REVISED CALCULATION OF OHMIC HEATING RATE IN THE SMALL OCTUPOLE

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June 1976

PLP 690

Plasma Studies

University of Wisconsin

I. Introduction

In this paper we present a calculation of the ohmic heating rate for the small octupole with the toroidal magnetic field added. The result may be used in the computer program SIMULT (described in PLP's 505, 556 and 607) to predict the time behavior of spatially averaged plasma parameters. The present calculation is a refinement of the one presented in PLP 643. It is recorded here in full detail for posterity.

II. The Calculation

The ohmic power input is given by the sum over all flux tubes of the average of the power input to each flux tube:

$$dP = \mathcal{V}^2/\mathcal{R} \qquad (1)$$

where $\mathcal{V}$ is the voltage drop along a magnetic field line for one trip the short way around the machine and $\mathcal{R}$ is the electrical resistance along the same path.

Resistance $\mathcal{R}$ is $\oint \eta ds/dA$ where η is the local plasma electrical resistivity and ds is the unit length along the path described above and is equal to $Bd\ell/B_p$ where B is the total field strength, B_p is the poloidal field and $d\ell$ is an element of unit length along a projection of a constant flux surface onto the poloidal plane. The area element dA is the cross-sectional area of the flux tube along which we are calculating voltage drop and resistance. It may be written as $dA = d\,\Phi_p/B$ where $d\Phi_p$ is the poloidal flux enclosed by neighboring surfaces of a constant poloidal flux. Thus,

$$\mathcal{R} = \langle\eta\rangle \oint \frac{B^2}{B_p} \quad \frac{d\ell}{d\Phi_p}. \qquad (2)$$

The voltage drop $\mathcal{V}$ receives contributions from the time-changing toroidal and poloidal fluxes:

$$\mathcal{V} = \dot{\Phi}_T + \frac{\Delta\theta}{2\pi}\,\dot{\Phi}_p. \tag{3}$$

(Cf. Lencioni's thesis PLP 276, eq. 15 & 16, p. 44-45.) The angle $\Delta\theta \equiv \oint \frac{B_T d\ell}{R\,B_p}$ is the angular advance in the toroidal direction for a field line progressing once around the machine in the poloidal direction.

Substituting equations 2 and 3 into 1 gives:

$$dP = \frac{\left(\dot{\Phi}_T + \frac{\Delta\theta}{2\pi}\,\dot{\Phi}_p\right)^2}{\langle\eta\rangle \oint \frac{B^2}{B_p}\frac{d\ell}{d\Phi_p}} \tag{4}$$

for the ohmic heating in one flux tube. The total power input is thus:

$$P = \int_{\psi\ \text{Hoop}}^{\psi\ \text{Limiter}} \frac{\left(\dot{\Phi}_T + \frac{\Delta\theta}{2\pi}\,\dot{\Phi}_p\right)^2 d\Phi_p}{\langle\eta\rangle \oint \frac{B^2}{B_p}\,d\ell} \tag{5}$$

The integral in the denominator can be rewritten as:

$$\oint \frac{B^2}{B_p}\,d\ell = \oint \frac{B_T^{\,2}}{B_p}\,d\ell + \oint B_p\,d\ell = B_{TO}R_O \oint \frac{B_T}{R}\,\frac{d\ell}{B_p} + \oint B_p\,d\ell =$$

$$B_{TO}R_O\,\Delta\theta + \mu_o I \tag{6}$$

where R_O is the outer wall major radius, B_{TO} is the value of B_T at R_O, and I is the current in the hoop or hoops enclosed by the path of integration.

The toroidal flux term is $\dot{\Phi}_T \equiv \int \dot{\vec{B}}_T \cdot d\vec{A}$. The area element is a shell between two neighboring surfaces of constant poloidal flux and may be written

$$dA \equiv V' \frac{d\psi}{2\pi R_c} \tag{7}$$

where $V' \equiv dV/d\psi$ and V is the volume inside a surface of constant poloidal flux ψ and R_c is the major radius to the center of the machine. Allowing the only approximation in this calculation (except for the averaging of resistivity η), B_T is set equal to its value at the machine's center, B_{TC}. Then

$$\dot{\Phi}_T \cong \frac{\dot{B}_{TC}}{2\pi R_c} \int \frac{dV}{d\psi}\, d\psi = \frac{\dot{B}_{TC}}{2\pi R_c} V \tag{8}$$

The poloidal flux term is $\dot{\Phi}_p = \frac{\dot{B}_p}{B_p} \psi_{core} \frac{(5+\psi)}{10}$ where the usual small octupole flux-surface labeling convention is followed. This convention is $\psi = -5$ at the hoops and $\psi = +5$ at the walls. Thus also,

$$d\phi_p = \psi_{core} \frac{d\psi}{10} \tag{9}$$

Designating $\langle\eta\rangle$ as the averaged resistivity along a flux tube averaged again over all flux tubes, ohmic heating power becomes

$$P = \frac{1}{\langle\eta\rangle} \int_{\psi_{hoop}}^{\psi_{limiter}} \frac{\left[\frac{\dot{B}_{TC}}{2\pi R_c} V - \frac{\Delta\theta}{2\pi} \frac{\dot{B}_p}{B_p} \psi_{core} \frac{(5+\psi)}{10}\right]^2 \psi_{core}\, d\psi}{[B_{TO} R_O \, \Delta\theta + \mu_o I] \quad 10} \tag{10}$$

The minus sign in the integrand arises from the geometry and sign conventions sketched in Figure 1. The quantities ψ_{core}, B_p and B_T are defined positive in the directions shown. Changing the sign of either B_p or B_T would change the sign of each term of $\mathcal{V}$ leaving the magnitude of $\mathcal{V}$ and P unchanged. Note that the toroidal electric field due to a <u>positive</u> B_p <u>increasing</u> in time is <u>anti-parallel</u> to $\vec{B}_T$ while the poloidal electric field due to a <u>positive</u> B_T <u>increasing</u> in time is in the <u>same direction</u> as $\vec{B}_p$. The voltage drop along a field line, and thus the ohmic heating, is minimized for $\dot{B}_T/B_T$ and $\dot{B}_p/B_p$ with the same sign.

It is convenient to write the integrand as a function of

$$\alpha \doteq \left.\frac{B_{TO}}{B_{po}}\right| \begin{matrix}\text{outer wall} \\ \cap \text{ midplane}\end{matrix} \tag{11}$$

Dividing numerator and denominator by B_{TO}^2, using $B_{TO}R_O = B_{TC}R_C$, and recognizing that I and ψ_{core} are linear with B_{po},

$$P = \frac{B_{TO}B_{PO}}{\langle\eta\rangle\ 10}\ \frac{\Psi_{core}}{B_{PO}} \int_{\psi\text{ hoop}}^{\psi\text{limiter}} \frac{\left[\frac{\dot{B}_{TO}}{B_{TO}}\frac{R_0}{2\pi R_c^{2}} V - \frac{\dot{B}_p}{B_p}\frac{\psi_{core}}{B_{po}}\frac{(5+\psi)}{20\pi}\frac{\Delta\theta}{\alpha}\right]^2 d\psi}{\left[\mu_o \frac{I}{B_{PO}} + R_o\,\alpha^2\ \frac{\Delta\theta}{\alpha}\right]} \qquad (12)$$

III. Numerical Details

From PLP 15, Case I, we find

$\psi_{core} = .3813\ B_{po}$

and $I = 2.995\ B_{po}$

for all four hoops.

The function $V'(\psi) = dV/d\psi$ is graphed by Lencioni in his thesis, PLP 276. An analytic fit (whose form was suggested by Jim Drake) is:

$$V'_p = [-37.45 - 3.75\,\psi + 51.7/\sqrt{\psi_s - \psi}\,] \times 10^{-3}\ m^3/\text{dory}$$

for the four hoop total in the private flux region and

$$V'_c = [1.336 + 1.782\,\psi + 35.52/\sqrt{\psi - \psi_s}\,] \times 10^{-3} m^3/\text{dory}$$

for the common flux region. The value of ψ at the separatrix is $\psi_s = -1.55$. Lencioni's graph and our analytic fit are shown in Figure 2. Straightforward integration gives

$$V_p = [51.756 - 37.45\,\psi - 1.875\,\psi^2 - 103.4\sqrt{\psi_s - \psi}\,] \times 10^{-3} m^3$$

and $V_c = V_p(\psi_s) + (-0.70 + 1.336\,\psi + .891\,\psi^2 + 71.04\sqrt{\psi - \psi_s}) \times 10^{-3} m^3$.

These functions are graphed in Figure 3. To check the volume normalization, the above formulae give

$V_p\ (\psi_s) = .1053\ m^3$ and $V_c\ (\psi_{wall}) = .3160\ m^3$

as compared with $V = .3211\ m^3$ obtained from the machine geometry:

$$V = [L^2 - 2\pi\,(r_i^{\,2} + r_o^{\,2}) - \tfrac{4}{2}\,x^2]\ 2\pi R_c$$

where $L = .356$ m is the length of the tank side, $r_i = 0.22$ m is the inner hoop radius, $r_o = .025$ m is the outer hoop radius and $x^2/2 = (.043)^2/2\ m^2$ is the area of each corner triangle, and $R_c = .43$ m is the major radius to the center of the tank.

The angular transform $\Delta\theta$ in degrees is graphed as a function of ψ by Poukey and Howard in PLP 91 and tabulated by Howard in PLP 106. An analytic fit in the private flux region is

$$\Delta\theta_p/\alpha = -3.101 + 2.41\,\psi + 43/\sqrt{\psi_s - \psi}$$

and in the common flux region

$$\Delta\theta_c/\alpha = 5 \qquad 127.3/\sqrt{\psi-\psi_s}.$$

Both graphs and analytic fits are shown in Figure 4.

