NEW HOOPS FOR TOKAPOLE II

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I. Introduction

Tokapole II was designed to have the highest conductivity hoops that would withstand a reasonable stress (see PLP 744). The chromium-copper alloy used (Ampcoloy 97) has a resistivity of 2.2 μΩ-cm and a yield strength of 43 kpsi. It was assumed that the plasma parameters would eventually be increased to the point where the L/R time of the plasma would match the L/R time of the hoops and that a flat plasma current of the order of 30 kA would be maintained for ~20 msec by a 450 volt power crowbar (see PLP 753 and 777).

After seven years of operation, the best plasmas still have a conductivity only half as high as expected, limiting the discharge length to ~10 msec and causing the discharge parameters to decay in time. Furthermore, the interest in low-q tokamak and RFP physics has caused us to run frequently with highly resistive, short-lived plasmas. The time has come to modify the machine to improve the operation with these plasmas.

II. Hoop Resistivity and Size Optimization

For 5-cm diameter hoops in the same location as the present hoops, the hoop resistivity required to make the hoop L/R time equal to the plasma L/R time is given in Table I as a function of the plasma conductivity temperature (T_e). As can be seen, the present chromium-copper hoops have an L/R time of ~18 msec (in the $t \rightarrow \infty$ limit) and are optimized for a plasma with a conductivity temperature of 125 eV. Our best plasmas have a conductivity temperature of ~80 eV and thus would be better matched to 6061 aluminum hoops with an L/R time of ~10 msec. The yield strength of 6061

TABLE I

OPTIMIZED HOOPS FOR TOKAPOLE LOW-q OPERATION

Hoop diameter = 5 cm   Flux = .1 Webers

Te	Iplasma	Ihoop	Resistivity	L/R time	
5	51.84318	230.8379	281.0562	.146034	
10	51.84318	230.8379	99.36834	.4130466	
15	51.84318	230.8379	54.08925	.7588153	
20	51.84318	230.8379	35.13201	1.168272	
25	51.84318	230.8379	25.13843	1.632709	
30	51.84318	230.8379	19.12345	2.146253	
35	51.84318	230.8379	15.1756	2.704588	
40	51.84318	230.8379	12.42104	3.304374	
45	51.84318	230.8379	10.40949	3.942916	
50	51.84318	230.8379	8.887776	4.618001	
55	51.84318	230.8379	7.703785	5.327739	← Be Cu
60	51.84318	230.8379	6.761165	6.070514	
65	51.84318	230.8379	5.996228	6.844929	
70	51.84318	230.8379	5.365388	7.649728	← 7178 al
75	51.84318	230.8379	4.837891	8.483811	
80	51.84318	230.8379	4.391502	9.346177	
85	51.84318	230.8379	4.009772	10.23593	← 6061 al
90	51.84318	230.8379	3.680311	11.15225	
95	51.84318	230.8379	3.393616	12.0944	
100	51.84318	230.8379	3.142303	13.06168	
105	51.84318	230.8379	2.920546	14.05345	
110	51.84318	230.8379	2.723697	15.06913	
115	51.84318	230.8379	2.548011	16.10816	
120	51.84318	230.8379	2.39043	17.17003	
125	51.84318	230.8379	2.248449	18.25425	← Cr Cu
130	51.84318	230.8379	2.119988	19.36037	
135	51.84318	230.8379	2.003307	20.488	
140	51.84318	230.8379	1.896951	21.6367	
145	51.84318	230.8379	1.799684	22.80609	
150	51.84318	230.8379	1.710453	23.99585	
eV	kAmps	kAmps	uOhm-cm	msec	

(40 kpsi) is very similar to the present hoops (43 kpsi) but may degrade more rapidly as the hoop temperature increases. With a total available core flux of 0.2 webers divided equally between inductive storage and resistive loss, one could expect to maintain a 52 kA plasma for 10 msec with a hoop current of 230 kA. The physical properties of various candidate hoop materials are shown in Table II.

One could also ask whether a 5-cm diameter hoop is the optimum size. Table III shows how the plasma and hoop currents vary with hoop size for a hoop of the optimum resistivity and a plasma with a fixed conductivity temperature of 80 eV and a fixed core flux. If the goal is to maximize the plasma current for a given hoop stress, and if the hoop stress is inversely proportional to D^4, a useful figure of merit is I_P/D^2I_H. This quantity increases about linearly with hoop diameter. Thus making the hoops smaller does not help, and making them larger provides only a small improvement. The computer code from which these results were obtained is shown in Fig. 1.

III. Time Dependence

The preceding discussion pertains only to the steady state (long time) limit. In order to examine in more detail the influence of different hoops, it is necessary to solve the time-dependent problem represented by the electrical equivalent circuit in Fig. 2. The voltage at the surface of a hoop (V_H) is calculated from the total hoop current (I_H) using the equivalent circuit shown in Fig. 3 where R_H is the dc resistance of the four hoops in parallel (see PLP 893 and 937).

For the first calculations, the plasma was removed from the circuit (L_P, $R_P \rightarrow \infty$). A useful figure of merit is $\int V_S dt/L_2 I_H(MAX)$, the volt-seconds available to drive a plasma on the separatrix for a given maximum hoop current. The integral is evaluated from t = 0 (when the switch is closed)

TABLE II: PHYSICAL PROPERTIES OF VARIOUS ALLOYS

Alloy	Material	Resistivity	Yield Strength
OFHC	Cu	1.7	10 (annealed)
Ampcoloy 97	(Cr)Cu	2.2	43
1100/1200	Aℓ	2.9	5 (annealed)
6061-T6	Aℓ	4.0	40
7178-T6	Aℓ	5.2	78
Berylco 27	(Be)Cu	7.8	165 (heat treated)
Nitronic 33	Stainless Steel	70	199 (cold worked)
		μΩ-cm	kpsi

TABLE III

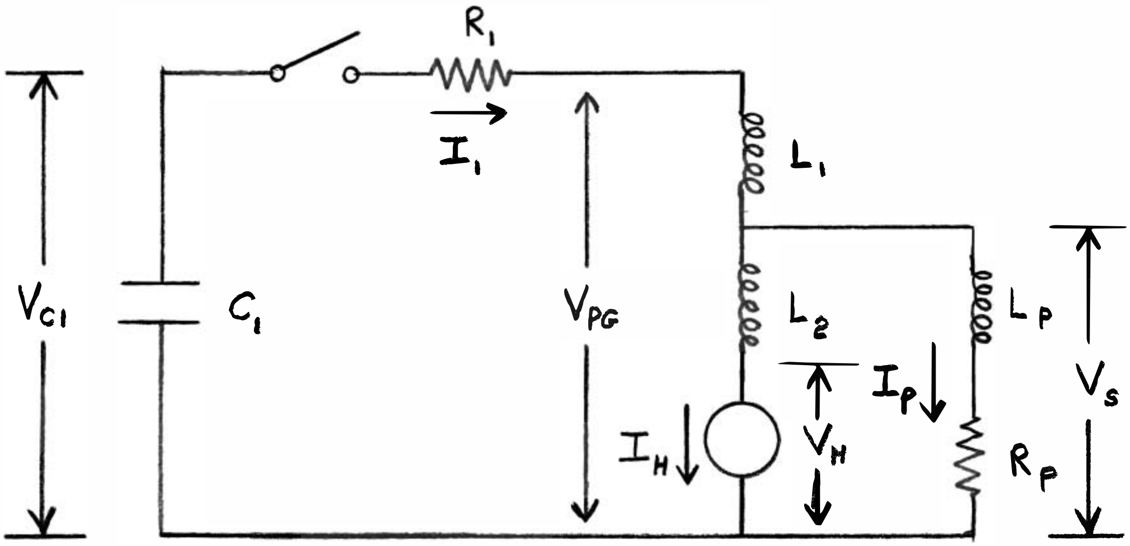
OPTIMIZED HOOPS FOR TOKAPOLE LOW-q OPERATION

