TOKAPOLE III?

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I. INTRODUCTION

As an exercise to help determine possible new directions for the Wisconsin Plasma Physics program, we examine here modifications to the Levitated Octupole that would permit operation as a low-q tokamak and/or reversed-field pinch (RFP). The goal is to significantly expand the range of operating conditions available to us while minimizing the required hardware changes.

II. POLOIDAL DIVERTOR TOKAMAK

Perhaps the simplest modification would be to run the machine as a 4-node poloidal divertor tokamak like Tokapole II. This would require little more than an upgrade of the toroidal field capability.

As a starting point, we take a "standard" Tokapole II discharge with the following nominal parameters:

$R = 50$ cm

$a = 9$ cm

$B_T = 5$ kG

$I_H = 280$ kA

$I_p = 20$ kA

$\langle q \rangle = 2.0$

$V_\ell = 3.2$ volts

$P_{OH} = 0.064$ MW

$T_{eo} = 150$ eV

$n = 1 \times 10^{13}$ cm^{-3}

$\tau_E = 0.5$ msec

For the Levitated Octupole with R=140 cm and I_H= 1 MA, we can estimate the plasma current I_p from PLP 777,

$$I_p \propto \alpha I_H L_H / L_p \tag{1}$$

where α=private flux/total flux (0.57), L_H is the internal ring (hoop) inductance and L_p is the plasma inductance, given in PLP 889 (but generalized to a machine of arbitrary major radius) by

$$L_p = 6.5 \times 10^{-7}\ R\ \frac{\bar{R}}{a} \tag{2}$$

where all units are in MKS (SI). The expected value is thus

$$I_p = 2 \times 10^4 \left(\frac{0.57}{0.5}\right)\left(\frac{1000}{280}\right)\left(\frac{0.432}{0.219}\right)\left(\frac{50}{140}\right)^{3/2} \sqrt{\frac{a}{0.09}} = 1.1 \times 10^5 \sqrt{a} \tag{3}$$

Because of the noses, the tokamak plasma will be somewhat vertically elongated, but we can approximate the tokamak region as a circle with an average radius of

$$a = 0.41 | I_p / I_H |^{1/4} \tag{4}$$

Combining (3) and (4) gives I_p=48 kA and a=19 cm. To achieve <q>=2, we thus require

$$B_T = \frac{4\times10^{-7} I_p R}{a^2} = 7400 \text{ gauss} \quad . \tag{5}$$

This amounts to a stored magnetic energy (in a volume of 8.6 m^3) of

$$U = \frac{B^2 V}{2\mu_o} = 1.9 \text{ MJ} \quad . \tag{6}$$

From this field, we can estimate the density using Murakami scaling from Tokapole II:

$$n = 10^{19} \, B_T/R = 5.3 \times 10^{12} \text{ cm}^{-3} \quad . \tag{7}$$

The confinement time is similarly estimated from Tokapole II using Alcator scaling:

$$\tau_E = 6.2 \times 10^{-21} \, na^2 = 1.2 \text{ msec} \quad . \tag{8}$$

Neo-Alcator scaling ($\tau_E = 1.15 \times 10^{-21} \, nR^{2.3} a^{0.8}$) gives a value of 3.5 msec, but since it overestimates Tokapole II confinement by a factor of four, we take the more conservative result of Eq. (8).

The electron temperature and loop voltage are solved simultaneously using the electron power balance equation and Spitzer resistivity again from Tokapole II using the same Z_{eff} to get

$$T_{eo} = 7.9 \times 10^{-3} (I_p/a)^{0.8} = 165 \text{ eV} \tag{9}$$

and

$$V_\ell = 4.8 \times 10^{-3} \left(\frac{I_p R}{a^2 T_{eo}^{3/2}}\right) = 4.2 \text{ volts} \quad . \tag{10}$$

One then concludes that a consistent set of parameters for such a machine is the following:

$R = 140$ cm

$a = 19$ cm

$B_T = 7.4$ kG

$I_H = 1$ MA

$I_p = 48$ kA

$\langle q \rangle = 2.0$

$V_\ell = 4.2$ volts

$T_{eo} = 165$ eV

$n = 5.3 \times 10^{12}$ cm^{-3}

$\tau_E = 1.2$ msec

It thus appears that the parameters are not impressive, and one would be constrained to the same physics that can already be done on Tokapole II.

III. CONVENTIONAL TOKAMAK

One drawback of the poloidal divertor tokamak with the existing Octupole rings is that the plasma is forced to a considerably smaller minor radius than would otherwise be allowed by the vacuum vessel. Furthermore, the majority of the volt-second capability of the iron core is wasted in generating magnetic flux external to the plasma. We could, however, imagine removing the Octupole rings and producing a conventional (non-diverted) tokamak with the plasma filling the available volume. Recall that when the rings were removed from the Small Octupole (PLP 754), the plasma leaned against the outer wall, occupied about half the volume of the vacuum vessel, and had a high resistivity. It would thus be necessary to add equilibrium field coils either outside the vacuum vessel (in which case control of the equilibrium would be difficult because of the skin time of the aluminum vessel) or inside (in which case dynamic control would be possible, but the installation would more difficult, and some of the minor cross-section of the vessel would be unaccessible to the plasma).