The square in the integrand of Eq. 12 may be expanded so that the heating power may be written:

$$P = \frac{\alpha B_{TO} B_{PO}}{\langle\eta\rangle} \frac{\psi_{core}}{10\; B_{PO}} \left[A\left(\frac{\dot{B}_{TO}}{B_{TO}}\right)^2 I_A + C\left(\frac{\dot{B}_P \dot{B}_{TO}}{B_P B_{TO}}\right) I_C + D\left(\frac{\dot{B}_P}{B_P}\right)^2 I_D \right] \qquad (13)$$

where

$$A = \left(\frac{R_o}{R_c}\right)^2 \frac{1}{(2\pi R_c)^2} = \left(\frac{.61}{.43 \times 2\pi \times .43}\right)^2 = .275$$

$$C = \left(\frac{R_O}{R_C}\right) \frac{1}{2\pi^2 R_c\; 10} \frac{\psi_{core}}{B_{PO}} = \frac{.61 \times .3813}{.43 \times 2\pi^2 \times .43 \times 10} = 6.373 \times 10^{-3}$$

$$D = \left(\frac{\psi_{core}}{B_P} \frac{1}{20\pi}\right)^2 = \left(\frac{.3813}{20\;\pi}\right)^2 = 3.683 \times 10^{-5}$$

and

$$I_A = 4 \int_{\psi_H}^{\psi_S} \frac{(V_p/4)^2\, d\psi}{D_p} + \int_{\psi_S}^{\psi_L} \frac{V_C^2}{D_C}\, d\psi$$

$$I_C = 4 \int_{\psi_H}^{\psi_S} \frac{d\psi\, (\Delta\theta}{D_p} \qquad \int_{\psi_S}^{\psi_L} \frac{V_c (\Delta\theta_c/\alpha)(5}{D_C}$$

$$I_D = 4\int_{\psi_H}^{\psi_S} \frac{(\Delta\theta_p/\alpha)^2[(5+\psi)/4]^2\, d\psi}{D_P} + \int_{\psi_S}^{\psi_L} \frac{(\Delta\theta_c/\alpha)^2\,(5+\psi)^2\, d\psi}{D_C}$$

where ψ_H, ψ_S and ψ_L designate the locations in ψ-space of the hoop surface, the separatrix and the limiter, and

$$D_P = \mu_o I/4 + R_O \alpha^2 \Delta\theta_p/\alpha = .7487 + .61\,\alpha^2\,\Delta\theta_p/\alpha$$

$$D_C = \mu_o I + R_O\,\alpha^2 \Delta\theta_c/\alpha = 2.995 + .61\,\alpha^2 \Delta\theta_c/\alpha .$$

The integrals I_A, I_C and I_D are done numerically. Functions of the form $K_1/(K_2+\alpha^2)$ fit these integrals extremely well. Combining the numerical coefficients of the integrals with the numerical coefficients of Equation 13 gives the final result for ohmic heating power density.

$$\frac{P}{\text{Vol.}} = \frac{\alpha B_{TO}B_{PO}10^{-3}}{\langle\eta\rangle}\left[\frac{C_1}{(C_2+\alpha^2)}\left(\frac{\dot{B}_{TO}}{B_{TO}}\right)^2 - \frac{C_3}{(C_4+\alpha^2)}\left(\frac{\dot{B}_{TO}\dot{B}_{PO}}{B_{TO}B_{PO}}\right) + \frac{C_5}{(C_6+\alpha^2)}\left(\frac{\dot{B}_{PO}}{B_{PO}}\right)^2\right] \qquad (14)$$

all in MKS units where the volume is taken to be $V(\psi_L)$. The constants C_i, i = 1 - 6, are tabulated in Table I for four values of ψ_L. The upper table is for α defined as B_{TO}/B_{PO}. The lower table is for α defined as B_{PO}/B_{TO}. The same formula for power density (Eq. 14) holds for either definition of α provided the correct coefficients C_i are used in each case.

This result differs slightly from the result of PLP 643 in both magnitude and α dependence. For typical conditions ($\alpha \approx 1$), the present result predicts a slightly smaller ohmic heating.

IV. Analysis of the Result

It is now interesting to calculate the ohmic heating power as a function of time for the existing experiment (see PLP's 623 and 674 for description of experiment).

The heating rate is a function of time because B_{PO}, B_{TO} and α are different functions of time.

The plasma quantities such as density n_e, electron temperature T_e and degree of ionization affect the ohmic heating rate because they affect the resistivity. The resistivity on axis has been found experimentally to be the sum

$$\eta = \eta_{sp} + \eta_L + \eta_n$$

where η_{sp} is the classical resistivity for z = 1 calculated by Spitzer:

$$\eta_{sp} = 5.21 \times 10^{-5}\ z\ \ell n\ \Lambda/T_e^{3/2} \quad \Omega - m$$

where $\ell n \Lambda \cong 13$ is the Coulomb logarythm for our usual plasma parameters and η_L is the resistivity measured at low densities by both Lencioni (see his thesis, PLP 276) and us (PLP 674):

$$\eta_L = 2.5 \times 10^7 \ \sqrt{T_e}/n_e \quad \Omega - m$$

and η_n is the resistivity due to electron collisions with neutral hydrogen:

$$\eta_n = .6 \times 10^{-5}\ n_H/n_e \quad \Omega - m.$$

For a nearly ionized plasma ($n_H << n_e$), η_n may be neglected.

Ohmic heating power as a function of time was calculated from Eq. 14 for moderate B_P and B_T capacitor bank voltages and the easily attainable density $n_e = 8 \times 10^{11}/cm^3$ for several values of electron temperature T_e. For simplicity, n_e and T_e were assumed constant in time. The results are graphed in Figure 5. The highest heating rate is attained for that value of T_e which minimizes resistivity for the given value of n_e. As the graph in Figure 7a shows, η is a minimum for $n_e \cong 10^{12}/cm^3$ when $T_e = 10$ eV. A higher plasma density would allow η to be minimized and hence heating power to be maximized at a higher value of T_e.

Note that the heating rate drops by roughly a factor of 100 during the experiment. This decline is due to the relative time scales and magnitudes of B_{TO} and B_{PO}. In Figures 6 - 11 the time behavior of ohmic heating power is explored through the existing available ranges of B_P and B_T for the typical plasma parameters

$n_e = 8 \times 10^{11}/cm^3$ and $T_e = 10$ eV. Because B_T has a period about three times shorter than B_p in our usual experiment, the $\dot{B}_T^2$ term dominates heating during the B_T rise time. Thus, the initial heating rate varies approximately as B_T^2, as shown in Figure 6. But changing B_T makes scant difference during the latter part of the experiment where heating is due to the small $\dot{B}_p^2$ term. Figure 7 shows the contribution from each term in Eq. 14 for a large B_T and moderate B_P. The heating rate begins high but drops very fast. After B_T peaks, the $\dot{B}_p\dot{B}_T$ cross term becomes negative and nearly cancels the contributions of the positive terms near the end of the experiment.

In Figure 8 the effect of varying B_P is displayed. Since the $\dot{B}_T^2$ term contributes most of the early power, the initial rate is hardly affected by changing B_P. But increasing B_P allows power to fall less sharply with time. Time behavior of the three terms for high B_P and moderate B_T is graphed in Figure 9.

As shown in Figure 10, the highest heating rates result from the largest possible B_P and B_T both. For equal capacitor voltages on each bank, power increases as the square of the fields. Figure 11 shows that in this case also the $\dot{B}_T^2$ term is initially very large. The $\dot{B}_P^2$ term is smaller than the initial heating rate, but dominates when B_T is peaking. Near the end of the experiment, the negative cross term unfortunately nearly cancels the positive contributions.

With the ability to calculate ohmic heating rates in the small octupole, we may investigate possible modifications of the experiment to try to increase magnitude and/or duration of ohmic power input to the plasma. The obvious variables besides magnitudes discussed above are relative timing and pulse lengths. A full study is left for the future, but Figures 12 and 13 show the effect of crowbarring B_T at its peak to give an e-folding decay time of 5 ms. Figure 12 compares heating power with and without crowbarring. After the fast drop of the initial high rate, the power is held between 55 and 100 kW for almost 2 ms by crowbarring B_T. The increased power is achieved by making the $\dot{B}_T\dot{B}_P$ cross term negligible after the B_T peak so that the full effect of the $\dot{B}_P^{\,2}$ term can be realized. This is shown in Figure 13.

Other ways to increase the ohmic heating input power and duration no doubt exist within the capabilities of the present experiment or with moderate modifications. Using the analytical form of Eq. 14 for input power will enable us to investigate various possibilities. Their effect on the experiment, however, also depends on the heat loss terms which are not yet fully understood.

V. Using the Result in SIMULT

The formula for ohmic heating input power (Eq. 14 with $\psi_L = 1$) was included in subroutine OHMIC which program SIMULT calls whenever there is a toroidal field. The program was run with the same parameters as those in PLP 643: $B_{T_{MAX}}$ on axis = 1.25 kG (2.0 kV on B_T bank), B_{PO} = 0.88 kG (2.0 kV on B_P bank), p = 1×10^{-5} torr (gauge), Z_{eff} = 1 with 1 kW of 2.45 GHz microwaves turned off and B_T turned on at 3.5 msec into the 5 msec poloidal field pulse. Since PLP 643, SIMULT has been refined in a number of other areas, the most significant of which are:

1) A more realistic time and density dependent microwave heating rate has been added.

2) The neutral reflux term has been modified to include ion impact desorption.

3) Losses due to the finite ion gyroradius have been included.

4) The classical diffusion term has been refined.

The results along with a current listing of SIMULT are included in the appendix. Note that the maximum density is 8.1×10^{11} cm^{-3} (vs 7.4×10^{11} cm^{-3} in PLP 643), the maximum electron temperature is 75 eV (vs 100 eV in PLP 643). The density is in reasonable agreement with the experiment (note that the plasma is 96% burned out), but the temperature is still higher than what is measured in the experiment (10 - 20 eV). The discrepancy may be due to a number of factors that we intend to investigate:

1) The resistivity measured on axis may not be typical of field lines well off the separatrix.

2) Impurity radiation may carry out much of the electron energy.

3) There may be additional particle or energy losses resulting from instabilities or waves, in the presence of the ohmic heating.

Table I. Coefficients for the Ohmic Heating Power Formula for the Small Octupole.