Conductivity Te = 80 eV   Flux = .1 Webers

Diameter	Iplasma	Ihoop	Resistivity	L/R time	
2	64.79125	133.3969	1.033299	12.48113	
2.1	64.31068	136.476	1.122103	12.34027	
2.2	63.83803	139.546	1.213409	12.20395	
2.3	63.37247	142.6104	1.307107	12.07177	
2.4	62.91326	145.6721	1.403092	11.94337	
2.5	62.45974	148.7338	1.50126	11.81847	
2.6	62.01132	151.7982	1.60151	11.69678	
2.7	61.56745	154.8676	1.703741	11.57807	
2.8	61.12766	157.9441	1.807856	11.46212	
2.9	60.6915	161.0298	1.913759	11.34875	
3	60.25855	164.1267	2.021357	11.23775	
3.1	59.82846	167.2365	2.130553	11.129	
3.2	59.40088	170.3611	2.241257	11.02233	← CrCu
3.3	58.97546	173.502	2.35338	10.9176	
3.4	58.55192	176.6609	2.466827	10.81471	
3.5	58.13002	179.8394	2.581513	10.71354	
3.6	57.70943	183.039	2.697348	10.61399	
3.7	57.28995	186.2611	2.814246	10.51595	
3.8	56.87133	189.5072	2.932118	10.41934	
3.9	56.45335	192.7787	3.050879	10.32408	
4	56.03579	196.0771	3.170442	10.23008	
4.1	55.61848	199.4037	3.29072	10.1373	
4.2	55.20117	202.7598	3.411633	10.04563	
4.3	54.78374	206.1469	3.533091	9.955036	
4.4	54.36598	209.5662	3.655012	9.865449	
4.5	53.94771	213.0193	3.77731	9.776814	
4.6	53.52877	216.5074	3.8999	9.689081	
4.7	53.109	220.0319	4.022697	9.602201	← 6061 Al
4.8	52.68826	223.5942	4.14562	9.516116	
4.9	52.26636	227.1957	4.268583	9.430789	
5	51.84318	230.8377	4.391497	9.346181	
5.1	51.41855	234.5219	4.514286	9.262235	
5.2	50.99234	238.2495	4.636855	9.178929	
5.3	50.56439	242.0221	4.759124	9.096217	
5.4	50.13458	245.8412	4.881004	9.014069	
5.5	49.70273	249.7081	5.002413	8.932439	
5.6	49.26874	253.6247	5.123258	8.851303	
5.7	48.83246	257.5924	5.24346	8.770623	← 7178 Al
5.8	48.39374	261.6128	5.362921	8.690376	
5.9	47.95245	265.6875	5.481557	8.610526	
6	47.50844	269.8185	5.599283	8.531036	
cm	kAmps	kAmps	uOhm-cm	msec	

```
10 CLS: KEY OFF: PRINT"TURN ON LINE PRINTER"
20 LPRINT TAB(11)"OPTIMIZED HOOPS FOR TOKAPOLE LOW-q OPERATION": LPRINT
30 PHI=.1
40 L1=1.1E-07
50 D=5
60 LPRINT TAB(11)"Hoop diameter =";D;"cm   Flux =";PHI;"Webers": LPRINT
70 LPRINT" Te"," Iplasma"," Ihoop"," Resistivity"," L/R time"
80 FOR TE=5 TO 150 STEP 5
90 L2=1.4925E-07+1.57E-07*LOG(5/D)
100 A=(3985.4*L2)^(2/7)
110 LP=2.3E-07/SQR(A)
120 RP=7.300001E-04/A/A/TE^1.5
130 IH=PHI/(L2+L1+(L1+LP)*L2/LP)
140 IP=IH*L2/LP
150 R1=RP*L2/LP
160 RHO=275000!*R1*D*D/25
170 LPRINT TE,.001*IP,.001*IH,RHO,1000*LP/RP
180 NEXT: LPRINT" eV"," kAmps"," kAmps"," uOhm-cm"," msec";
```

Fig. 1: IBM-PC Basic program for calculating optimum hoop resistivity for a given hoop diameter and conductivity temperature.



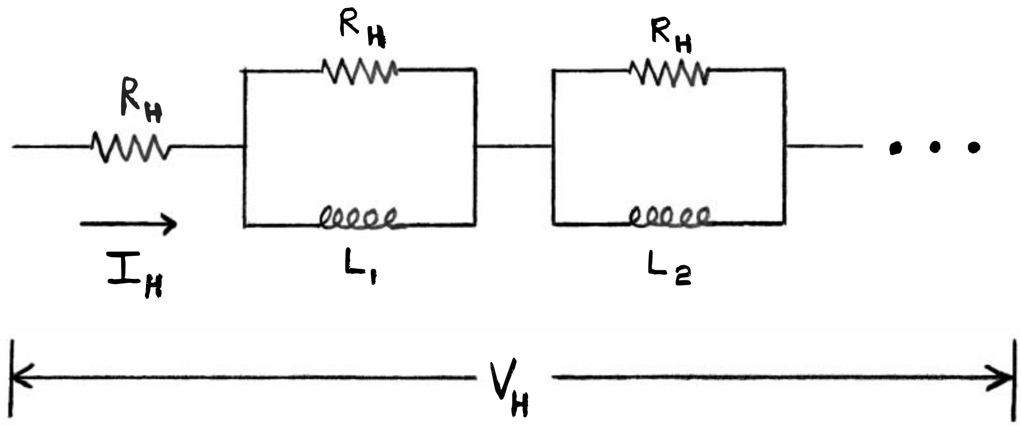
$C_1 = 0.0072\ N^2$ farads

$R_1 = 13 \times 10^{-6} + 8.34 \times 10^{-3}/N^2$ ohms

$L_1 = 1.1 \times 10^{-7}$ henries

$L_2 = 1.1 \times 10^{-7}$ henries

Fig. 2: Electrical circuit model for Tokapole II.



$R_H = 8 \times 10^{-6}$ ohms (four CrCu hoops in parallel)

$L_i \simeq 3.18 \times 10^{-8}/(i + 0.24)^2$ henries (four 5-cm hoops in parallel)

Fig. 3: Electrical equivalent circuit for Tokapole hoops.

up to the time when V_S reverses sign. For a perfectly conducting hoop, this quantity would be unity, and this provides a check on the calculation. This figure of merit was calculated for hoops of various resistivity for turns ratios of N = 40 and N = 80, and the results are shown in Table IV. The N = 40 case can be thought of as increasing the volts for the present pulse length, and the N = 80 case can be thought of as increasing the pulse length for the present gap voltage. The figure of merit increases by roughly the same proportion for the two cases. The column labeled F in Table IV represents the average of the two cases normalized to the present hoops and to the square root of the yield strength of the various materials. The 7178 aluminum is better by a factor of 1.68, and the Beryllium-Copper is better by a factor of 2.86 than the present hoops.

The plasma can be included in the circuit by assuming an inductance

$$L_P = 2.3 \times 10^{-7}/\sqrt{a}$$

and a resistance

$$R_P = 7.3 \times 10^{-4}/a^2 T_e^{1.5}$$

where

$$a = 0.174(I_P/I_H)^{1/4}$$

is the average radius to the separatrix in meters (see PLP 889). A number of cases were run with different hoop resistivities and plasma conductivity temperatures for a turns ratio of N = 40 and the capacitor bank voltage adjusted to give a peak hoop current of 300 kA $\times \sqrt{Y/43\text{ kpsi}}$ to correspond to

TABLE IV: PROPERTIES OF UNIFORM HOOPS OF VARIOUS ALLOYS

		η	Y	Figures of Merit		
				N=40	N=80	F
Ampcoloy 97	CrCu	2.2	43	1.33	1.52	1.00
6061-T6	Aℓ	4.0	40	1.49	1.80	1.11
7178-T6	Aℓ	5.2	78	1.59	1.98	1.68
Berylco 27	BeCu	7.8	165	1.79	2.40	2.86
		μΩ-cm	kpsi			

what is considered a safe operation of the present hoops. Table V shows the amp-seconds in the plasma discharge. The improvement in amp-seconds follows closely the figure of merit in Table IV, but the results serve to emphasize that a small increase in plasma conductivity temperature is as effective as a large change in hoop resistivity. The total flux in the iron core ranges from 0.078 webers for the present hoops with low T_e to ~0.2 webers for the Beryllium-Copper hoops with high T_e. Cases above ~0.1 webers will require core biasing as shown in Fig. 4, but we should be able to reach 0.2 webers with a proper bias circuit. The computer code from which these results were obtained is shown in Fig. 5.

IV. Soak-in of Magnetic Field to the Hoops

The preceding discussion ignores the fact that as magnetic flux soaks into the hoops, the amount of private flux between the perturbed separatrix and the plasma decreases as a function of time and eventually goes to zero. This places an upper limit on the pulse length if we require good confinement of plasma in the region between the separatrix and the hoop surface.