Because of the noses in the Octupole vacuum vessel, the plasma would presumably form a doublet-shaped cross-section. If that were undesirable, or if we wanted to leave space for internal equilibrium field coils, we could shrink the plasma by means of a poloidal limiter of the desired shape. Rather than do a detailed design incorporating optimization of the plasma shape, let´s just assume that the plasma is circular with a minor diameter equal to the geometric mean of the distance between noses (73.5 cm) and the height of the vessel (109 cm). This gives an effective minor radius of 45 cm (versus 19 cm for the poloidal divertor option). With the internal rings removed and all the volt-seconds of the iron core available to the plasma, the plasma current is constrained only by the toroidal field and the Kruskal-Shafranov limit. To permit a direct comparison with the previous case, assume the same toroidal field, B_T=7.4 kG. Then for $\langle q \rangle$=2, we get a plasma current of

$$I_p = 5 \times 10^6 \frac{a^2 B_T}{\langle q \rangle R} = 268 \text{ kA} \quad . \tag{11}$$

If the plasma density is limited by Murakami scaling (Eq. (7)), we get the same density as for the previous case (5.3×10^{12} cm^{-3}). However, because of the larger minor radius, Alcator scaling (Eq. (8)) gives an energy confinement time of 6.6 msec, whereas neo-Alcator scaling gives 7.0 msec. As before, electron temperature and loop voltage are solved simultaneously (Eqs. (9) and (10)) to get T_{eo}=330 eV and V_ℓ=1.5 volts. Now we can calculate the pulse length permitted by our iron core from which we can get about 1.4 volt-seconds with a modest reverse biasing scheme. The volt-seconds consumed to produce the poloidal field for a 268 kA discharge (assuming constant current density) is estimated to be only

$$\Phi = 2\pi \times 10^{-7}\ IR = 0.24 \text{ volt-sec} \quad . \qquad (12)$$

The remaining 1.16 volt-seconds would thus be available to sustain the plasma. With V_ℓ=1.5 volts, we would hold the plasma for 770 msec, neglecting any volt-seconds consumed during the high resistance startup phase. The power crowbar would have to provide 400 kW at a voltage on the 90-turn primary of 135 volts.

A consistent set of parameters for a low-field conventional tokamak using the Levitated Octupole vacuum chamber is thus:

R = 140 cm

a = 45 cm

B_T = 7.4 kG

I_p = 268 kA

$\langle q \rangle$ = 2.0

V_ℓ = 1.5 volts

P_{OH} = 0.4 MW

T_{eo} = 330 eV

n = 5.3×10^{12} cm^{-3}

τ_e = 6.6 msec

Although one might do somewhat better by exceeding the Murakami limit (which most tokamaks now do) and by lowering Z_{eff} (from the Tokapole II value of ~2), it appears that one would not approach state-of-the-art tokamak conditions because of the low toroidal field, and hence it becomes an exercise of dubious value.

IV. CONVENTIONAL RFP

To make a reversed-field pinch with the highest confidence, we consider something that resembles as closely as possible the Los Alamos ZT-40M, but that makes use of our existing iron core and aluminum vacuum vessel. Perhaps the easiest way to proceed would be to remove the internal rings and insert a circular aluminum shell (2.2 cm thick) inside the existing vacuum vessel. The shell would have both poloidal and toroidal gaps, but would not need to be vacuum tight and could consist of a number of toroidal sectors. If one wanted to even more closely approximate the ZT-40M design, one could add an Inconel liner inside the shell, but the liner need not be vacuum tight. We could use the existing poloidal and toroidal field systems on the Octupole with some modification to the capacitor banks, and equilibrium field coils would presumably be needed either inside or outside the vacuum vessel to keep the discharge centered in the shell. The parameters of ZT-40M upon which we base the design are as follows:

$R = 114$ cm

$a = 19.6$ cm

$\langle B_T \rangle = 1.5$ kG

$I_p = 200$ kA

$V_\ell = 40$ volts

$P_{OH} = 8$ MW

$T_{eo} = 300$ eV

$n = 2.5 \times 10^{13}$ cm^{-3}

$\tau_E = 0.2$ msec

These parameters may not represent the best case, but rather are typical values for a sustained ($\gtrsim$8 msec) discharge in ZT-40M.

A shell of the identical size could almost be accommodated in the existing Octupole vessel, but in order to reduce the required equilibrium field currents and facilitate the installation of equilibrium field coils, it would be better to use a 140 cm major radius shell. Presumably this would only change the required loop voltage (to 49 volts) and ohmic input power (to 10 MW). Of the 1.4 volt-second capacity of the iron core, Eq. (12) predicts that 0.18 volt-seconds is stored in the plasma. External to the plasma, we estimate the flux to be

$$\Phi = 4\pi \times 10^{-7} \, IR \, \ln \frac{b}{a} \qquad (13)$$

where b is an effective radius of the vacuum vessel. For b=56 cm, equation (13) gives Φ=0.18 volt-sec. Therefore, just over one volt-sec is available to sustain the plasma. For V_ℓ=49 volts, we get a pulse length of 20 msec, neglecting any volt-seconds consumed during the high resistance startup phase. The power crowbar would have to provide 8 MW (160 kJ) to sustain the plasma, neglecting losses in the windings, shell, etc.