$\alpha \equiv [B_{To}/B_{po}|_{\text{outer wall} \cap \text{midplane}}$

ψ_L	c_1	c_2	c_3	c_4	c_5	c_6
1.0	2.40	1.69	4.13	1.51	1.99	1.04
2.0	3.89	1.88	6.18	1.72	2.69	1.26
3.0	5.49	1.99	8.58	1.86	3.56	1.44
5.0	8.51	2.01	13.9	1.94	5.85	1.68

$\alpha \equiv [B_{po}/B_{To}|_{\text{outer wall} \cap \text{midplane}}$

ψ_L	c_1	c_2	c_3	c_4	c_5	c_6
1.0	1.42	.591	2.74	.663	1.92	.962
2.0	2.06	.533	3.60	.583	2.14	.794
3.0	2.76	.503	4.62	.539	2.47	.693
5.0	4.24	.498	7.18	.516	3.48	.595

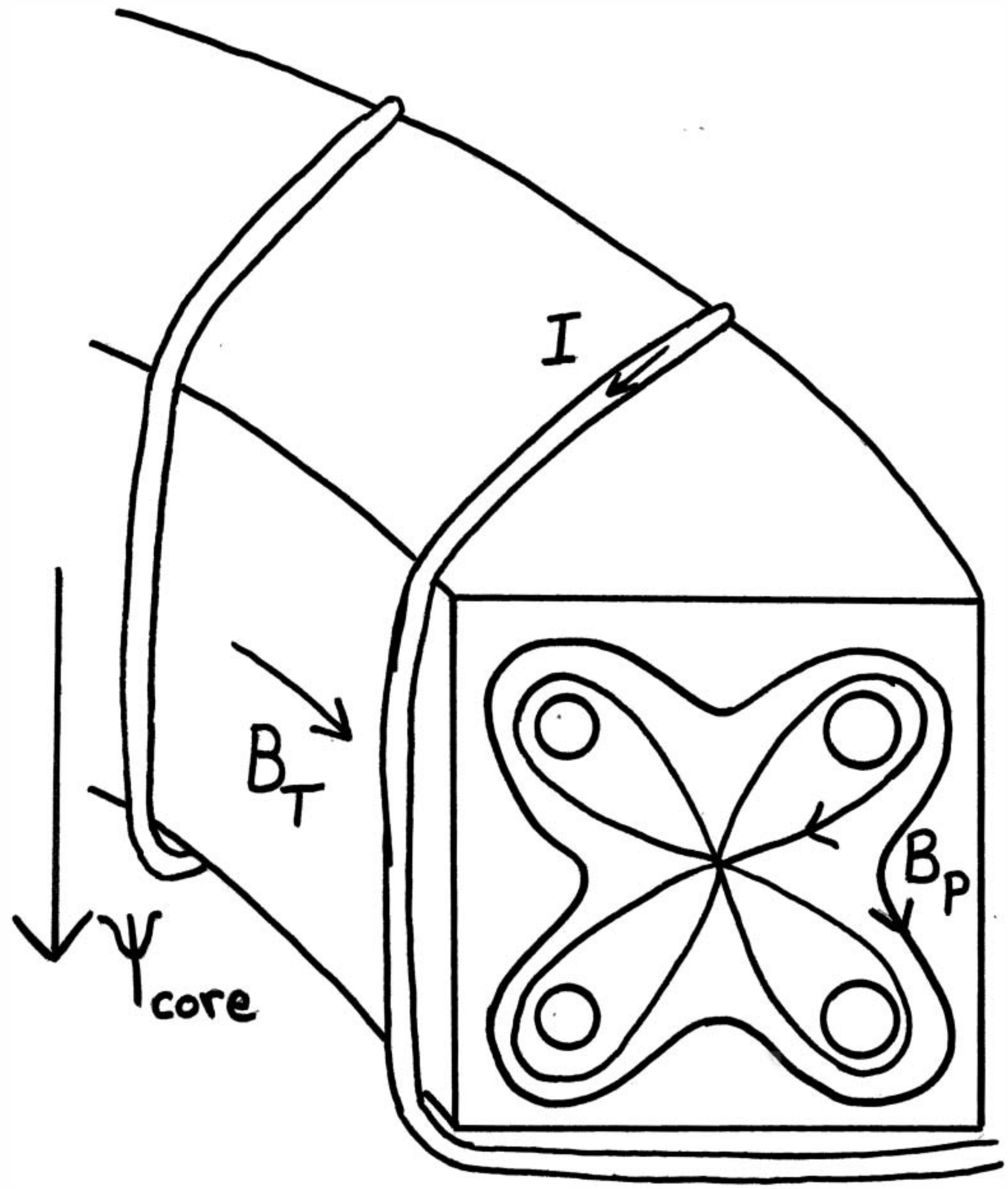

Figure 1. Magnetic Field Geometry and Sign Conventions.