The fraction of total flux that is lost in the hoop can be calculated as a function of time during a pulse from the circuit model in Figs. 2 and 3 by evaluating the ratio $\int V_H dt / \int V_{PG} dt$. This was done for the special case of I_H = const and no plasma, and the result is displayed in Fig. 6. If we define the end of the useful pulse as the time at which 50% of the flux has soaked into the hoop, we conclude that the pulse length varies from 23 msec for the present hoops to 6.4 msec for Beryllium-Copper hoops. Thus we pay a serious penalty (proportional to hoop resistivity) in pulse length when we use stronger hoops. For completeness, Fig. 7 gives the hoop resistance

TABLE V: AMP-SECONDS IN PLASMA DISCHARGE

N = 40 $\quad I_H(MAX) = 300\ kA \times \sqrt{Y/43\ kpsi}$

T_e(eV)	Ampcoloy 97 (300 kA)	6061-T6 (289 kA)	7178-T6 (404 kA)	Berylco 27 (588 kA)	Cu Clad SS (496 kA)
10	15	16	24	40	24
20	57	63	95	160	94
40	138	154	233	394	235
60	183	203	308	518	316
80	208	230	346	577	360
100	222	244	367	609	387

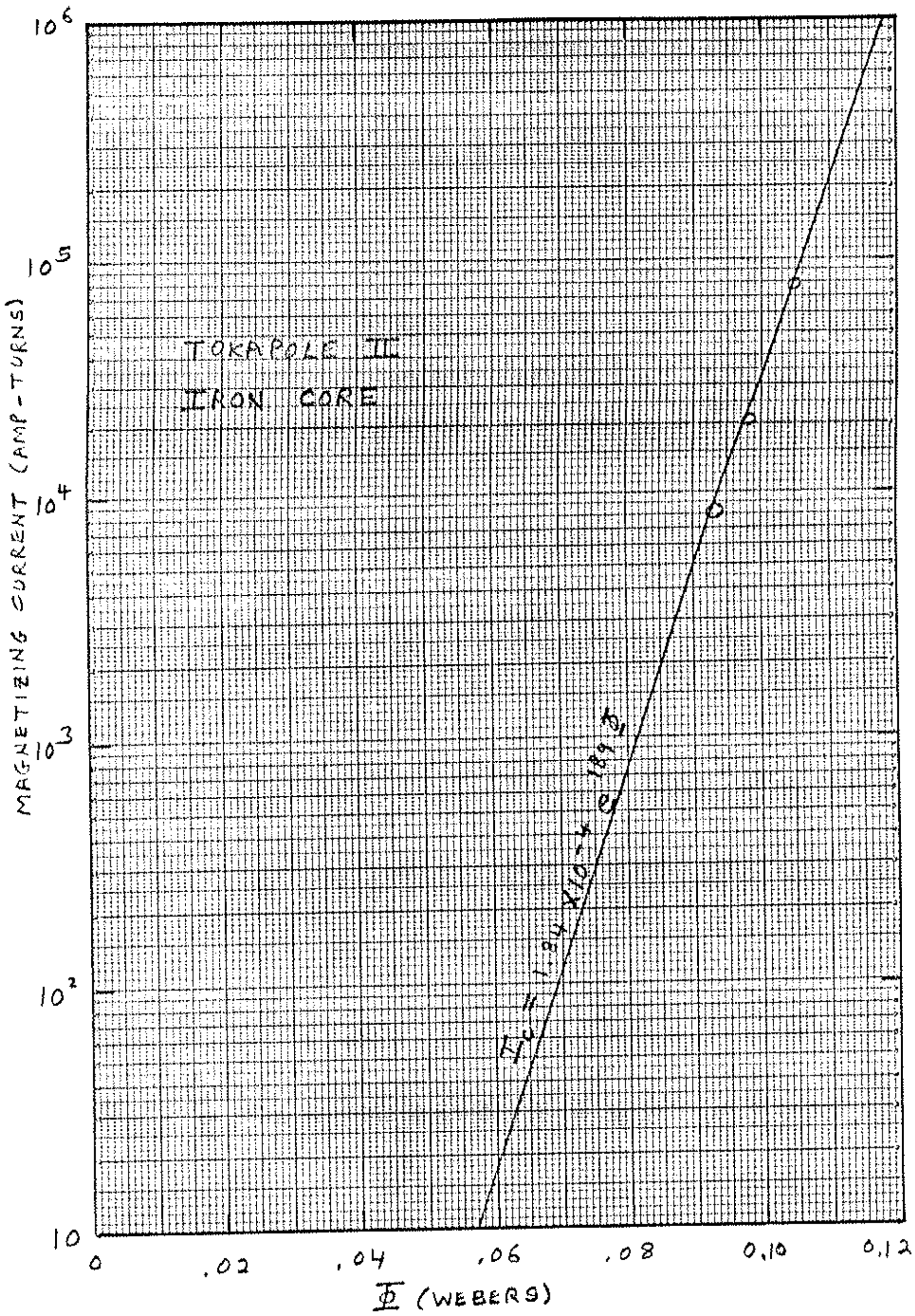


Fig. 4: Experimentally measured magnetization curve for the Tokapole II iron core.

