath thickens and an instability develops.
4. At low initial temperatures, the instability develops early in disagreement with Tayler-Kruskal[2,3] theories.
5. These data indicate the importance of obtaining a high-temperature plasma.

The experimental results show an additional advantage of magnetic energy storage over the conventional capacitor supply; namely, the source is essentially a constant current device and when the current in the z-pinch discharge has been established, the voltage across the tube is reduced to low (~ 5 kV) values. With a conventional circuit, the high voltage that normally exists on the capacitors causes a second gas breakdown at the wall. This prevents further compression of the z-pinch column and causes the release of impurities. By using magnetic energy storage, a secondary breakdown is not observed.

## IV. ADVANTAGES OF TOROIDAL GEOMETRY

The primary purpose of the proposed experiment is to avoid electrodes and end effects. Loss of hot plasma from the ends in the linear experiment limits lifetimes of 1 keV ions to a few microseconds. Also, the electrodes cool the plasma by thermal conduction so that after ~ 3 μsec a cold plasma is confined.

We have considered whether the next logical step should be a simple increase in the length of the linear experiment to, for example, 240 cm. A longer discharge tube would increase the distance between electrodes with an increased time during which the central part of the discharge would be unaffected by electrode effects. However, the proposed experiment is to avoid all end effects and the toroidal geometry does this.

In addition, z-pinches in toroidal geometry exhibit gross equilibrium (Sec. VI). It has been our experience with z-pinches that going from linear to toroidal geometries results in a reduction of the growth rates of instabilities. It is therefore expected that the results of the fast linear z-pinch will be improved by turning to toroidal geometry.

## V. NUMERICAL HEATING CALCULATIONS

Figure 3 shows one-dimensional MHD numerical calculations of average ion and electron temperatures in a cylindrical geometry. In view of the relatively large aspect ratio of the proposed experiment, the validity of these results is expected to extend to the toroidal configuration.

The discharge tube, radius 5.3 cm, is initially filled with deuterium at a pressure of 10m Torr. The gas is assumed to be fully ionized and preheated to a temperature of 10 eV. The implosion is driven by a trapezoidal z-current of magnitude 300 kA and rise time 0.1 μsec. The $B_z$-flux, created by an initial bias field of 3 kG, is assumed to be conserved.

Figure 3(a) is obtained with a classical (Spitzer) electrical resistivity. Shock heating and a relatively long equipartition time result in a large temperature difference between ions and electrons.

Figure 3(b) is obtained with a selectively anomalous (Bohm-type) resistivity. The classical resistivity is replaced locally by an anomalous resistivity whenever the electron drift velocity exceeds the sound velocity. The ion temperature is seen to be approximately the same as in the classical case. Because of effective Ohmic heating by the z-current at the plasma boundary and θ-current at the shock front, the electrons are heated to a temperature close to that of the ions.

The temperature fluctuations (Fig. 3) are caused by repeated bouncing of the imploding plasma from the axis of the discharge. Averaged over these oscillations, the ion temperature achieved after ~ 0.2 μsec in the experiment is predicted to be of the order of 1.5 keV.

## VI. TOROIDAL EQUILIBRIUM

In the proposed experiment, the discharge will be in a toroidal configuration. Equilibrium will be provided by an outer conducting wall. Clearly there will be at least two new effects.

1. The discharge will shift radially outward. From past experience in toroidal z-pinches with similar aspect ratios, the radial shift was $\lesssim 10\%$ of the minor radius in agreement with theoretical predictions.

2. Because the experiment uses $\dot{B}$ to shock heat and because the $B_\theta$ magnetic field on the inside of

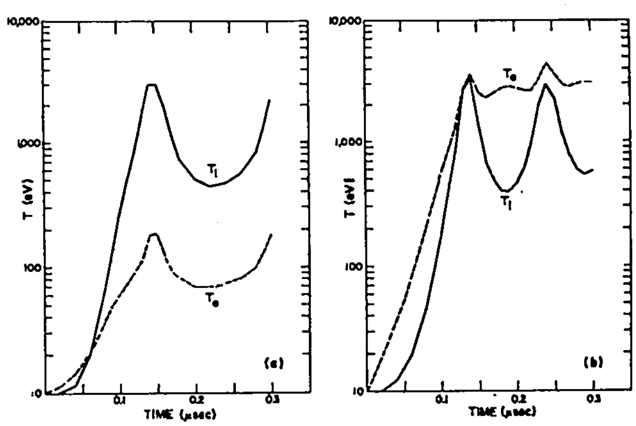


Fig. 3. Calculated ion and electron temperatures using (a) classical (b) anomalous resistivity.

the torus is 13% larger than on the outside, the shock will be stronger on the inside. The experiment will be designed so that the smallest $\dot{B}_\theta$ will still meet the conditions found necessary in the fast linear z-pinch.