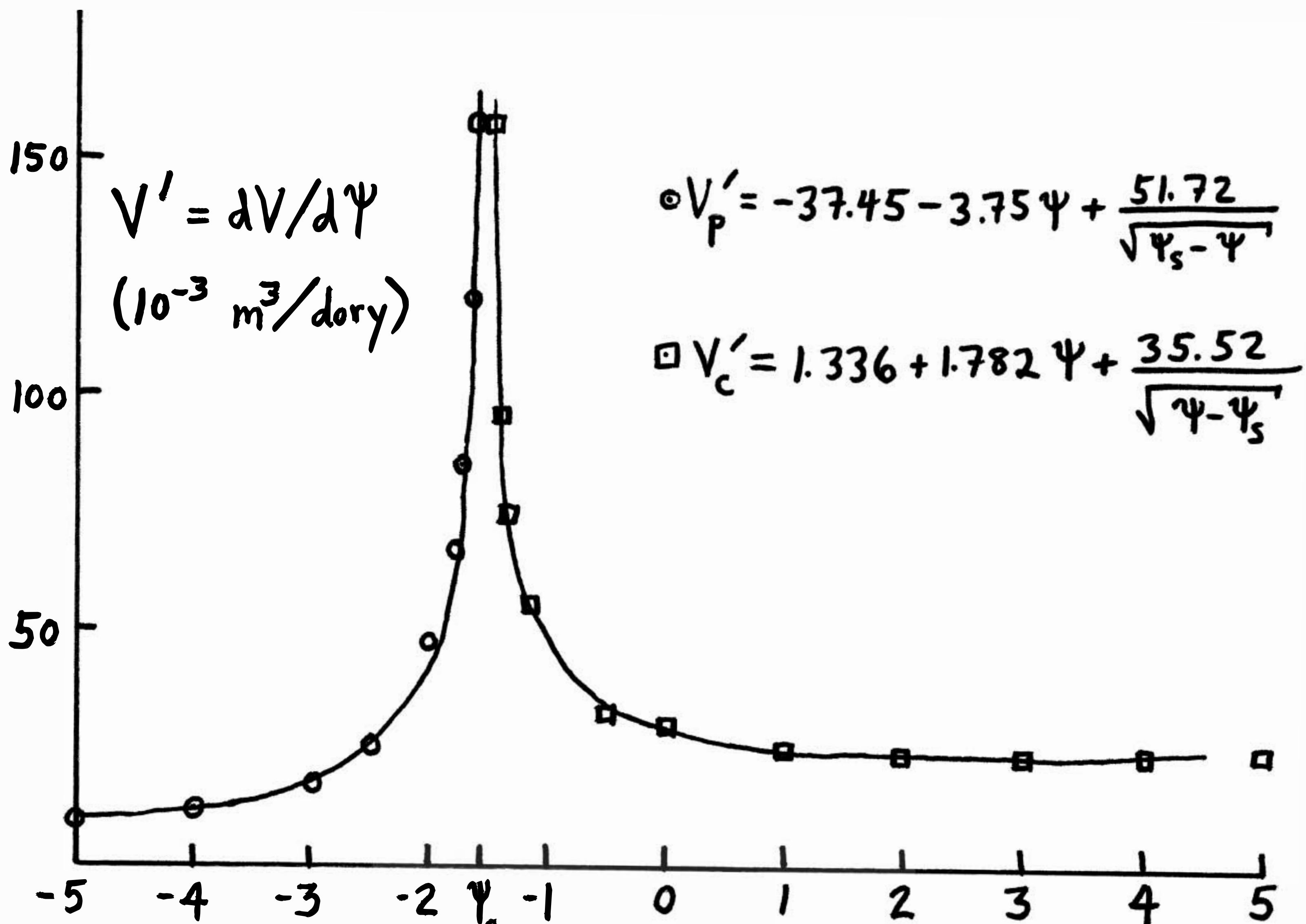

Figure 2. $V'(\Psi)$

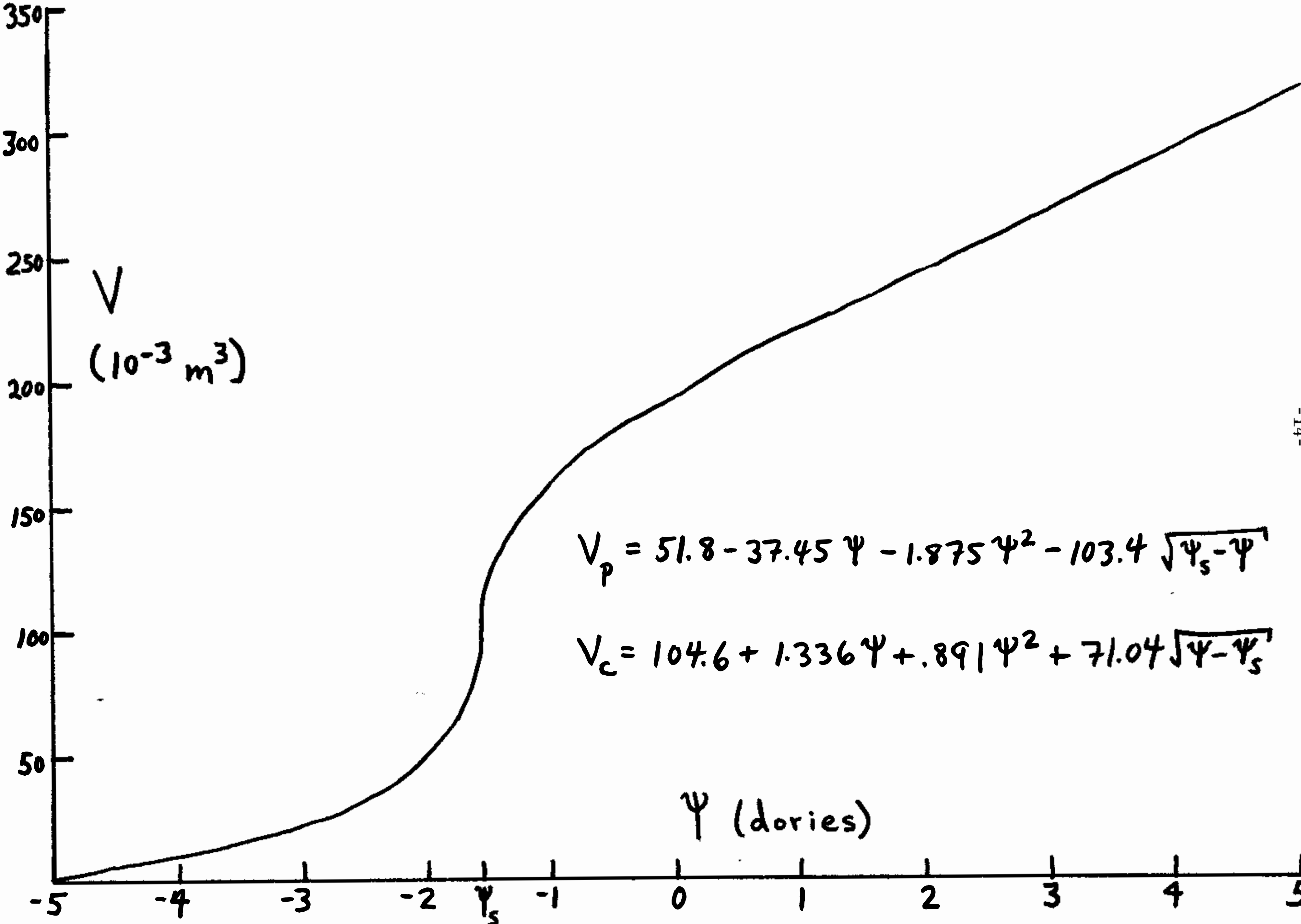
V
(10^-3 m^3)
350
300
250
200
150
100
50
$V_p = 51.8 - 37.45\,\Psi - 1.875\,\Psi^2 - 103.4\sqrt{\Psi_s - \Psi}$
$V_c = 104.6 + 1.336\,\Psi + .891\,\Psi^2 + 71.04\sqrt{\Psi - \Psi_s}$
Ψ (dories)
-5
-4
-3
-2
Ψ_s
-1
0
1
2
3
4
5

Figure 3. V(Ψ)

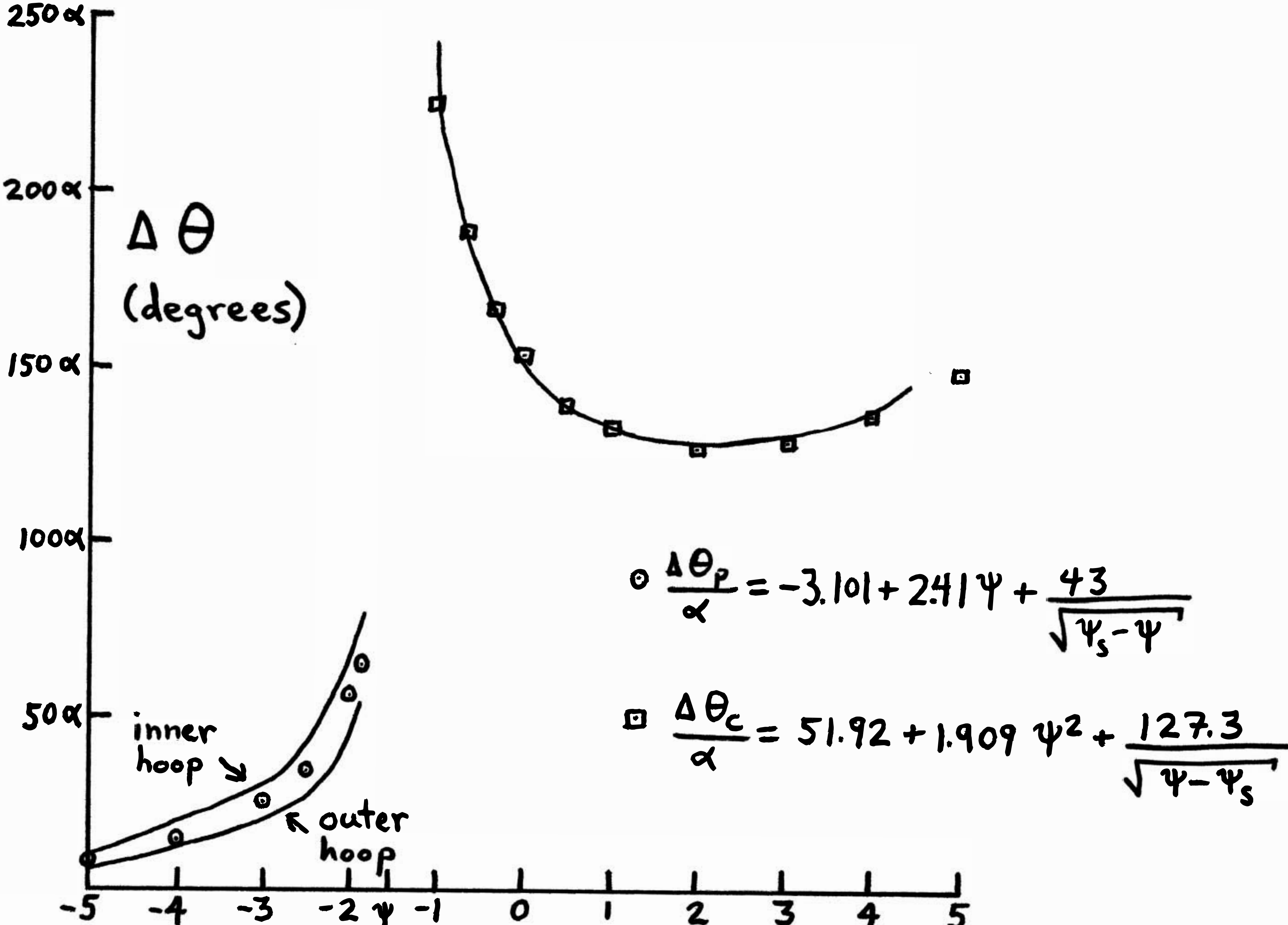

Figure 4. $\Delta\Theta(\psi)$ ψ (dories)

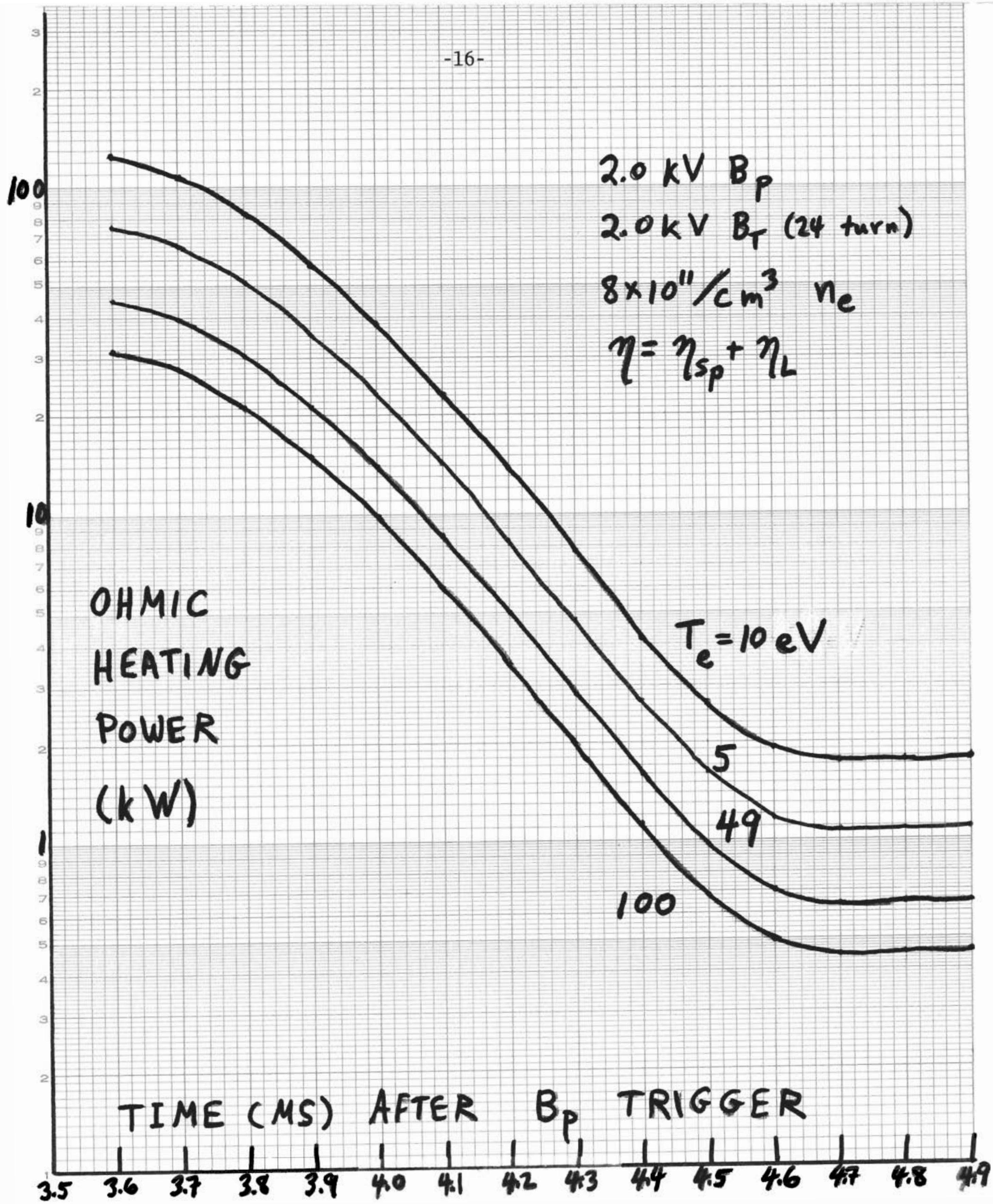

Figure 5. OHMIC HEATING POWER VERSUS TIME FOR VARIOUS T_e CORRESPONDING TO VARIOUS $\overline{\langle\eta\rangle}$.