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10 CLS: PRINT,,"HOOP CURRENT WAVEFORM": PRINT
20 DIM IH(10),VH(10),LH(10)
30 N=40: RHO=2.2: C1=.0072*N*N: R1=.000013+.00834/N/N: L1=1.1E-07: L2=1.1E-07: R
H=.000008*RHO/2.2: VC1=2500/N: DT=.00001
40 LH(1)=2.14E-08: LH(2)=6.4E-09: LH(3)=3.032E-09: FOR I=4 TO 10: LH(I)=3.18E-08
/(I+.245)^2: NEXT: FOR I=11 TO 100: L2=L2+3.18E-08/(I+.245)^2: NEXT
50 TE=50: LP=.0000008
60 PRINT "TIME","VC1","IHOOP","IPLASMA","AMP-SEC"
70 T=T+DT
80 VC1=VC1-DT*I1/C1
90 I1=I1+DT*(VC1-13/N-I1*R1-VS)/L1
100 IH=IH+DT*(VS-VH)/L2
110 IP=IP+DT*(VS-IP*RP)/LP
120 IF IP<0 THEN 220
130 A=.174*(IP/IH)^.25: LP=2.3E-07/SQR(A): RP=7.300001E-04/A/A/TE^1.5
140 VS=((VC1-13/N-I1*R1)/L1+VH/L2+IP*RP/LP)/(1/L1+1/L2+1/LP)
150 GOSUB 270
160 IF VC1-13/N-I1*R1>0 THEN VSEC=VSEC+DT*(VC1-13/N-I1*R1)
170 IF IHMAX<IH THEN IHMAX=IH
180 AS=AS+DT*IP
190 PRINT INT(1000000!*T+.5)/1000,VC1,IH/1000,IP/1000,AS
200 IF INKEY$=CHR$(27) THEN GOTO 250
210 GOTO 70
220 PRINT" mSec"," Volts"," kAmps"," kAmps"," Amp-sec"
230 PRINT"Peak hoop current =";IHMAX/1000;"kAmps"
240 PRINT"Core flux swing =";VSEC;"Webers"
250 END
260 REM THIS SUBROUTINE CALCULATES VH(T) FROM IH(T)
270 VH=IH*RH
280 FOR I=1 TO 10: IH(I)=IH(I)+DT*VH(I)/LH(I): VH(I)=(IH-IH(I))*RH: VH=VH+VH(I):
 NEXT
290 RETURN
```

Fig. 5: IBM-PC Basic program for calculating the time-dependent hoop and plasma current in Tokapole II with a plasma of fixed conductivity temperature (T_e).

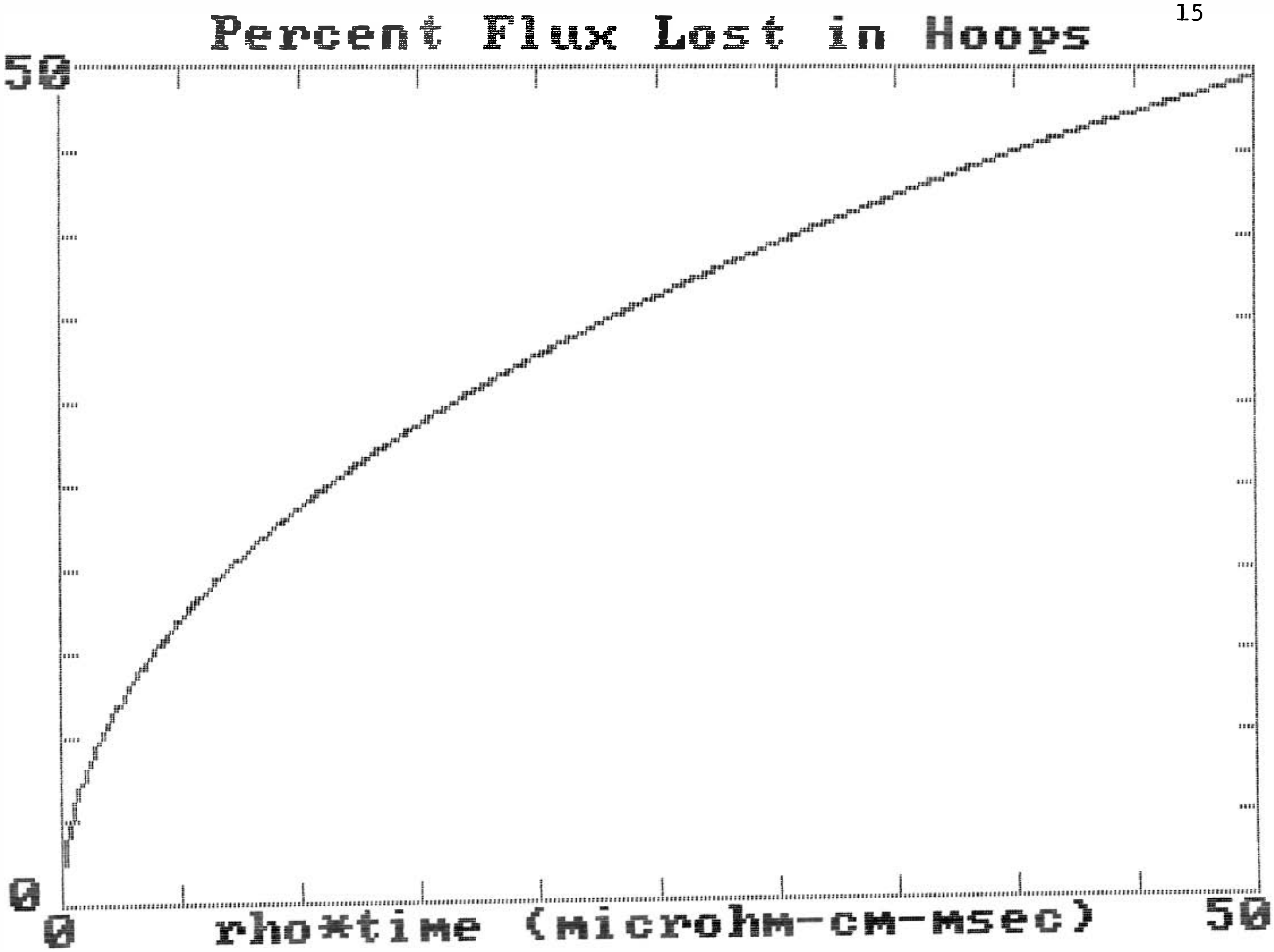

Fig. 6: Percentage of the total flux entering the gap that is lost into the Tokapole II hoops vs time for a constant hoop current. Rho is the hoop resistivity.

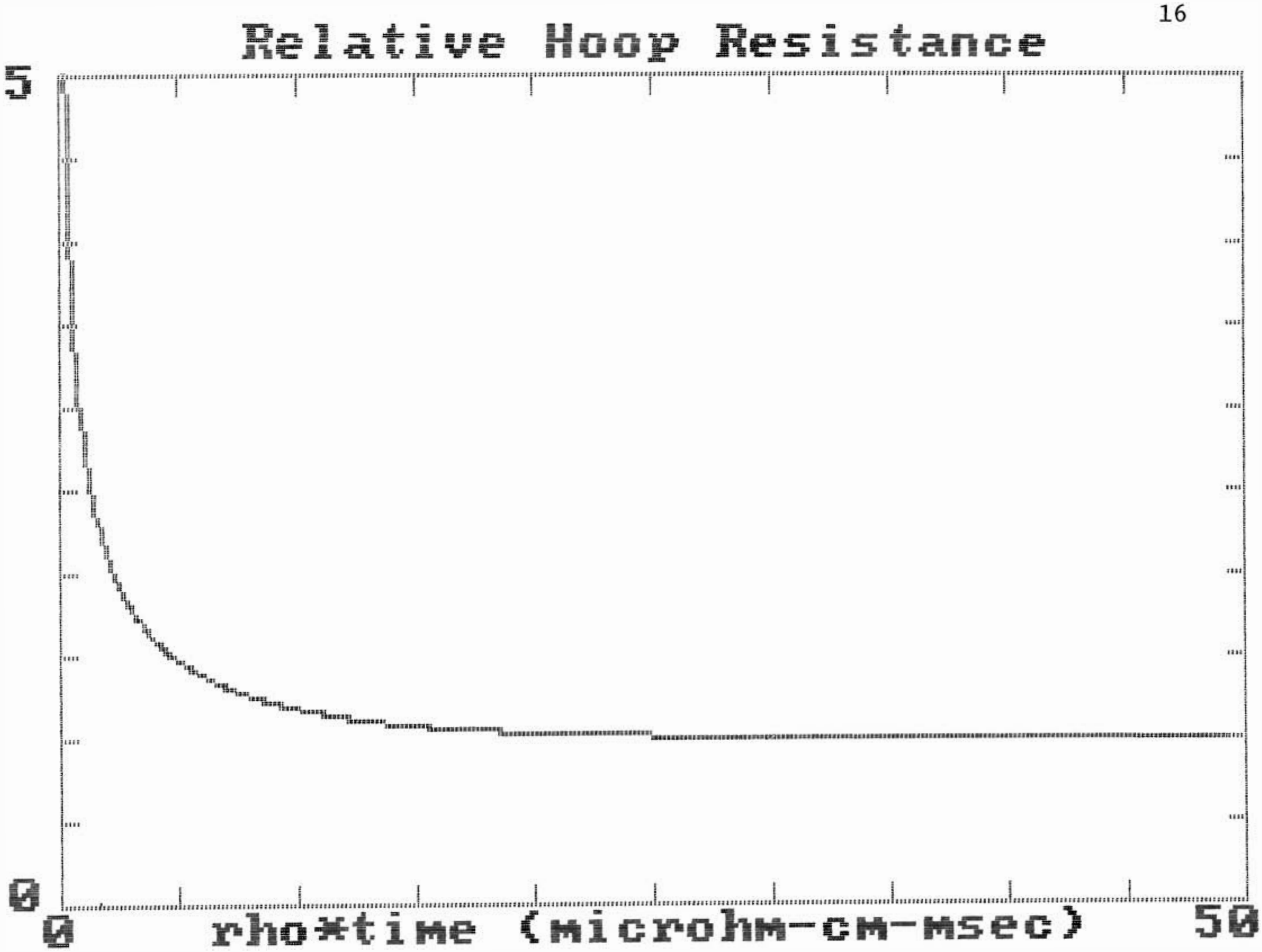

Fig. 7: Resistance of Tokapole II hoops relative to their dc resistance vs time for a constant hoop current. Rho is the hoop resistivity.

(relative to its dc value) as a function of time for a constant current pulse. Note that the hoop resistance approaches its dc value very rapidly.

V. Hoop with Non-uniform Resistivity

The major difficulty with using higher resistivity hoops is that the flux plot changes shape as the field soaks into the hoops, and eventually the separatrix intercepts the hoop surface as shown in the previous section. This difficulty could conceivably be eliminated if hoops could be made with an appropriate distribution of electrical resistivity over their cross-section. By making the resistivity low where the magnetic field at the surface of the hoop is high and vice versa, the shape of the flux plot could remain constant as the field soaks into the hoops.

The solution for the desired resistivity variation, $\eta(r,\theta)$, is obtained from the diffusion equation

$$\nabla^2\vec{B} - \frac{\nabla\eta}{\eta} \times (\nabla \times \vec{B}) = \frac{\mu_o}{\eta}\frac{\partial\vec{B}}{\partial t}$$