A set of parameters that represents a simple extrapolation from ZT-40M is thus:

R = 140 cm

a = 19.6 cm

$\langle B_T \rangle$ = 1.5 kG

I_p = 200 kA

V_ℓ = 49 volts

P_{OH} = 10 MW

T_{eo} = 300 eV

n = 2.5×10^{13} cm^{-3}

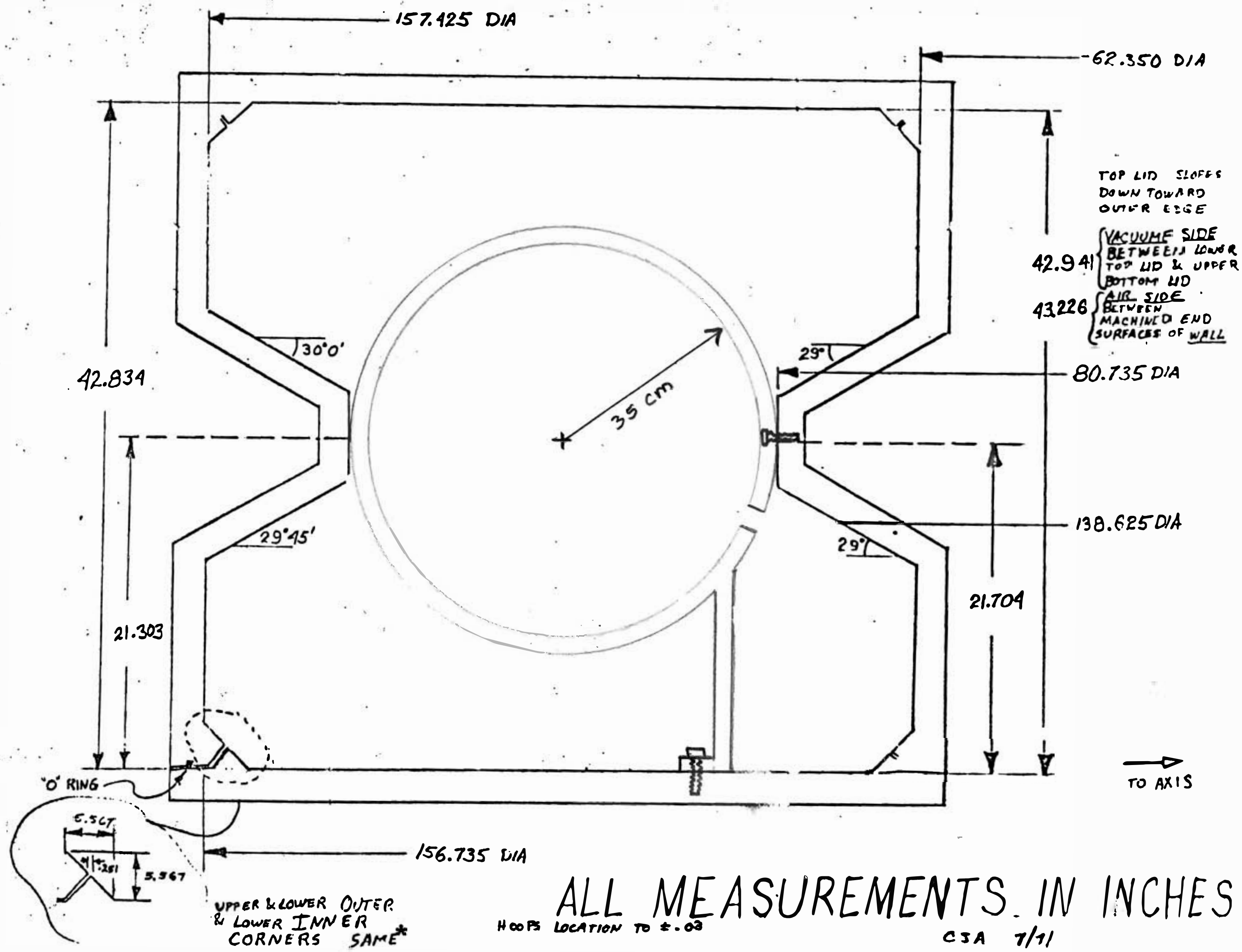
τ_E = 0.2 msec

T = 20 msec

V. LARGE RFP

Since we already have a large vacuum vessel, it is tempting to consider an RFP with a larger minor radius than ZT-40M. In fact, the existing vessel could accommodate a 35 cm minor radius circular shell without modification (Fig. 1). If we assume a constant plasma current density (1.6 MA/m^2) and scale from the previous case, we get a current of 640 kA. In order to maintain the same value of the pinch parameter θ, the average toroidal field must scale as $\langle B_T \rangle \propto I_p/a$, and hence we require $\langle B_T \rangle = 2.7$ kG. Since $I/N(=I_p/\pi a^2 n)$ tends to be constrained to a narrow range, we assume the density n is unchanged since the current density is unchanged. The temperature is assumed to scale as $T_{eo} \propto \beta_\theta (I/N) I$, and so if β_θ is the same as in ZT-40M (~0.1), we predict a temperature of $T_{eo}=1$ keV. Now the loop voltage required to sustain the discharge is smaller because of the higher conductivity, $V_\ell \propto IR/a^2 T_{eo}^{3/2}$, so that we obtain $V_\ell = 8$ volts and $P_{OH} = V_\ell I_p = 5.1$ MW. At constant current density, it actually takes less power to sustain a large RFP than a small one! If energy confinement time scales as $\beta_\theta T_{eo}^{3/2} a^2 / Z_{eff}$ and β_θ and Z_{eff} remain unchanged, we expect $\tau_E = 3.9$ msec. The poloidal flux stored in the plasma is estimated to be 1.1 volt-seconds, and so we have only ~0.3 volt-seconds left to sustain the ohmic loses. However, since $V_\ell = 8$ volts, we can achieve a pulse length of 37.5 msec neglecting any volt-seconds consumed during the startup phase. A set of parameters for such a device is as follows:

R = 140 cm


157.425 DIA
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TOP LID SLOPES
DOWN TOWARD
OUTER EDGE
42.941
VACUUME SIDE
BETWEEN LOWER
TOP LID & UPPER
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AIR SIDE
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MACHINED END
SURFACES OF WALL
42.834
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156.735 DIA
UPPER & LOWER OUTER
& LOWER INNER
CORNERS SAME*
HOOPS LOCATION TO ±.03
ALL MEASUREMENTS IN INCHES
CSA 7/71