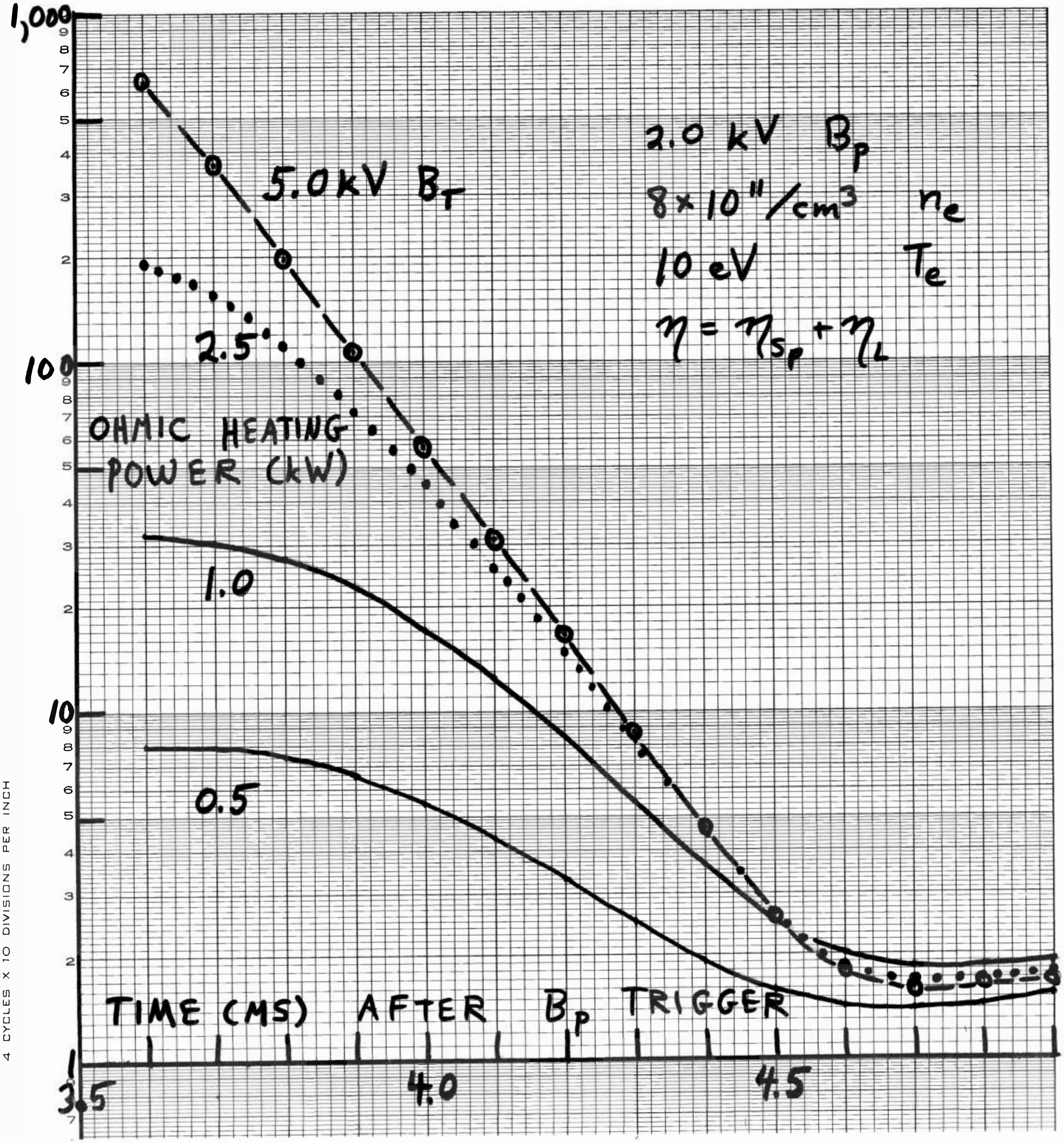

Figure 6. OHMIC HEATING POWER VERSUS TIME FOR VARIOUS B_T

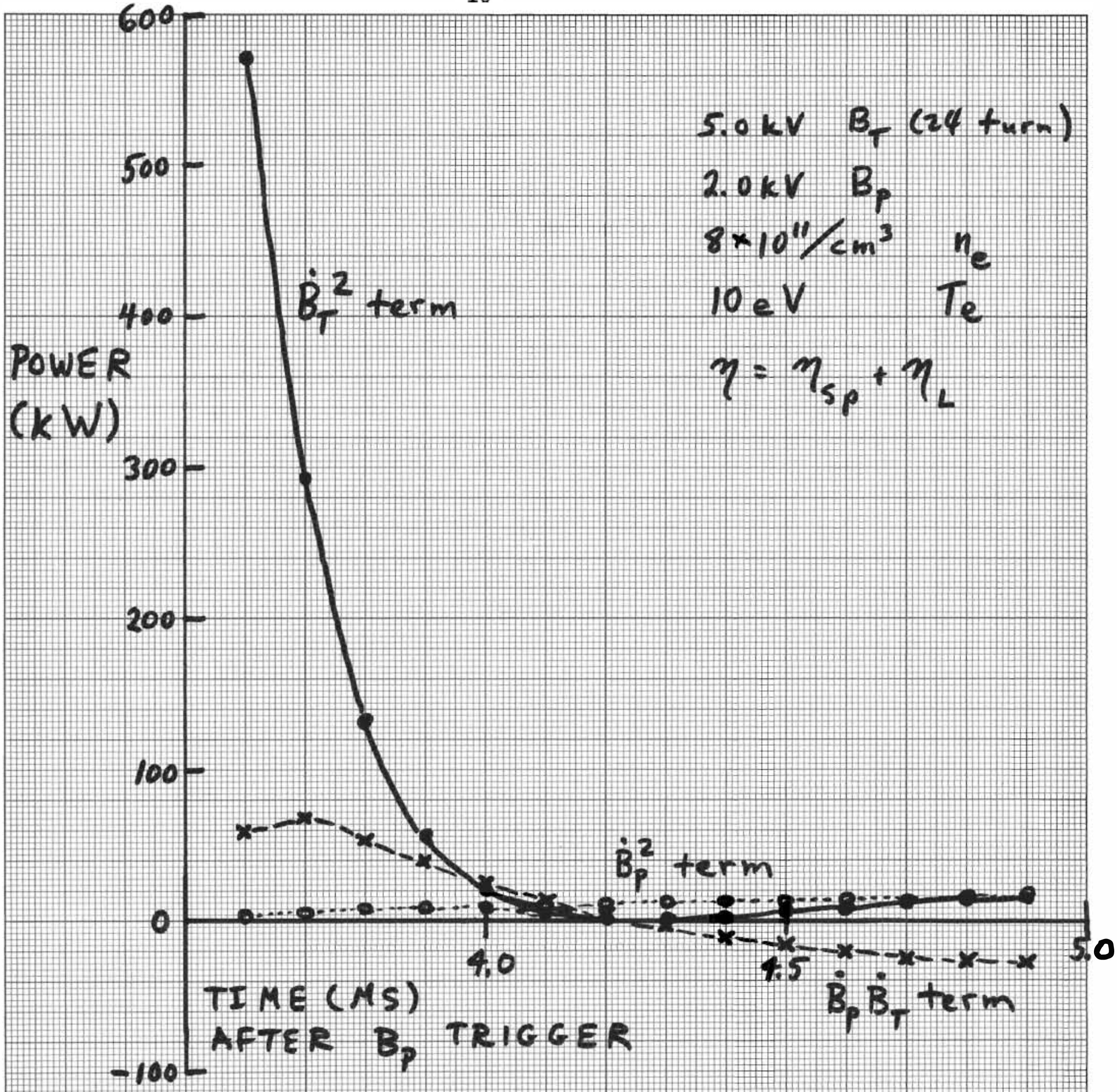

Figure 7. THE THREE CONTRIBUTIONS TO OHMIC HEATING POWER VERSUS TIME FOR LARGE B_T AND MODERATE B_p.

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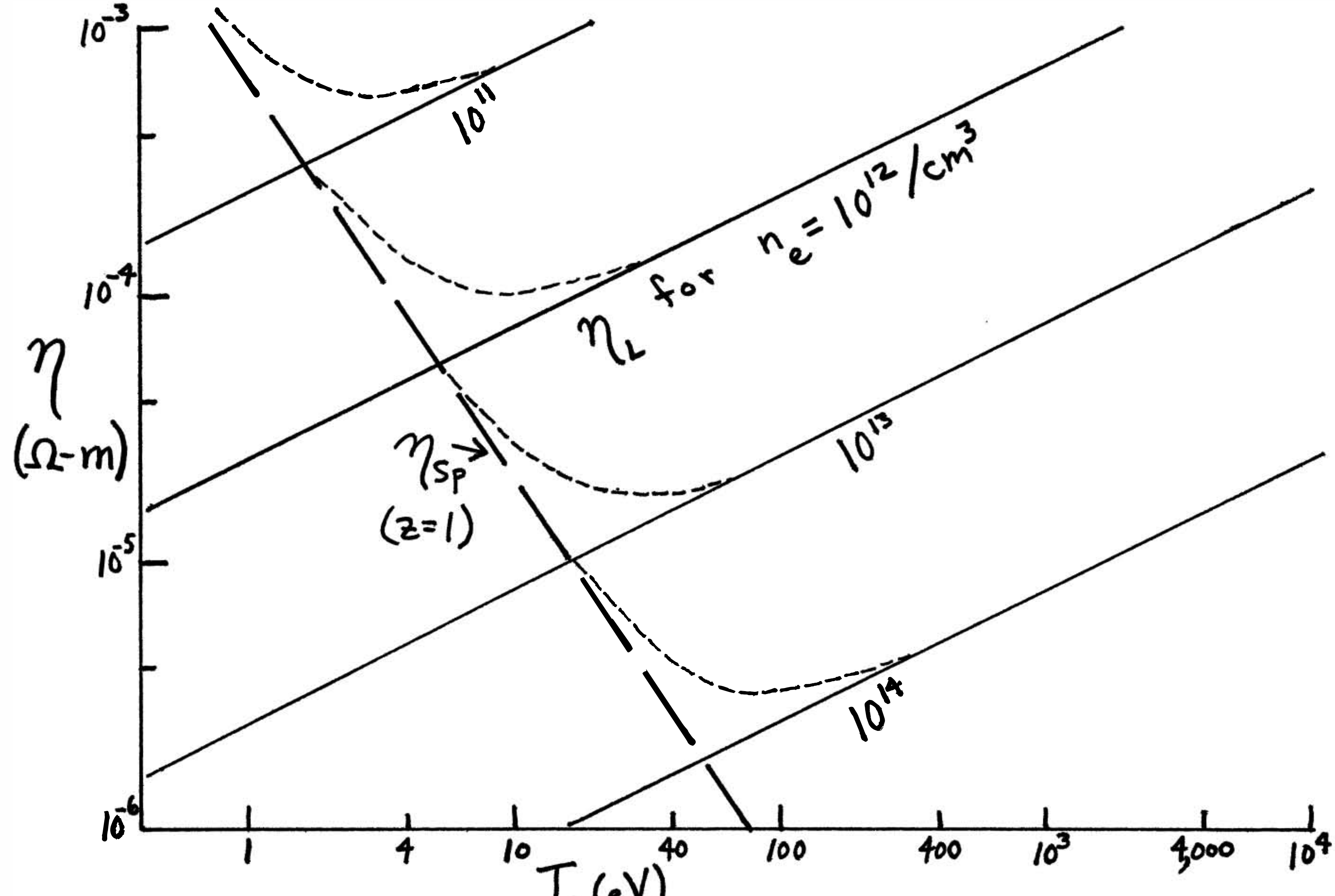

Figure 7a. Resistivity η as a function of T_e for several values of n_e.