subject to the boundary conditions

$$B_r(r_o,\theta) = 0$$

$$B_\theta(r_o,\theta) = f(\theta)$$

where r_o is the minor radius of the hoop and $f(\theta)$ is the magnitude of the magnetic field at the hoop surface. The quantity $f(\theta)$ varies by about a factor of two in the absence of plasma, and a bit more with a plasma current.

Although the solution of the diffusion equation with a spatially varying resistivity is an interesting academic exercise, we will not pursue it because there does not appear to be any practical way to construct a hoop with a continuously variable resistivity that also meets the other requirements such a strength and toroidal axisymmetry. Rather, we will turn our attention to a design that represents a reasonable compromise and that could actually be built with only a modest effort.

VI. Copper-clad Stainless Hoop

We will consider now a hoop consisting of a high strength, high resistivity core such as stainless steel with a thin, low strength, low resistivity, variable thickness cladding such as oxygen-free, high conductivity (OFHC) copper (see Fig. 8). The strategy is to vary the thickness of the copper in proportion to the strength of the magnetic field at the surface of the hoop before any soak-in has occurred so that after a long time (a few msec) the velocity with which field lines soak into the hoop is inversely proportional to the density of field lines at the surface. In this case, an equal number of webers of flux will soak in per unit time at each point along the minor circumference of the hoops, and the flux plot will maintain its shape as the field soaks in. An alternate viewpoint is to consider that for a given voltage applied around the major circumference of a hoop, the current density will be constant everywhere in the copper (after a few msec), and if the copper is thin, an effective surface current will flow on the hoop of just such a magnitude to maintain the required field strength at the hoop surface. A suitable alloy for the core might be Armco Nitronic 33 (Y = 199 kpsi, η = 70 μΩ-cm), which is nonmagnetic even after severe cold working. The copper cladding could be sliced toroidally for

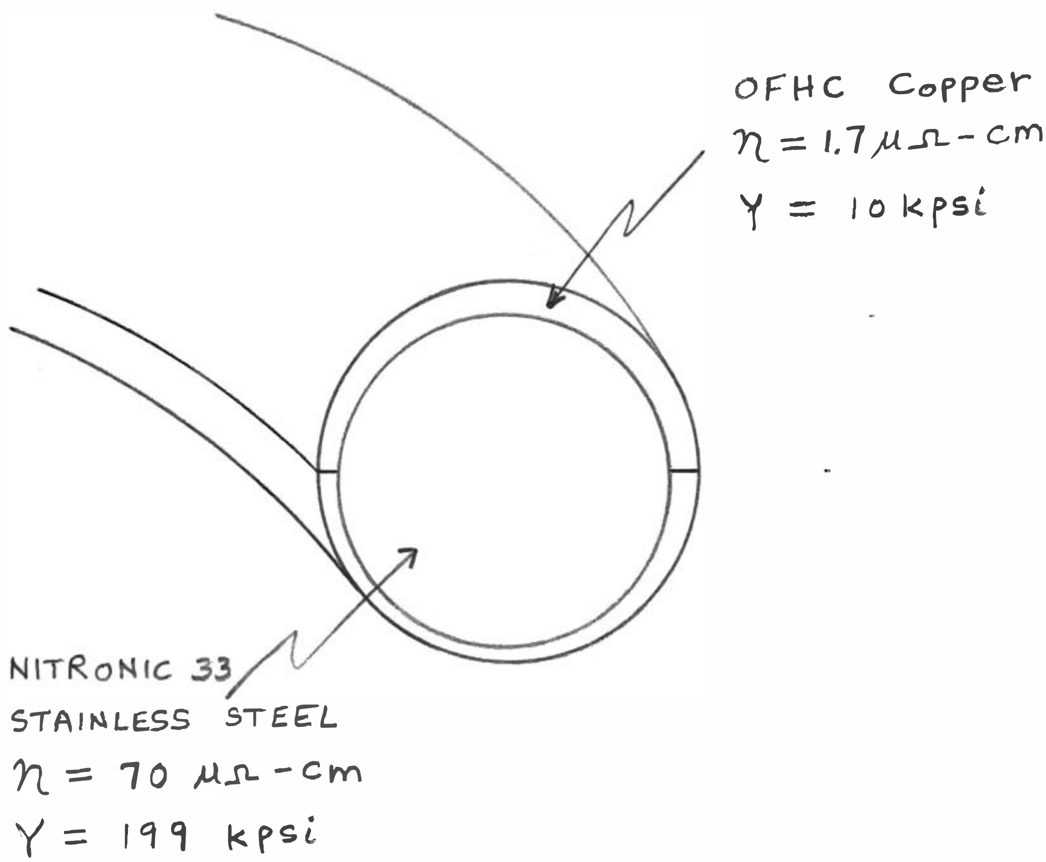

Fig. 8: Schematic illustration of proposed new Tokapole II hoops.

installation as shown in the figure. The magnetic forces would press the copper into the stainless.