It is hoped that plasma containment will be improved in the toroidal z-pinch because exact microscopic z-pinch equilibria exist in the toroidal geometry but not in the finite straight geometry. Moreover, these possible toroidal equilibria include a class of rigid drift equilibria and this has been shown to imply a similarity to the relatively successful Tokamak[4] and $\theta$-pinch devices relative to microscopic phenomena.[5]

## VII. HYDROMAGNETIC STABILITY

When a hot plasma is generated in the fast linear z-pinch experiment, no evidence for an $m = 1$ instability is observed for times $\approx 8$ μsec. However, when the plasma is cold, the initial gas pressure is higher and it is observed to go unstable in times ~ 5 μsec. This occurs even though the cold plasma has six times the mass density of the hot plasma and inertial effects should have resulted in a slower development of an instability. In both cases the experimental parameters satisfied the stability prediction of the thin sheath MHD model of Tayler-Kruskal.[2,3] Evidently, the temperature has an effect upon the plasma behavior in a manner not considered by the theory. There is, however, a general agreement with the theory because the plasma goes unstable when the stability conditions are not satisfied. The applicability of the MHD model and the effect of temperature should be made amenable to study by the elimination of the complicated end effects in a linear device.

The experiment will be designed to permit the addition of programmed profiles of $B_z$ and $B_\theta$ radial distributions if found necessary for MHD stability.

## VIII. COMPARISONS WITH OTHER EXPERIMENTS

Advantages of this experiment over those being examined at other laboratories include:

1. The study of a hot (~ 1 keV) plasma which can be extended to temperature of interest in a CTR reactor. The Culham experiment,[6] a programmed toroidal pinch, and Tokamak presently depend on Joule heating and it is debatable whether the required temperatures can ever be practically achieved by this method.
2. The z-pinch in toroidal geometry has gross equilibrium.
3. As the $B_z$ field outside the plasma column is small, or zero, the dangerous $m = 1$ Kruskal-Shafranov instability may not appear. In Tokamaks, the $I_z$ current, and the plasma pressure, is severely limited by this instability.
4. The confining magnetic pressure on the plasma column can be ~ 9 times that in $\theta$-pinches because the magnetic pressure on the walls in both geometies is limited by the strength of materials.

## IX. DIAGNOSTICS FOR THE PROPOSED SHOCK-HEATED TOROIDAL DEVICE

As a model for this discussion, we will assume that the plasma is a uniform torus of 5 cm minor diameter with an electron density of $3.0 \times 10^{15}/cm^3$. The desired information will be (1) the electron temperature as a function of radius and time, (2) the electron density as a function of time and radius, (3) similar measurements for the ions, (4) energy loss mechanism, and (5) a knowledge of the existence and modes of MHD instabilities.

### A. Measurement of $T_e$ and $n_e$

1. Density measurements can be made by using the infrared transitions of a HeNe gas laser with the modulated beam technique of Baker et. al.[7] Under the assumed conditions there will be a 0.04 fringe shift per pass for the preionized plasma and ~ 0.08 for the pinched plasma which is within the sensitivity (~ 0.01 fringe) of the method.

2. Thomson scattering of ruby laser light at 90° will result in a local measurement of both the electron density and the temperature. This method, while not requiring the assumption of uniform temperature or needing Abel inversion, relies upon shot-to-shot reproducibility to obtain density and temperature profiles.

3. Measurements of the bremsstrahlung continuum in the visible region yield a measure of the $n_e^2$ assuming that the electron temperature is unknown. Images of the cords of the plasma column are

projected onto individual photomultipliers. The center channel is assumed to be normalized to the measurement made with the HeNe interferometer mentioned above. Assuming a uniform electron temperature, Abel inversion should give the electron density distribution.

4. Time dependence of impurity line radiation in the vacuum ultraviolet will result in an upper and lower bound of the electron temperature assuming one has a knowledge of the electron density.

5. Measurement of the ultraviolet bremsstrahlung by the double foil absorption method will give an average $T_e$ as a function of time on one discharge.

B. Measurement of $T_i$ and $n_i$

It is assumed that within the experimental error the electron density is equal to the ion density.

1. Forward scattering of the ruby laser will measure the ion temperature if the plasma is not overly turbulent.

2. Neutron production is a function of the ion temperature and density if they are of thermonuclear origin.

3. Pressure balance from magnetic probe data will lead to a measure of the sum of the temperature and density product of the ions and electrons. From this an ion temperature can be extracted.