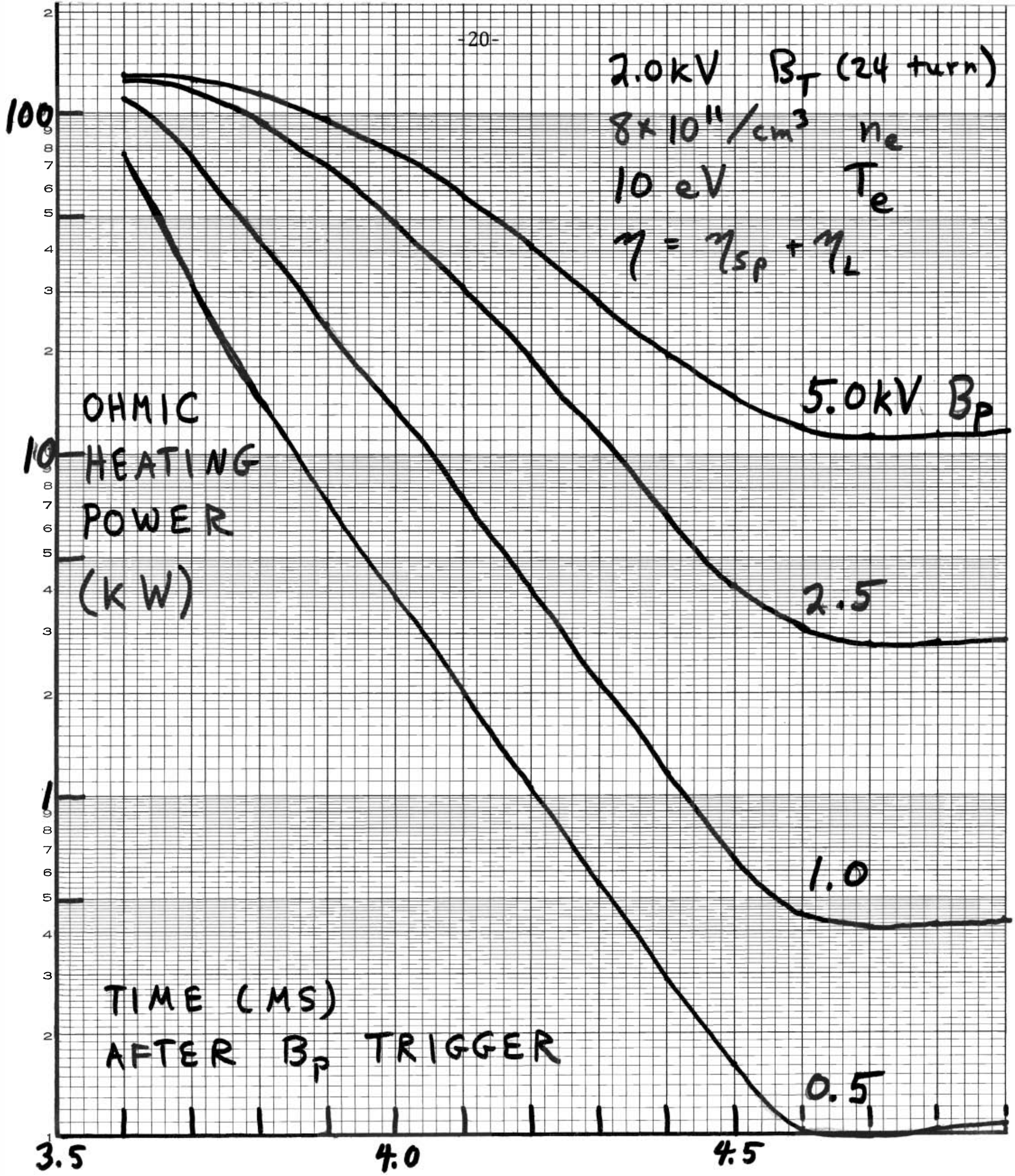

Figure 8. OHMIC HEATING POWER VERSUS TIME FOR VARIOUS B_p

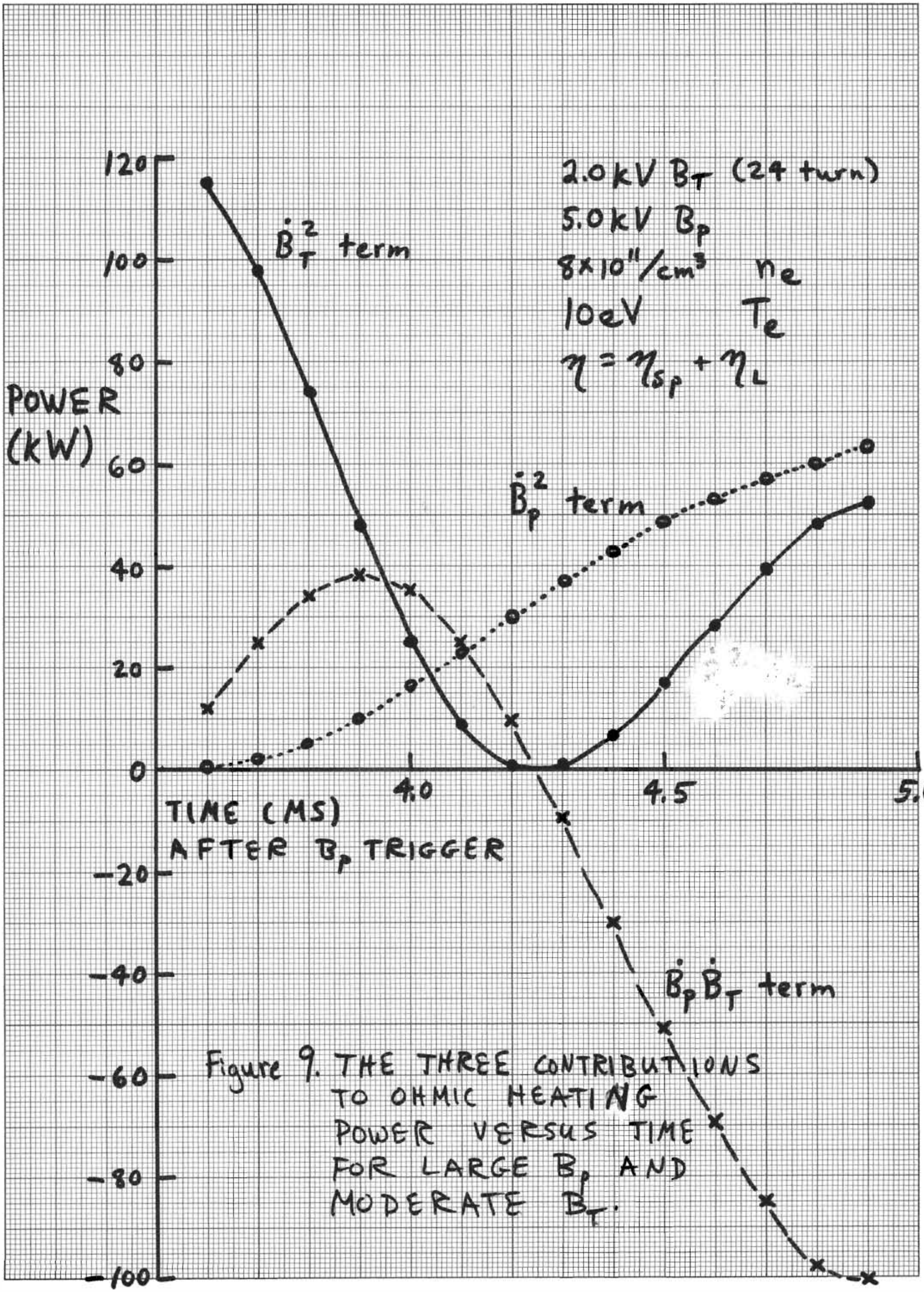

Figure 9. THE THREE CONTRIBUTIONS TO OHMIC HEATING POWER VERSUS TIME FOR LARGE $\dot{B}_p$ AND MODERATE $\dot{B}_T$.