As a design example, suppose we optimize for 60 eV conductivity temperature which according to Table I requires a hoop with an average resistivity of 6.8 μΩ-cm (3× that of the present hoops). If we obtain that value using a shell of 2.5 cm outer radius, the required average thickness of the shell is $d_o = r_o \eta / 2\bar{\eta} = 3.1$ mm for $\eta = 1.7$ μΩ-cm (OFHC copper). The thickness would actually vary from ~1.5 mm on the weak field side of the hoops to ~4.7 mm on the high field side. The exact variation of thickness with minor circumference depends upon the ratio of plasma current to hoop current and requires a more detailed numerical calculation. Furthermore, if we optimize for a higher ratio of plasma current to hoop current than we presently use, we would probably want to reposition the hoops slightly to restore a square cross-section (degenerate separatrix). If we want the OD of the hoops to be the same as the present hoops (5 cm), the OD of the stainless core would be 4.38 cm, and the effective yield stress would be $199\ (4.38/5)^4 = 117$ kpsi. Numerical calculations indicate that these numbers give a figure of merit of F = 1.90, which is to be compared with the values in Table IV for uniform resistivity hoops. In the case of a plasma with a time-independent conductivity temperature, the resulting amp-seconds closely resemble the 7178-T6 aluminum hoop case of Table V. But the important difference is that this case has no pulse length limit associated with the separatrix soaking into the hoop. In the highest temperature case the core flux is only 0.14 webers, and thus a modest core bias circuit would be required. Furthermore, in the steady state, a power crowbar capable of providing 12 volts/turn would be required to maintain the hoop current at 496 kA. This considerably exceeds the capability of our present electrolytic bank. A slight additional improvement ($F \approx 2.06$) could be gained by increasing the hoop size so that the stainless core is a full 5 cm in outside diameter and raising the hoop current to 646 kA, although in that case one would probably consider increasing the average thickness of the copper to perhaps 5 mm.

VII. Conceptual Design

If pressed to provide an engineering design for new Tokapole hoops that would roughly double the volt-seconds available to drive the plasma (and hence the amp-seconds of a plasma with a given conductivity temperature), the result would be as shown in Table VI. This case is actually optimized for a 52 eV plasma conductivity temperature. The pulse length at full field (I_H = 500 kA, I_P = 80 kA) would be limited by saturation of the iron core to 6.3 msec, but at reduced current (I_H = 250 kA, I_P = 40 kA) we could obtain 22.5 msec pulses with only 6.2 volts on the poloidal gap and a flux swing of 0.2 webers. The present 450 volt power crowbar would work only up to about 220 kA of hoop current.