FIGURE 1

a = 35 cm

$\langle B_T \rangle$ = 2.7 kG

I_p = 640 kA

V_ℓ = 8 volts

P_{OH} = 5.1 MW

T_{eo} = 1000 eV

n = 2.5×10^{13} cm^{-3}

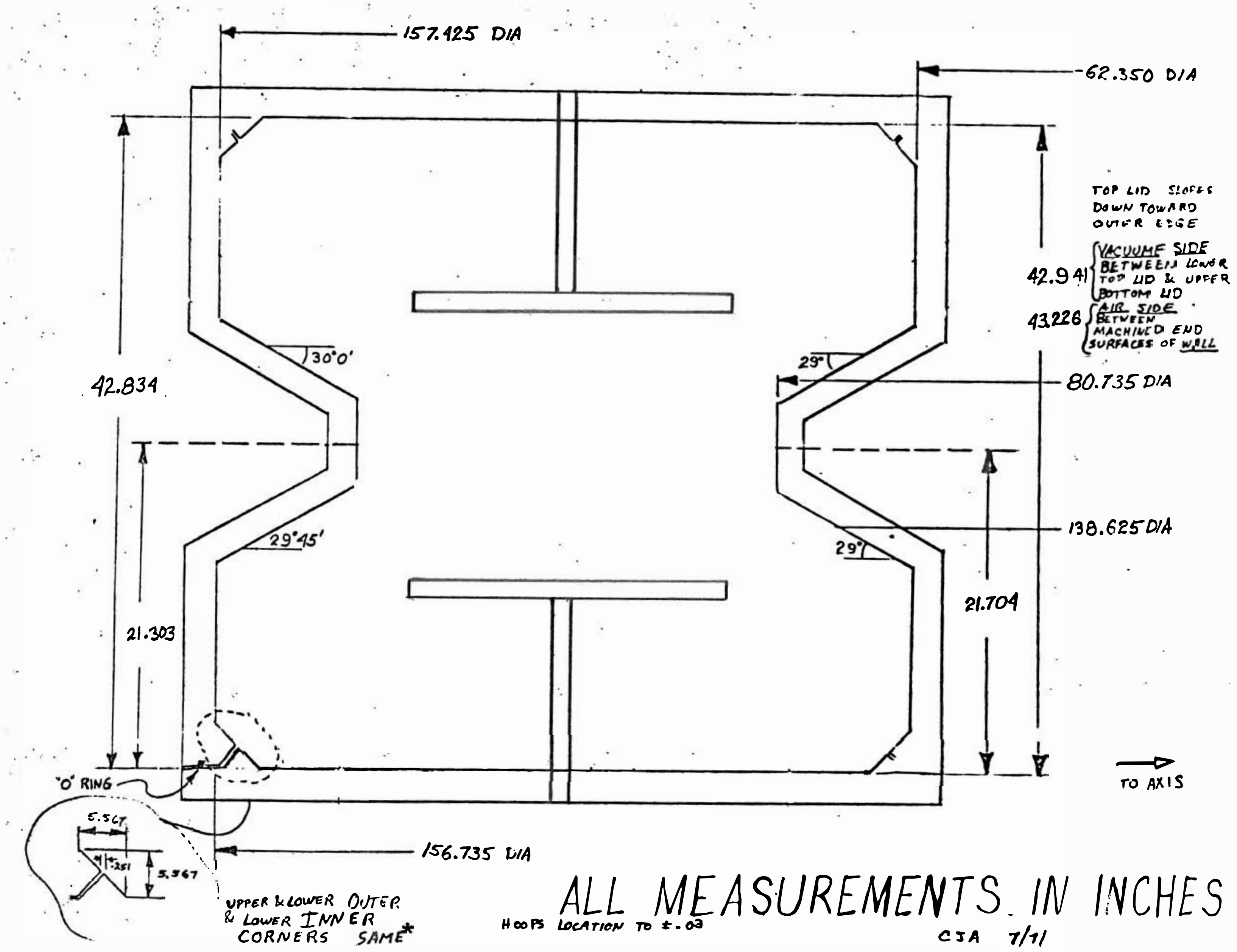
τ_E = 3.9 msec

T = 37.5 msec

This would make a very impressive device. If one were willing to risk departures from a circular cross-section shell, the shell could be made square (or rectangular) like the Tokapole II vacuum chamber to reduce construction costs considerably. One might even imagine using the existing Octupole noses as the inner and outer walls and just installing plates on the top and bottom which could be movable without breaking the vacuum (Fig. 2). This would facilitate future operation with a four-node poloidal divertor.