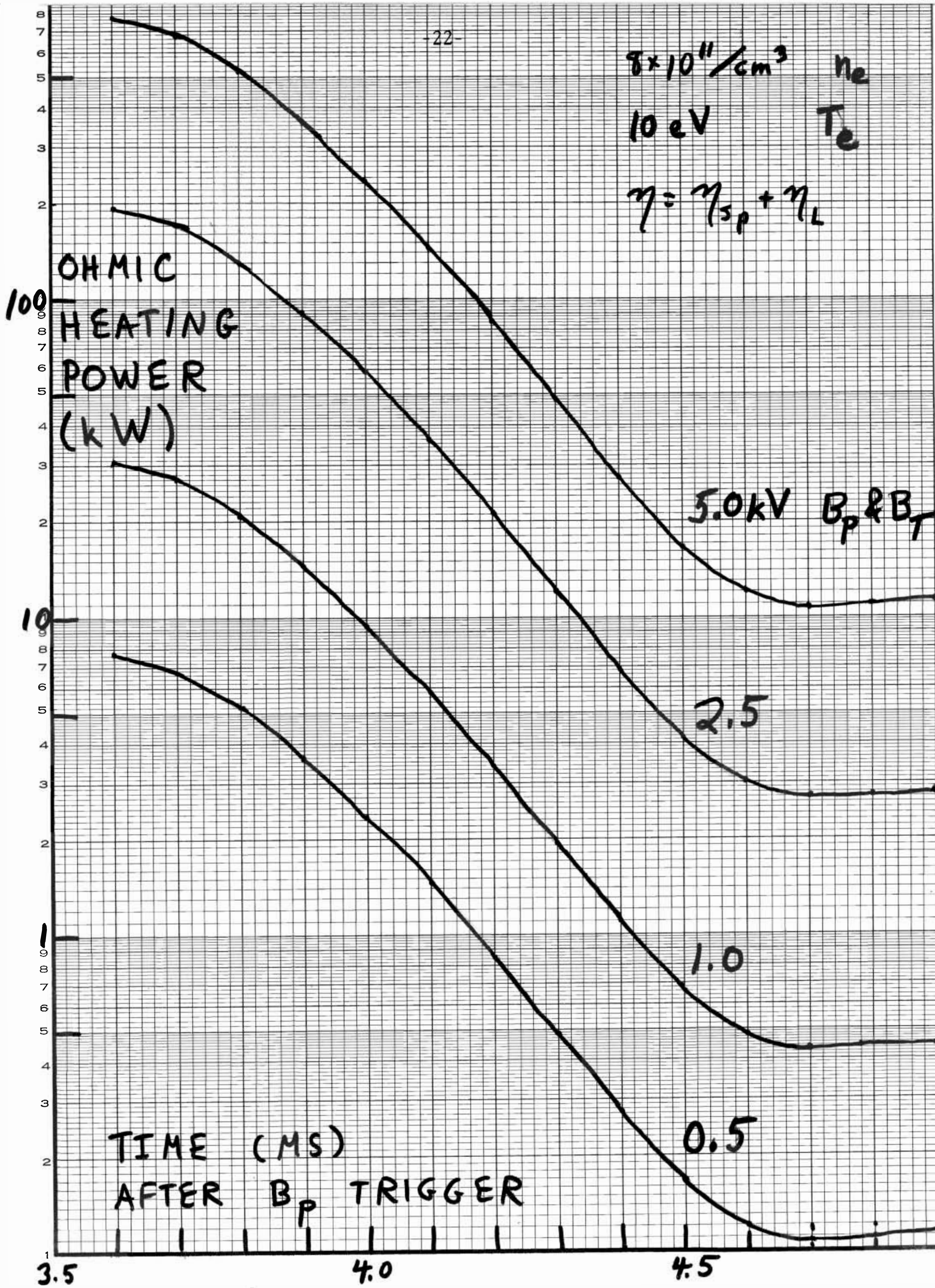

Figure 10. OHMIC HEATING POWER VERSUS TIME FOR VARIOUS B_P AND B_T BUT SAME RATIO OF PEAK VALUES

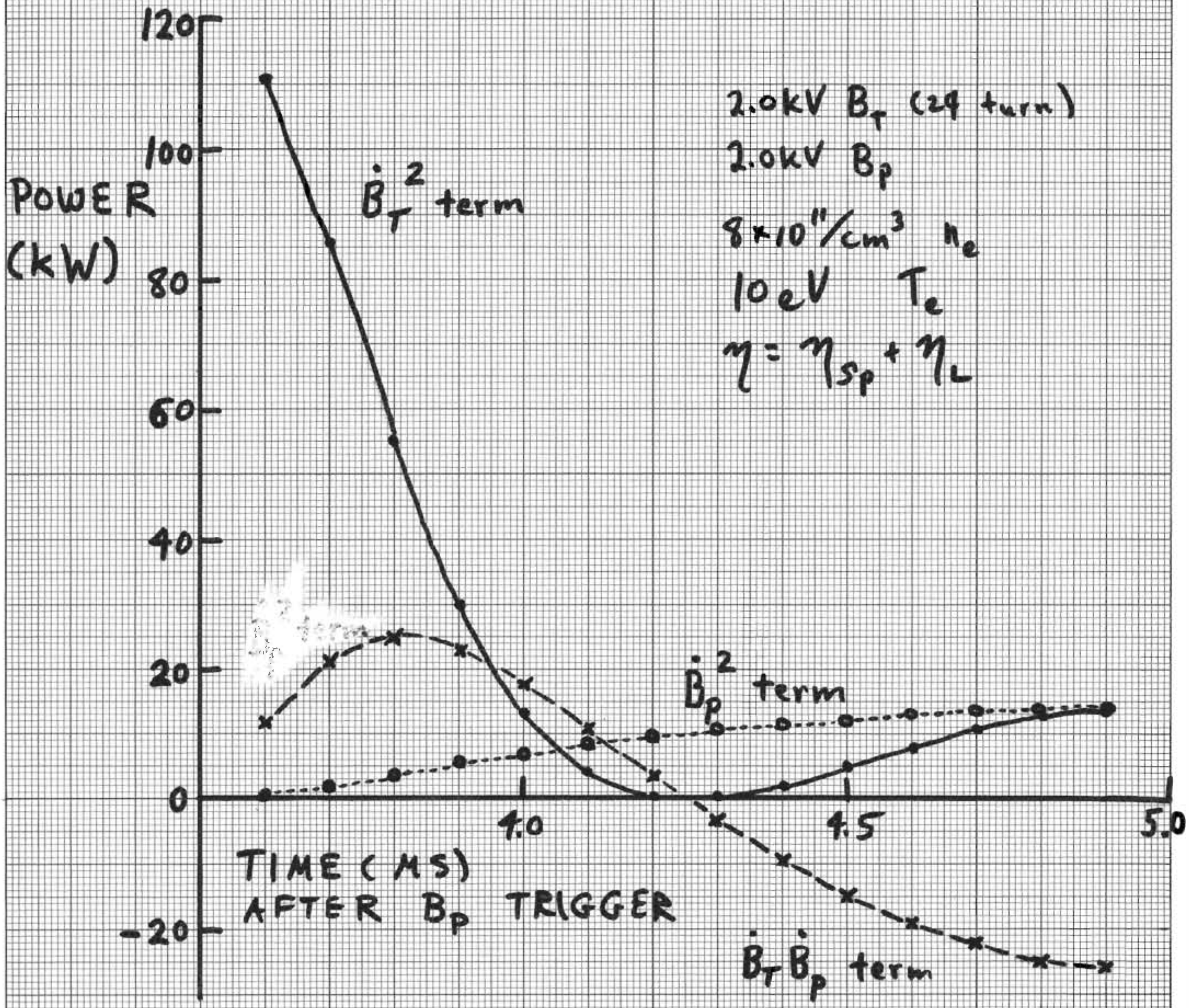

Figure 11. THE THREE CONTRIBUTIONS TO OHMIC HEATING POWER VERSUS TIME FOR SAME CHARGE OF B_T AND B_p CAPACITOR BANKS.

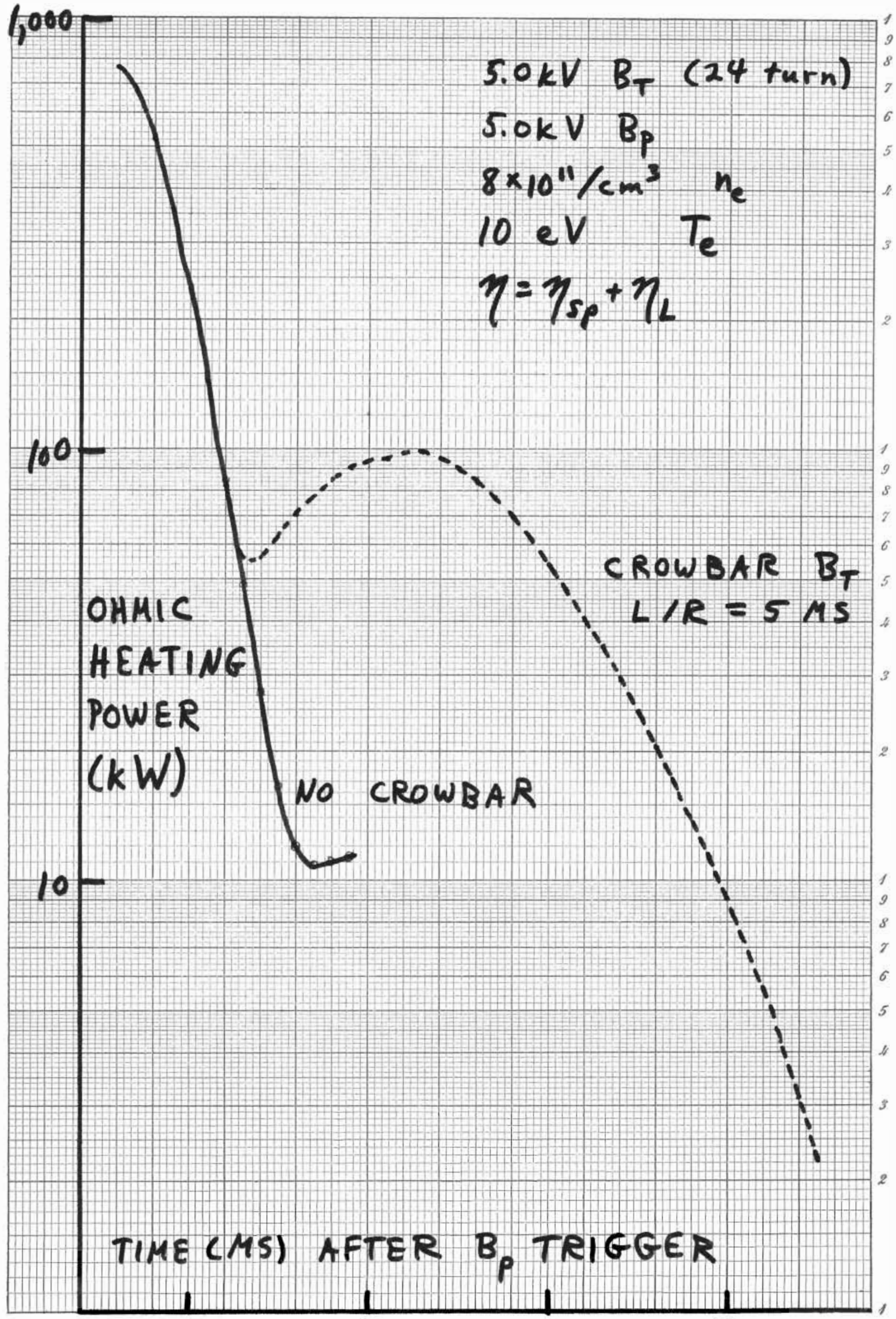

Figure 12. OHMIC HEATING POWER VERSUS TIME FOR CROWBARRED AND UNCROWBARRED B_T.