4. Analysis of the deuterium neutrals escaping from the plasma after charge exchange will give an ion temperature.

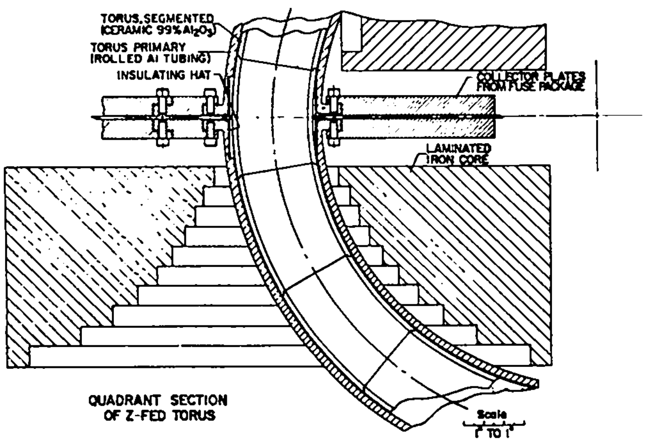


Fig. 4. Typical electrical feedpoint and primary of the torus.

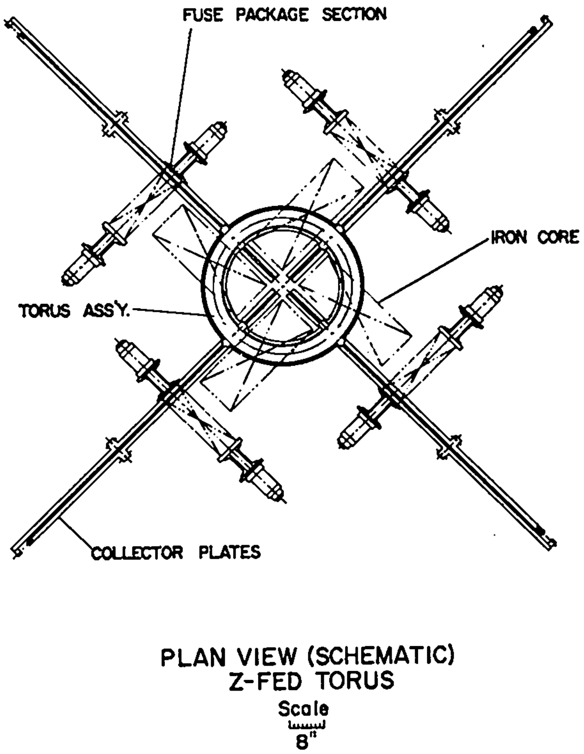


Fig. 5. Schematic view of the z-fed torus.

C. Energy Loss Mechanisms and MHD Stability

1. Streak and image converter pictures will aid considerably in determining the overall gross motion of the plasma column and any instability modes present.

2. Magnetic field probes, both internal and external to the plasma, will be the most definitive diagnostic for determining stability.

3. Wall colorimeters will be used to measure directly energy loss to the walls.

It is expected that the design of the apparatus will incorporate the appropriate access ports for the diagnostics.

X. DESIGN

One of the designs considered for the experiment is shown in Figs. 4, 5, and 6. The torus has four feedpoints equally spaced around the major circumference. Each feedpoint energizes 60 cm of the circumference which is twice the length of the present fast linear z-pinch. The major radius is dictated by the cross-sectional area in the center