VI. VERY LARGE, NONCIRCULAR RFP

Encouraged by the favorable size scaling of the RFP and the existence of the large Octupole vacuum chamber which resembles the shell of an RFP (2" thick aluminum), we are led to consider the case in which the internal rings are removed, external equilibrium field coils added, and the plasma allowed to fill the entire available volume (8.6 m^3). The plasma would presumably be somewhat doublet-shaped. Since very little is known about the scaling of non-circular RFP´s, to get an idea of what we might expect, we take the case of a circular RFP with the minor radius adjusted to give the same volume as the non-circular device. Hence we take a=56 cm and scale everything as in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HOOPS LOCATION TO ±.03
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FIGURE 2

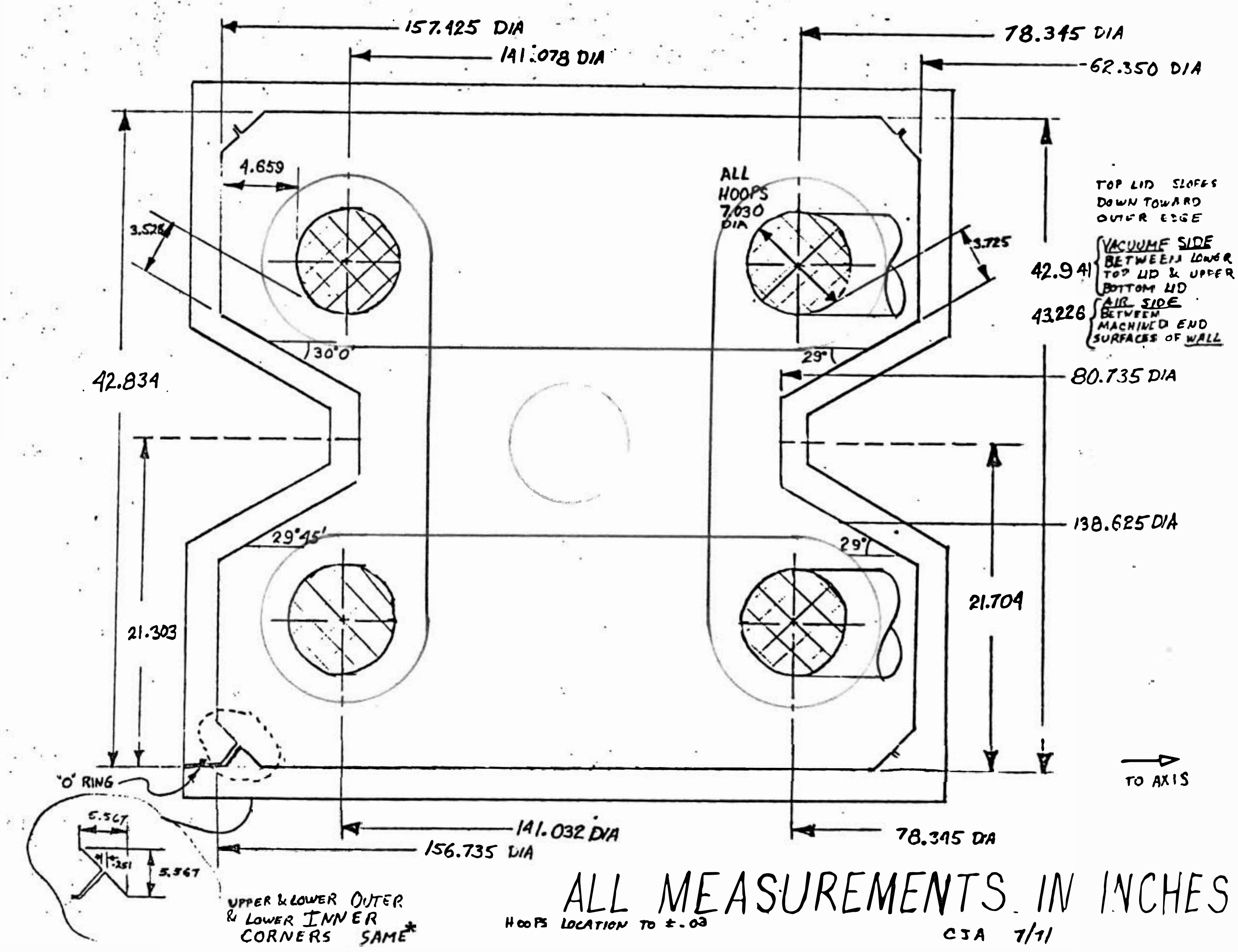
the previous section. Unfortunately, the full 1.4 volt-second capability of the core would be consumed just to produce the poloidal flux internal to the discharge. We are thus forced to back off a bit in current, say to 1 MA (which gives a current density of 1 MA/m^2). This allows us to use a toroidal field of $\langle B_T \rangle$=2.6 kG. To keep the same I/N and β_θ, we need $n=1.6\times10^{13}$ cm^{-3} and T_{eo}=1500 eV. The loop voltage becomes V_ℓ=2.7 volts, and the ohmic heating power is 2.7 MW. The confinement time is 18 msec, and the poloidal flux stored in the discharge is 0.9 volt-second, so that we can sustain the ohmic losses for 185 msec with our iron core. The parameters for such a device are thus:

R = 140 cm
a = 56 cm
$\langle B_T \rangle$ = 2.6 kG
I_p = 1000 kA
V_ℓ = 2.7 volts
P_{OH} = 2.7 MW
T_{eo} = 1500 eV
$n = 1.6 \times 10^{13}$ cm^{-3}
τ_E = 18 msec
T = 185 msec

The low loop voltage is nice because it allows us to use an electrolytic power crowbar bank with the existing 90 turn primary (240 volts on primary) in a manner similar to what we presently do on Tokapole II.