A possible concern is the significantly higher current density than in the present hoops. The joule heating of the copper results in an abrupt temperature rise during the pulse that is limited by the heat capacity of the hoops and a slow approach to a steady state temperature (after thousands of successive shots) that is limited by radiative cooling. The steady state temperature should be comparable to that of the present hoops, since in both cases most of the energy of the poloidal banks ends up in the hoops. Thus if the surface emissivities of the hoops are comparable and if we don't alter the charging supply on the poloidal field banks, the steady state temperature should be similar to the temperature of the present hoops

TABLE VI. CONCEPTUAL DESIGN OF NEW TOKAPOLE HOOPS

Hoop core material	Nitronic 33 stainless steel
Core minor diameter	4.38 cm (circular)
Inner hoop core major diameter	71.707 cm
Outer hoop core major diameter	128.774 cm
Cladding material	OFHC copper (1.7 mW-cm)
Cladding thickness	1.5 mm (min), 4.7 mm (max)
Total hoop dc resistance	24.7 mW
Inner hoop current	160 kA (each)
Outer hoop current	90 kA (each)
Plasma current	80 kA
Inductance	0.210 mH
Inductive flux	0.122 webers
Inductive energy	35.3 kJ
Inner hoop vertical force	13,000 lb
Outer hoop vertical force	11,400 lb
Inner hoop horizontal force	21,700 lb
Outer hoop horizontal force	7,620 lb
Pulse length at full field	6.3 msec (for DF = 0.2 webers)

(~100°C). The temperature rise during a pulse is determined from the ohmic energy deposited in the hoops:

$$U = \int I_H V_H dt = I_H (\Delta\Phi - L_H I_H) \quad .$$

The ohmic energy is largest when the total hoop current is equal to $\Delta\Phi/2L_H$ = 476 kA for $\Delta\Phi$ = 0.2 webers. The energy deposited in each hoop is given by $\frac{1}{2} I_H \Delta\Phi$ or 15.2 kJ for each inner hoop and 8.6 kJ for each outer hoop. Thus the most serious heating is on the inner hoops. If we ignore heat conduction and radiation, the temperature rise for 9.76 kg of copper (specific heat of 0.093 cal/gm/°C) is 4.0°C/pulse for the inner hoops. This value seems perfectly tolerable. There will be a rise in the hoop resistance as they heat up. The resistivity of copper doubles for a temperature rise of ~250°C. The stresses due to the differential expansion of the copper and stainless with temperature would have to be examined.

A number of other modifications to the machine would be required to take full advantage of the new hoops:

1) New, slightly stronger hoop supports would have to be installed.
2) A core bias circuit, capable of providing $\gtrsim$10,000 ampere-turns during the pulse, would have to be installed.
3) Either the turns ratio on the poloidal field would have to be lowered to ~20:1 or a new power crowbar bank or pulse forming network capable of providing ~500 volts across the present 40-turn primary would have to be constructed.
4) Improved insulation of the poloidal gap and correction of an apparent vacuum leak at the inner triple joint would be highly desirable.

VIII. Predicted Waveforms