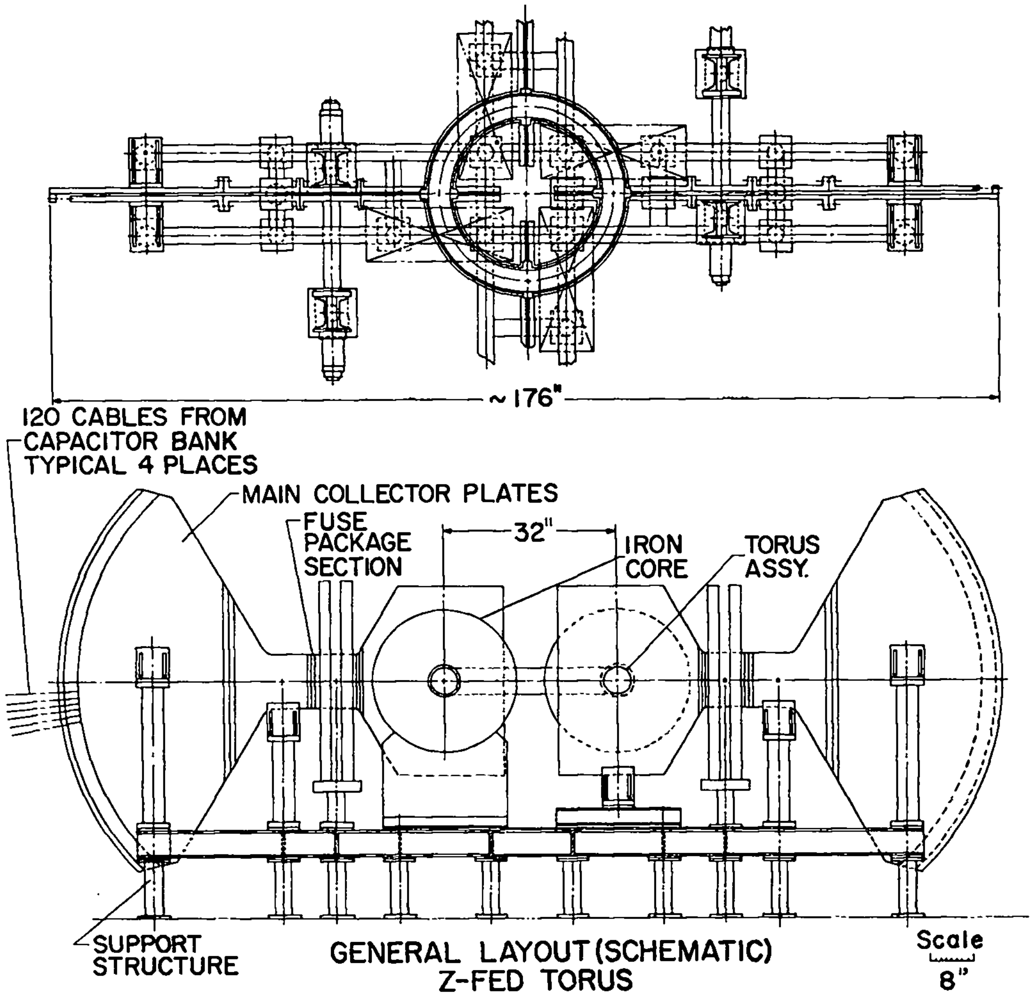


Fig. 6. Side elevation of the z-fed torus.

of the torus for the feedpoint collector plates and for the transformer iron.

XI. DESIGN DETAILS

1. Iron cores. Iron is necessary to increase the inductance of the primary to maximize the plasma current. Past experience with toroidal discharges showed that with an air core transformer of these aspect ratios the secondary gas current is only ~ 50% of the primary.

It is estimated that 0.05 volt-sec of iron is required for each quadrant which calls for ~ 420 $cm^2$ cross-sectional area, assuming a saturation field of 15 kG and packing fraction of 0.8. A proposed cross section of the iron which allows access for diagnostics is shown in Fig. 3. Tests will be made on the speed and losses of iron before an order is placed.

2. Feedpoints. A preliminary design consisting of a low inductance parallel plate transmission line is shown in Fig. 4. Tests will again be made on the current distributions at the feedpoints.

3. Fuses. Fuses at each of the four feedpoints are in series and will require simultaneity to $\lesssim$ 0.1 μsec for maximum voltage.

4. Primary capacitor bank. 0.5 MJ of 20 kV capacitors is available together with the necessary spark gaps. Additional hardware for the collector plates and fuse clamps must be procurred.

5. Torus. The aluminum primary winding is split in the plane perpendicular to the major axis and insulated to allow penetration of $B_z$ field lines. The discharge tube presents a challenging problem. Tolerances are tight (~ 0.005 in.) to keep parasitic inductances small. A promising design is suggested in Fig. 3 in which the torus is made up of a series of pieces cemented together.

6. $B_z$ bias field. A relatively small capacitor bank with large inductance will give fields $\lesssim$ 6 kG.

7. Space. The proposed experiment will fit into available space. The capacitors will line the walls and be connected by coaxial cable to the four manifolds.

8. Manpower. All members of LASL Group P-14 will be involved and Robert Dike, Group P-16, and his staff will assist.

9. Cost estimate.

| | |
|---|---|
| Iron cores, 4 required (~ 2 tons) | $30,000 |
| Ceramic torus | 4,000 |
| Aluminum primary | 3,000 |
| Collector plates, 4 required at $8,000 each | 32,000 |
| Support stand | 2,000 |
| Fuse clamp 4 required at $2,000 each | 8,000 |
| | $79,000 |

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