VII. POLOIDAL DIVERTOR RFP

A desirable capability would be the addition of a poloidal divertor to the RFP to compare the stability features of magnetic limiters and conducting shells. The existing Octupole rings could provide such a capability if the ratio of current in the plasma to current in the rings (I_p/I_H) could be suitably adjusted. Suppose we were to use the existing rings in their present position to produce a square-shaped separatrix similar to that in Tokapole II (Fig. 3). In order to get a sufficiently large plasma cross-section and still have some private flux around the rings with a moderate amount of soak-in, we place the nulls 12 cm from the center of the rings (3 cm from the present ring surface) in order to give a plasma with an equivalent minor radius of 30 cm. Using scaling laws from the previous sections, we conclude that $\langle B_T \rangle$=2.3 kG and I_p=470 kA. To place the nulls in the desired locations would then require a total ring current of approximately 590 kA. The remaining plasma parameters are determined from the previous scaling laws: V_ℓ=14 volts, P_{OH}=6.6 MW, T_{eo}=700 eV, $n=2.5\times10^{13}$ cm^{-3}, and τ_E=1.7 msec. To get the desired ratio of I_p/I_H(=0.8), the rings must either be driven externally with a current equal to 1.25 I_p, or their inductance and resistance have to be adjusted to values equal to 80% of the inductance and resistance of the plasma. The plasma inductance as estimated from Eq. (2) is 2.0 μhy. This agrees almost perfectly with the simple estimate of $L_p=2\pi\times10^{-7}R(1+2\ell nb/a)$=2.0 μhy which was used for the cases without a divertor. The plasma resistance is given by $R_p=V_\ell/I_p$=30 μohms. Thus the plasma L/R time is 67 msec. Now using the electrical circuit model of PLP 777 as shown below,


157.425 DIA
141.078 DIA
78.345 DIA
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ALL HOOPS 7.030 DIA
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TOP LID SLOPES DOWN TOWARD OUTER EDGE
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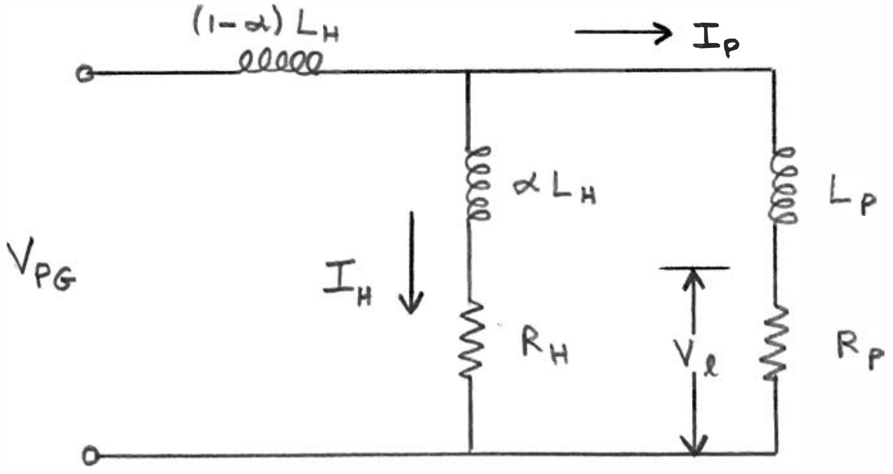
FIGURE 3



we can calculate the required internal ring resistance and inductance:

$$R_H = R_p\left(\frac{I_P}{I_H}\right) = 24\ \mu\text{ohms} \tag{14}$$

and

$$L_H = \frac{L_P}{\alpha}\left(\frac{I_P}{I_H}\right) = \frac{1.6}{\alpha}\ \mu\text{hy} \tag{15}$$

where α is the fraction of the total poloidal flux that is private to the rings in the absence of plasma. To see how close the present rings come to these conditions, we estimate R_H=2.3 μohms and αL_H=0.28 μhy. We thus have to raise both the ring resistance and inductance substantially. The simplest way to do this is to reduce the minor diameter of the rings. In so doing, the common flux portion of the ring inductance will remain fixed at $(1-\alpha)L_H$=0.2 μhy, and we need to add 1.32 μhy to the private inductance of the rings. This would require a ring diameter of 8.3 cm (3.3"). To get the correct resistance would require a resistivity of 6.1×10^{-8} ohm-meters. This is about the resistivity of brass. One could thus imagine replacing the present Octupole rings with 3.3" diameter brass rings (perhaps stainless-clad to increase the strength, raise the initial resistivity and reduce outgassing) and having a reasonably good RFP with a four-node poloidal divertor. This does not constitute an optimized design, but is meant to illustrate feasibility. The required poloidal gap voltage will be somewhat larger than V_ℓ,

$$V_{PG} = \frac{1}{\alpha} V_\ell = 1.125\ V_\ell = 16 \text{ volts} \quad . \tag{16}$$

In addition to the 6.6 MW ohmic heating requirement, an additional energy of $I_H^2 R_H$=8.4 MW is required to drive the ohmic losses in the rings. The total flux stored in the field is 1.15 volt-seconds, which leaves 0.25 volt-seconds to sustain the ohmic losses, or a pulse length of 16 msec. One could trade off current (and plasma performance) for pulse length if it were desired. One could add plates to the poloidal divertor RFP (Fig. 4) to enhance stability, provide some control over the plasma size, and allow some differential pumping of the divertor chamber. If the plates were movable, one could study the effect of moving the separatrix from inside to outside the conducting shell, but this could also be accomplished with fixed plates and movable rings and a varying plasma radius. A consistent set of parameters for such a poloidal divertor RFP is as follows:

R = 140 cm

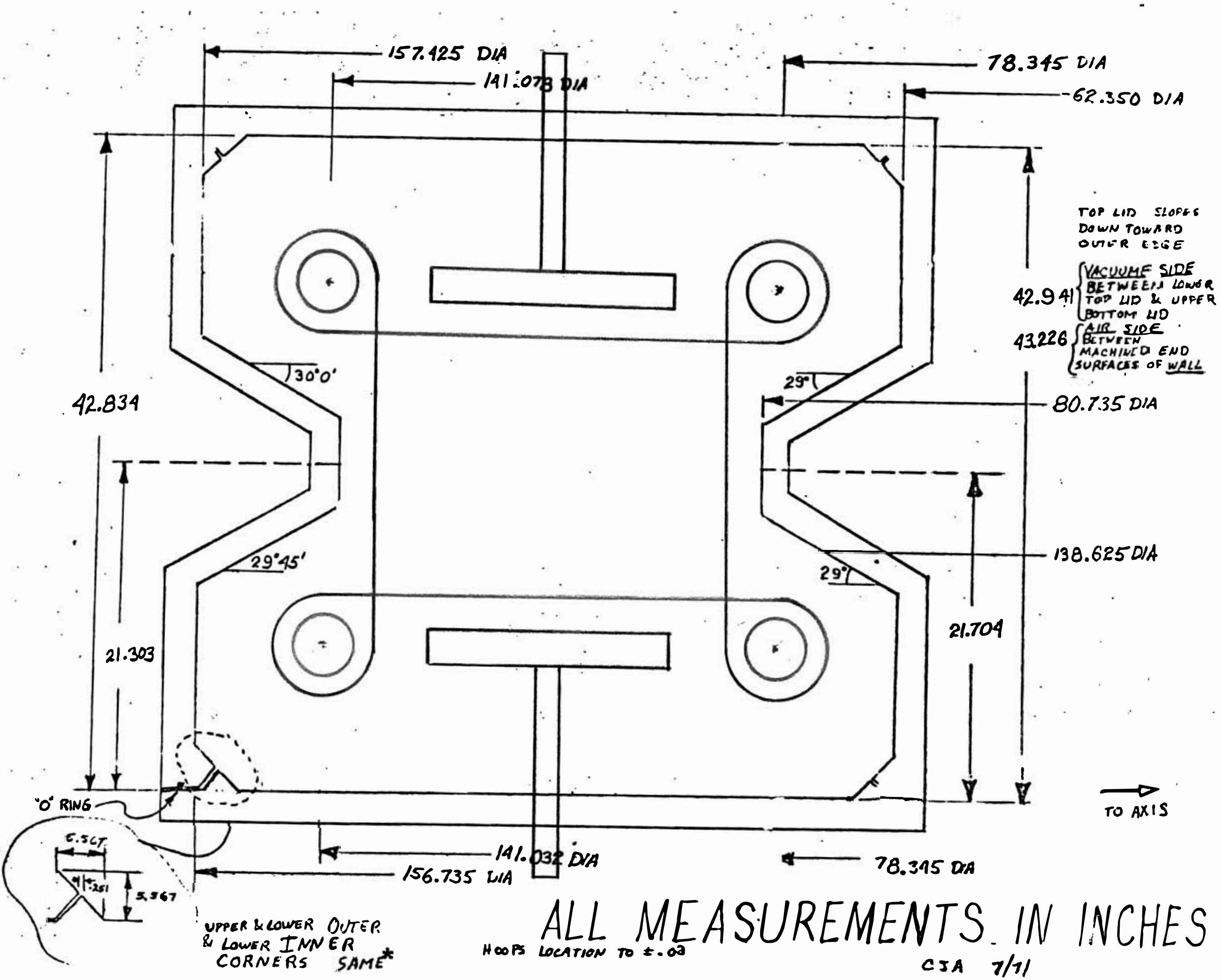
a = 30 cm

$\langle B_T \rangle$ = 2.3 kG

I_H = 590 kA

I_P = 470 kA

V_ℓ = 14 volts



TOP LID SLOPES DOWN TOWARD OUTER EDGE

42.941 VACUUME SIDE BETWEEN LOWER TOP LID & UPPER BOTTOM LID

43.226 AIR SIDE BETWEEN MACHINED END SURFACES OF WALL

UPPER & LOWER OUTER & LOWER INNER CORNERS SAME*

HOOPS LOCATION TO ±.03

ALL MEASUREMENTS IN INCHES

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FIGURE 4

P_{OH} = 6.6 MW

T_{eo} = 700 eV

$n = 2.5 \times 10^{13}$ cm^{-3}

τ_E = 1.7 msec

T = 16 msec

One could also imagine trying to make a poloidal divertor RFP with the existing rings. The difficulty is that the plasma L/R time would be shorter than the ring L/R time by a factor of about 200 (1 msec versus 200 msec), and thus one could not hope to achieve sustained operation. Furthermore, a poloidal gap voltage of 186 volts would be required, and the resulting plasma would only have T_{eo}=72 eV. This does not look like an attractive option.

VIII. A POSSIBLE EXPERIMENTAL PROGRAM

We suggest here a five-stage evolutionary program (Fig. 5) which encompasses most of the options previously described while minimizing the cost and interruption of the physics. Each stage would take about a year with stage 1 commencing immediately (summer of 1983). A more aggressive program would certainly be possible, but would require a higher funding level.