The waveform of plasma current has been predicted using the code IPFORM which analyzes a circuit similar to that in Fig. 2 except that it includes the magnetizing current in the iron core, a power crowbar (0.96 farads/440 volts), and a plasma conductivity temperature calculated self-consistently from neo-Alcator scaling

$$\tau_E = 1.92 \times 10^{-21}\ \bar{n}_e R_o^{2.04}\ a^{1.04}$$

with an adjustable Z-effective.

As a starting point, Fig. 9 shows the predicted plasma current waveform for a charging voltage of 2500 volts and Z = 1 for the present hoops. The waveform is surprisingly similar to our best high-q discharges. The conductivity temperature is about 80 eV. If Z-effective is raised to 3, the waveform in Fig. 10 results. The predicted peak temperature is 90 eV. This is typical of our low-q discharges or of what we consider a "dirty machine." These results lend credence to the numerical model.

If we change to hoops as described in the previous section, the resulting waveform for Z = 1 is as shown in Fig. 11. For this case, no change was made in the capacitor bank. With Z = 3 and the banks left the same, the result is as shown in Fig. 12. This case is much worse than the Z = 1 case of Fig. 11 but better than the case in Fig. 10 with the present hoops. However, if one raises the capacitor bank voltage to 3900 volts to increase the hoop current to the design limit of 500 kA, the result in Fig. 13 is obtained. Finally if one raises the voltage to 3900 volts and also reconfigures the power crowbar to

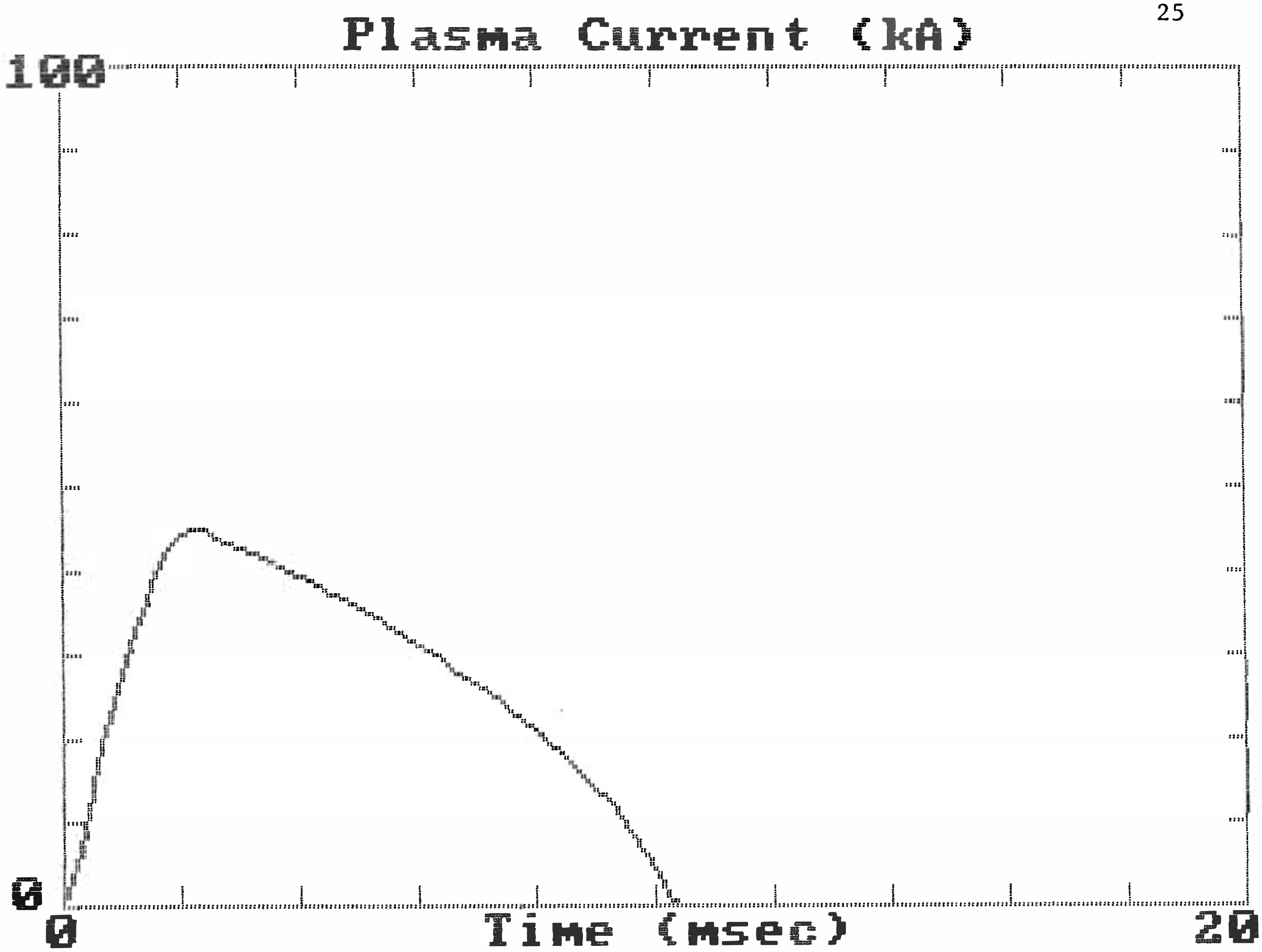

Fig. 9: Plasma current waveform for V_c = 2500 volts and Z = 1 with the present hoops.

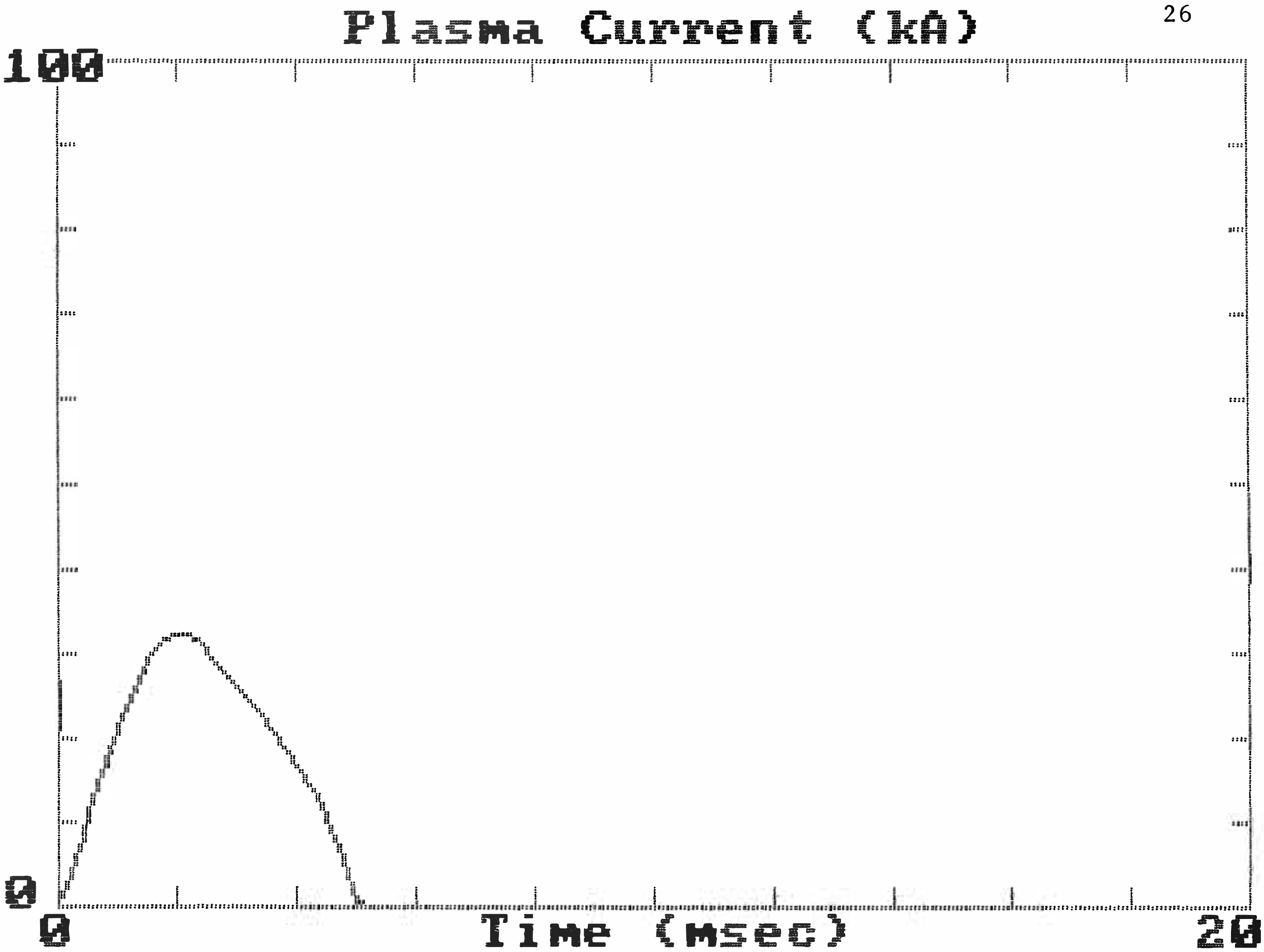

Fig. 10: Plasma current waveform for V_c = 2500 volts and Z = 3 with the present hoops.

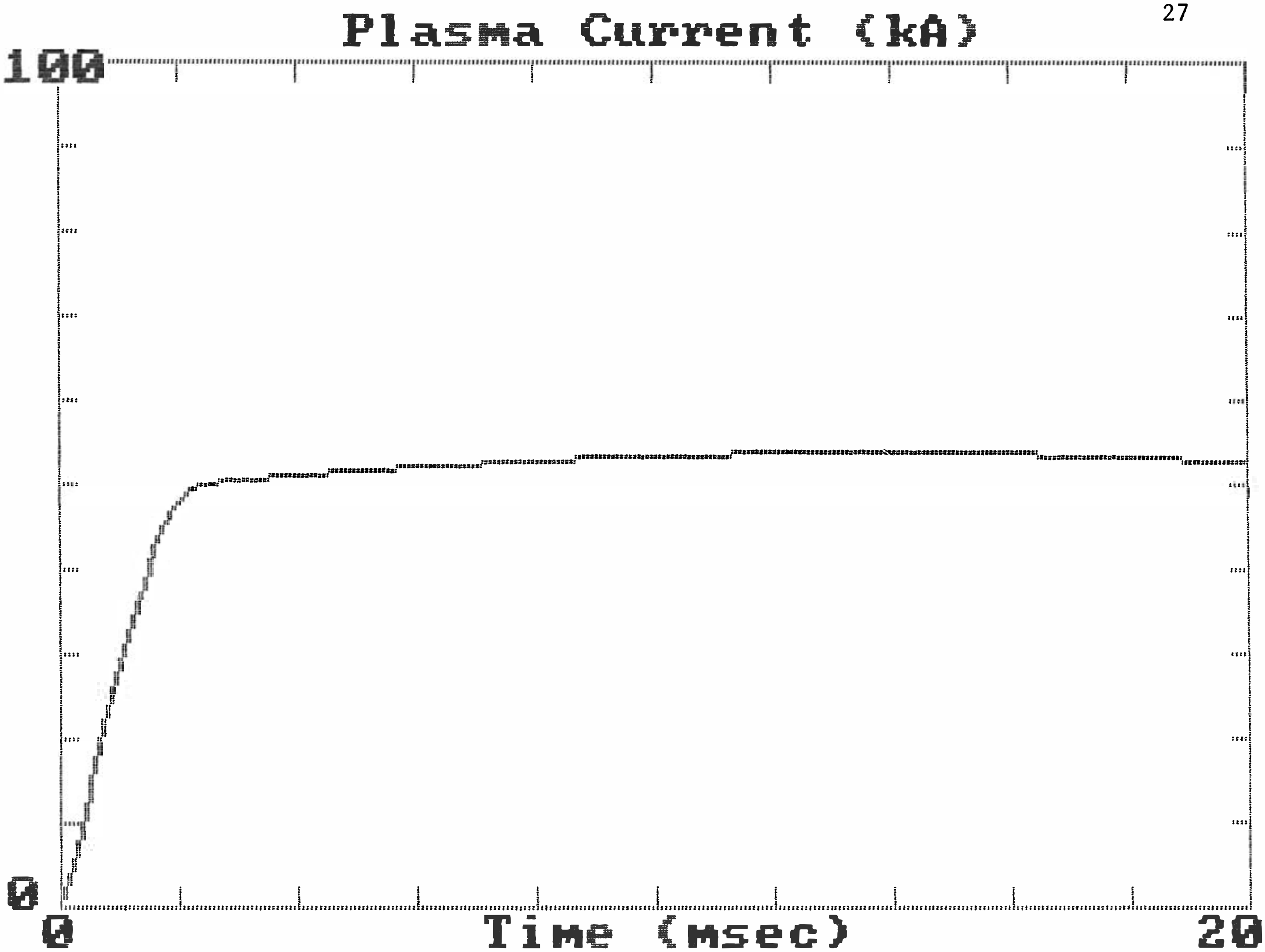

Fig. 11: Plasma current waveform for V_c = 2500 volts and Z = 1 with the proposed new hoops.

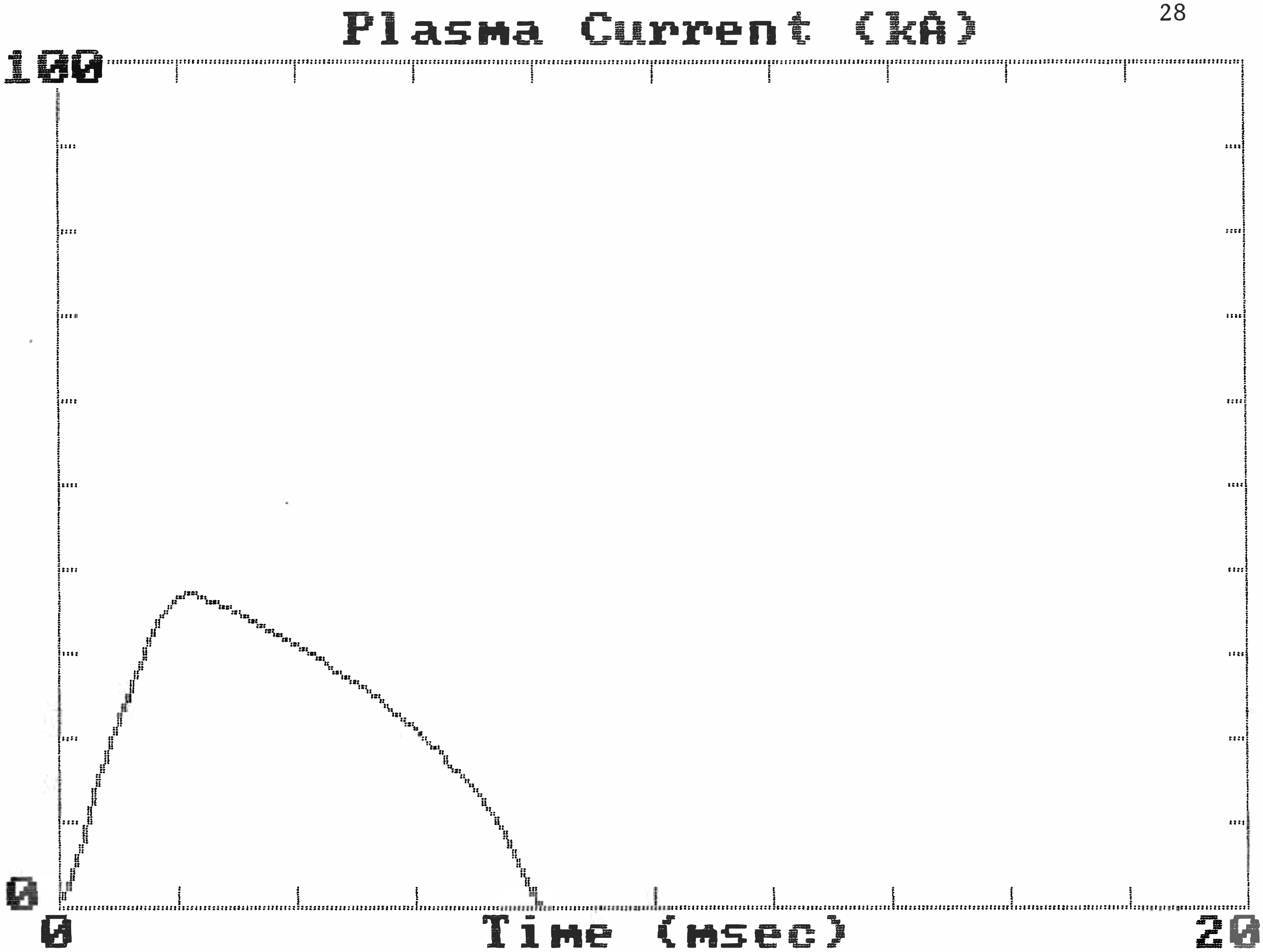

Fig. 12: Plasma current waveform for V_c = 2500 volts and Z = 3 with the proposed new hoops.

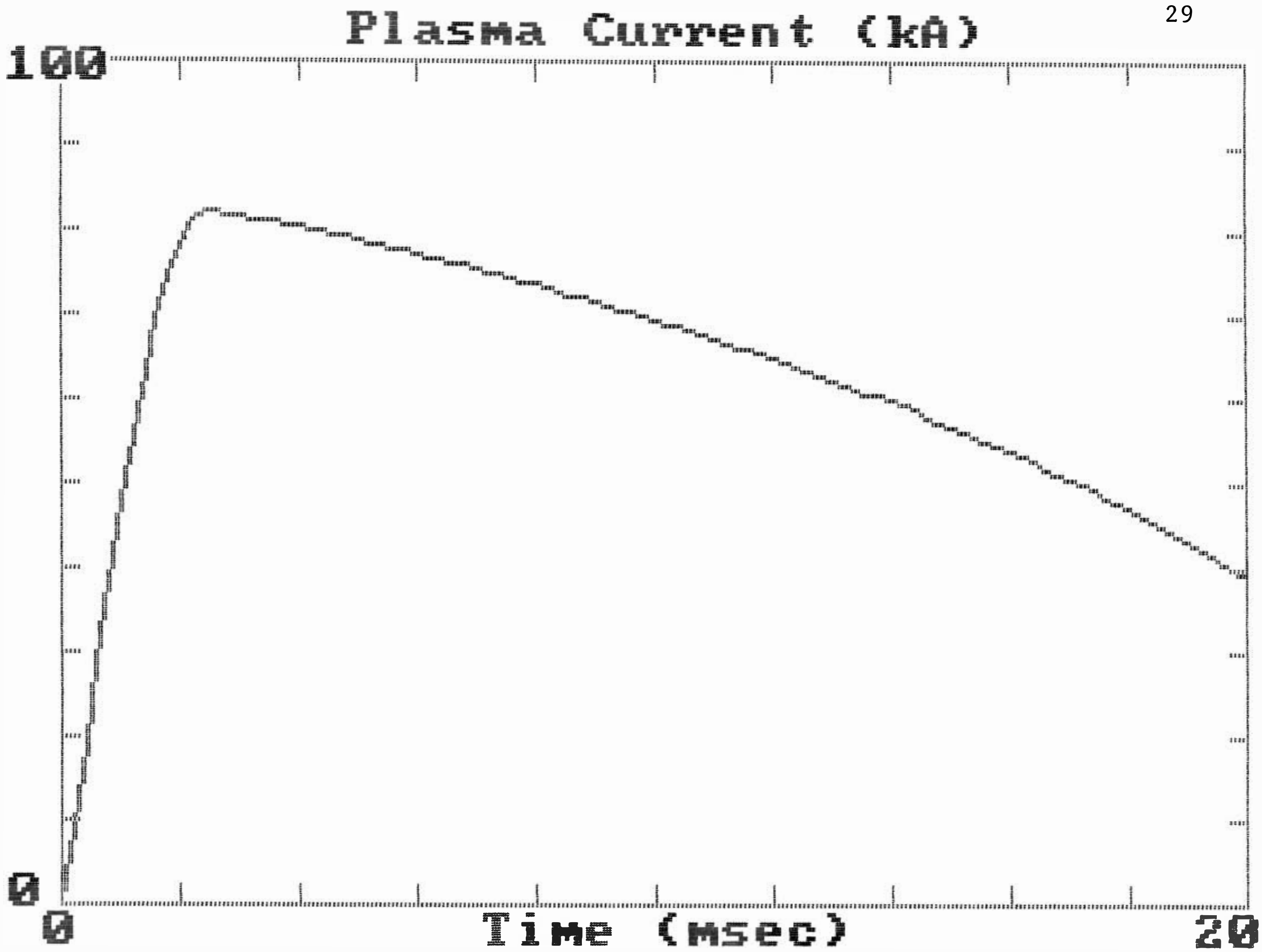

Fig. 13: Plasma current waveform for V_c = 3900 volts (I_{hoop} = 500 kA) and Z = 3 with the proposed new hoops.

provide 880 volts at 0.24 farads, the waveform in Fig. 14 results. Clearly much can be gained by intelligent programming of the gap voltage. The electron temperature T_e scales approximately as $Z^{0.4} I_p^{0.8}$, and thus doubling the plasma current should nearly double the electron temperature for a given Z-effective. All of these cases have assumed a core bias of 1.35 tesla, which is well within the capability of our existing core bias circuit.

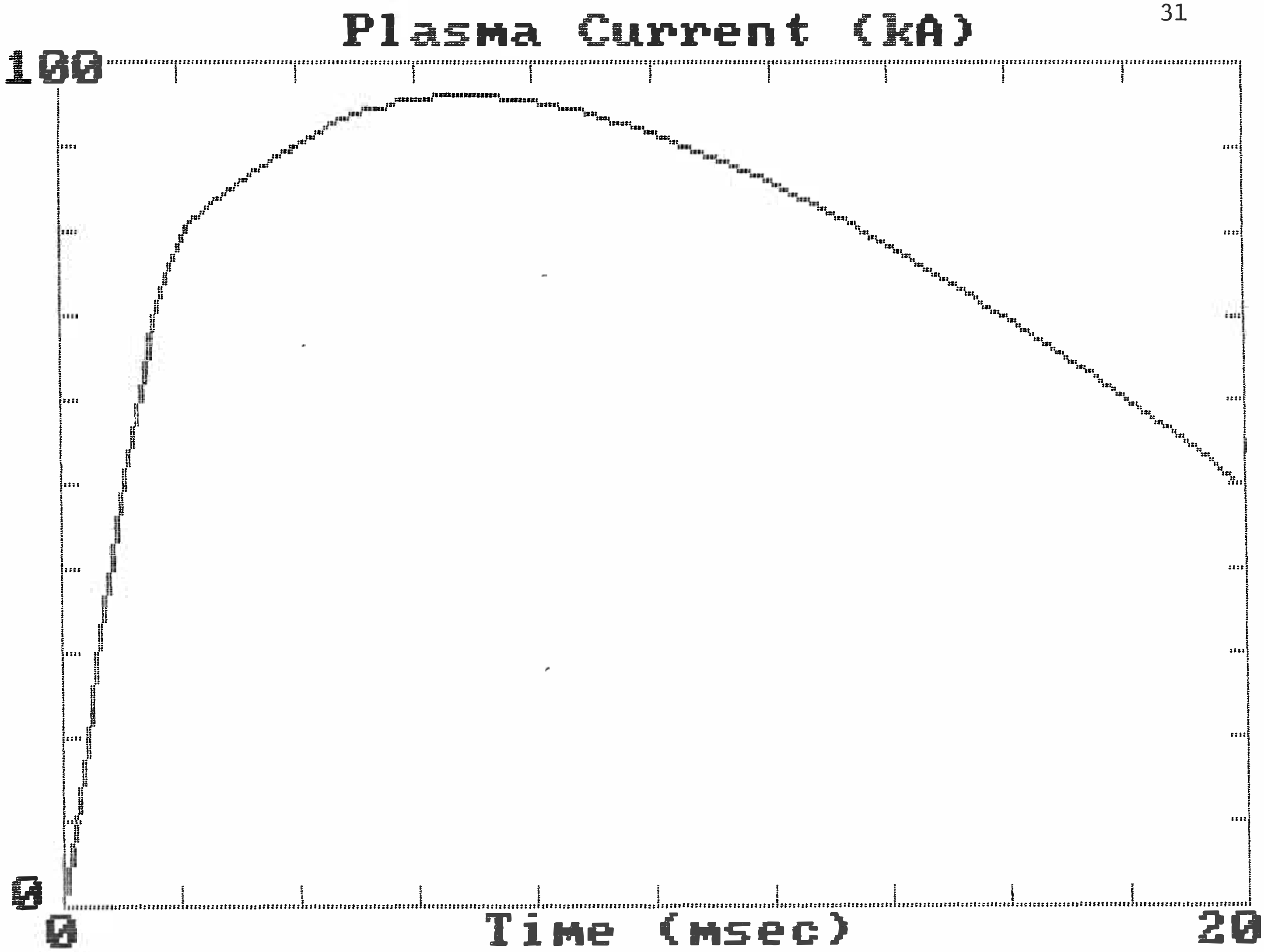

Fig. 14: Plasma current waveform for V_c = 3900 volts (I_{hoop} = 500 kA) and Z = 3 with the power crowbar reconfigured for 0.24 farads/880 volts and the proposed new hoops.