Stage 1: An attempt would be made to operate Tokapole II in a non-sustained RFP mode. This would require a rapid reversal of B_T and crowbarring with B_T reversed at the edge. The hardware is already in place to do this. Unfortunately, the volt-second capability of the core (~0.15) would severely limit the duration of the discharge ($\lesssim$1 msec), and the presence of the high conductivity divertor rings would preclude quasi-steady-state operation. This would provide us with valuable experience with field programming and diagnostics of the reversed field

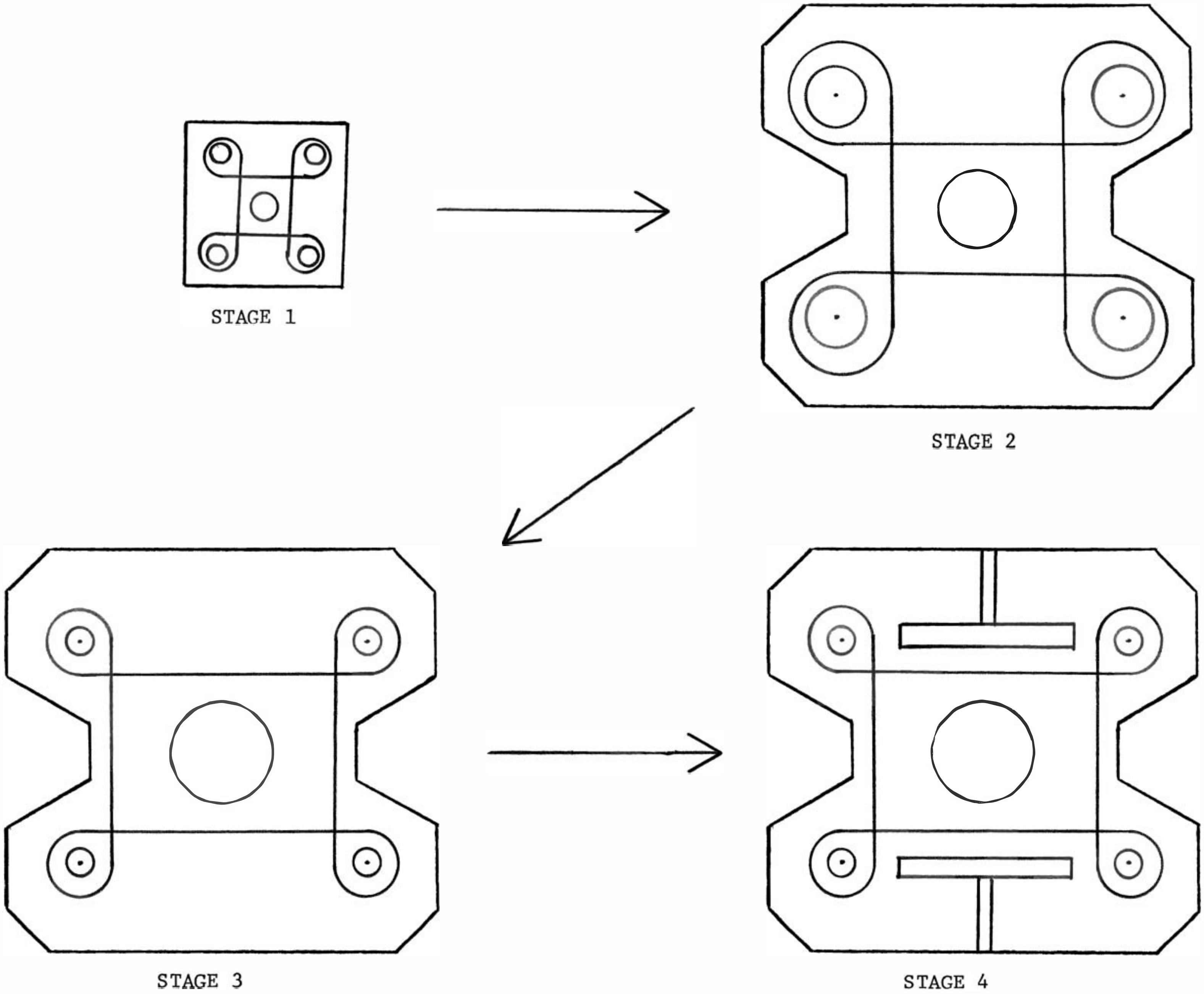

FIGURE 5

state, however. A byproduct would be tokamak operation at values of q lower than 0.4.

Stage 2: The stage 1 experiment would be transferred to the Octupole (Fig. 3). This is the case described in the last paragraph of section VII in which a 72 eV plasma might be achieved for ~1 msec. Stage 2 could be bypassed if the results of stage 1 are sufficiently discouraging.

Stage 3: Here one would replace the present aluminum Octupole rings with smaller ones of higher resistivity, rigidly attached to the levators or to Tokapole II type hangers so that their vertical position could be adjusted. If the separatrix plus the existing distant aluminum walls provided adequate stability, one might hope for a 470 kA, 700 eV, 16 msec discharge as described in section VIII.

Stage 4: Add adjustable thick aluminum plates on the top and bottom (Fig. 4) to enhance stability and provide control of the equilibrium and differential pumping of the divertor region. Plates of various thickness could be tried.

Stage 5: Increase the toroidal field to permit better tokamak operation for comparison with the RFP case. Allowing for 50% wasted energy, and assuming energy storage costs are 10 cents/joule, we could have 7.4 kG for ~$380K.

TABLE I. SUMMARY OF CASES CONSIDERED

		PDTOK	TOK	RFP	LRFP	NCRFP	PDRFP
R	cm	140	140	140	140	140	140
a	cm	19	45	19.6	35	(56)	30
$\langle B_T \rangle$	kG	7.4	7.4	1.5	2.7	2.6	2.3
I_H	kA	1000	--	--	--	--	590
I_p	kA	48	268	200	640	1000	470
$\langle q \rangle$		2.0	2.0	--	--	--	--
V_ℓ	volts	4.2	1.5	49	8	2.7	14
P_{OH}	MW	0.2	0.4	10	5.1	2.7	6.6
T_{eo}	eV	165	330	300	1000	1500	700
n	10^{13} cm^{-3}	0.53	0.53	2.5	2.5	1.6	2.5
τ_E	msec	1.2	6.6	0.2	3.9	18	1.7
T	msec	--	--	20	37.5	185	16