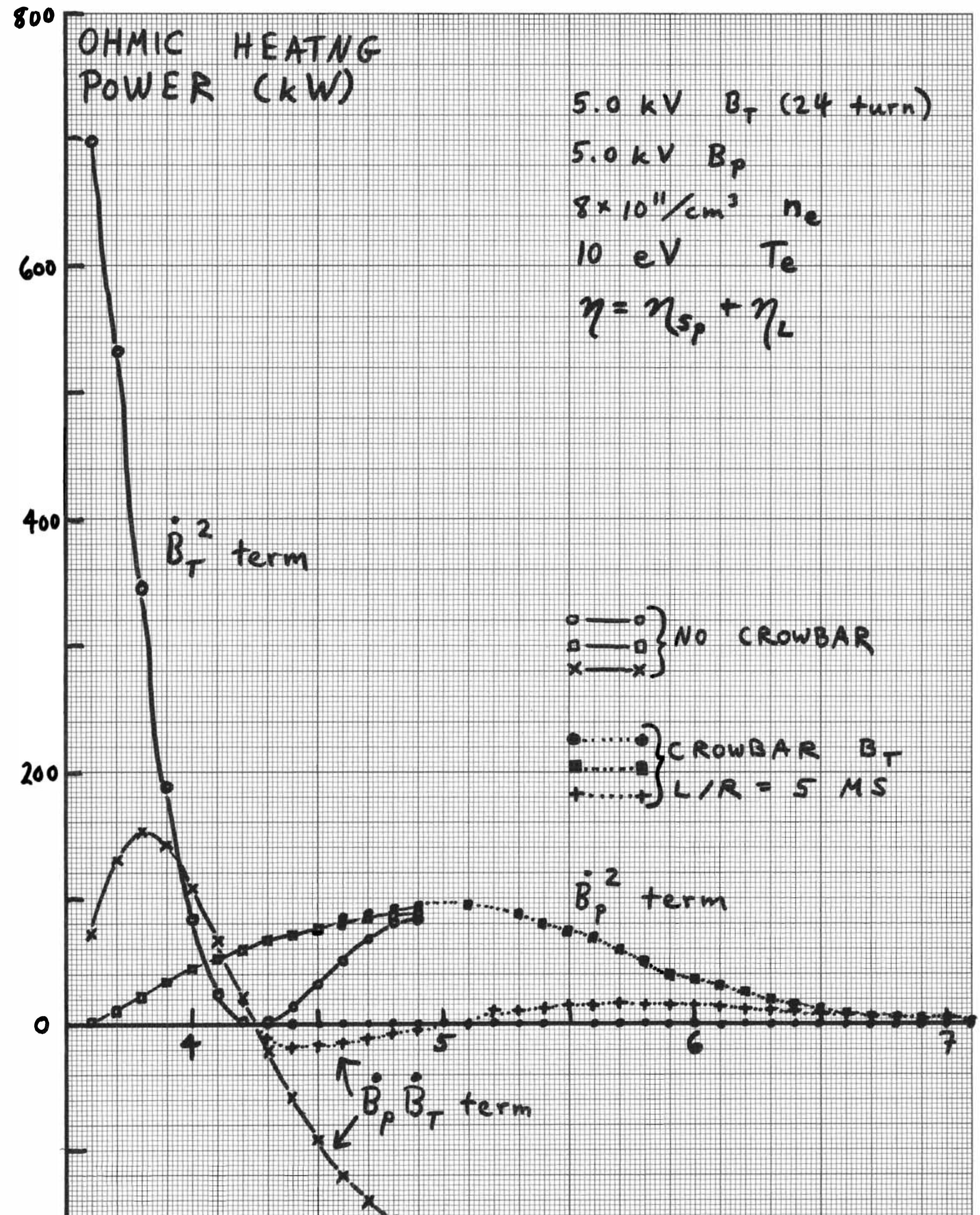

Figure 13. THE THREE CONTRIBUTIONS TO OHMIC HEATING POWER VERSUS TIME FOR CROWBARRED AND UNCROWBARRED B_T

APPENDIX: SIMULT PROGRAM AND RESULTS

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* * * UNIVAC 1110 TIME/SHARING EXEC --- MULTI-PROCESSOR SYSTEM --- VER. MACC 31.6
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)TT,2980,4126810219.2M
,SIMULT
ACC 1.17S-06/08/76-14:43:19                    SIMULT
      C      PROGRAM SIMULT  -  J.C. SPROTT  -  JAN 25, 1973
             EXTERNAL OHMIC,HTCRH,HECRH
             DIMENSION T(101),DE(101),TE(101),TI(101)
             DIMENSION DN(101),BP(101),PP(101),SJ(101)
             DIMENSION SD(5),STE(6),STI(4),D(5),PE(6),PI(4)
      C                      DEFINE FUNCTIONS  -  OCTUPOLE
      C      D1 IS DN/DT DUE TO IONIZATION
             D1(DENS,DNEUT,TE)=371.0*DENS*DNEUT*SQRT(TE)*EXP(-15.6/TE)*(TE/(20.
            20*TE+15.6)+ALOG(1.5625+0.1*TE))/(TE+15.6)
      C      D2 IS DN/DT DUE TO DIFFUSION
             D2(DENS,TE)=DENS*(DENS/SQRT(TE)+0.026*DNEUT*TE)/B/B/A/A
      C      D3 IS DN/DT DUE TO OBSTACLE LOSSES
             D3(DENS,TE)=2.0E5*DENS*AO*SQRT(TE+TIA)/A/A/AL
      C      D4 IS DN/DT DUE TO FIELD DECAY
             D4(DENS)=0.5*DENS*AMAX1(0.0,BOLD-B)/BOLD/DT
      C      D5 IS DN/DT DUE TO FINITE ION GYRORADIUS
             D5(DENS,TI)=1300.0*DENS**2/TI**1.5/EXP(AMIN1(2.4*A*A*B*B/TI,88.0))
      C      PE1 IS DUE/DT DUE TO MICROWAVES
             PE1(P)=2.0E9*P*G*DEA/(G*DEA+12.35*P*F/Q)/A/A/AL
      C      PE2 IS DUE/DT DUE TO ION COLLISIONS
             PE2(DENS,TE,TI)=2.3*DENS**2*(TE-TI)*ALOG(5.2E11*TE**3/ABS(DENS)
            2/(40.0+TE))/TE**1.5
      C      PE3 IS DUE/DT DUE TO EXCITATION
             PE3(DENS,DNEUT,TE)=29.1*D1(DENS,DNEUT,TE)*EXP(6.98/(TE+0.1))
      C      PE4 IS DUE/DT DUE TO BREMSSTRAHLUNG
             PE4(DENS,TE)=1.0E-4*DENS*DENS*SQRT(TE)
      C      PE5 IS DUE/DT DUE TO SYNCHROTRON RADIATION
             PE5(DENS,TE)=3.87E-3*DENS*B*B*TE*(1.0+TE/2.04E5)
      C      PE6 IS DUE/DT DUE TO THERMAL CONDUCTION
             PE6(DENS,TE)=(2.5*D2(DENS,TE)+2.0*D3(DENS,TE)+1.5*D4(DENS)+1.5*D5(
            2DENS,TIA))*(TE-TWALL)
      C      PI3 IS DUI/DT DUE TO CHARGE EXCHANGE
             PI3(DENS,DNEUT,TI)=.0732*DENS*DNEUT*SQRT(TI)*(TI-TWALL)
            2*(1.0+0.00585*TI**1.5)/EXP(0.0582*SQRT(TI))
      C      PI6 IS DUI/DT DUE TO THERMAL CONDUCTION
             PI6(DENS,TE,TI)=(2.5*D2(DENS,TE)+2.0*D3(DENS,TE)+1.5*D4(DENS))*(TI
            2-TWALL)+(2.4*A*A*B*B-1.5*TWALL)*D5(DENS,TI)
      C      PI7 IS DUI/DT DUE TO IONS BORN AT TEMP OF WALL
             PI7(DENS,DNEUT,TE)=1.5*D1(DENS,DNEUT,TE)*TWALL
      C      PI8 IS DUI/DT DUE TO ELASTIC COLLISIONS WITH NEUTRALS
             PI8(DENS,DNEUT,TI)=10.0*DENS*DNEUT*(TI-TWALL)/(570.+TI**2.4)**.29
      C                      SPECIFY PARAMETERS
      C      ICOND=0:NO AUXILIARY HEATING, 1:OHMIC HEATING, 2:ICRH, 4:ECRH
      C      IIMAX IS NUMBER OF ITERATIONS
      C      PO IS PEAK MICROWAVE POWER IN WATTS
      C      DEA IS INITIAL DENSITY IN 10**9/CC
      C      TWALL IS WALL TEMPERATURE IN EV
      C      AL IS LENGTH IN CM
      C      A IS RADIUS IN CM
      C      AO IS OBSTACLE AREA IN SQ CM
      C      PRES IS NEUTRAL PRESSURE IN 10**-5 TORR
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C       BO IS FIELD AT OUTER WALL IN KGAUSS
C       F IS MICROWAVE FREQUENCY IN GHZ
C       Q IS THE MICROWAVE CAVITY Q
C       S IS PUMPING SPEED IN LITERS / SEC
C       TMAX IS DURATION OF EXPERIMENT IN SECONDS
C       TOFF IS MICROWAVE TURNOFF TIME IN SEC
        NCASE=1
        DO 800 ICASE=1,NCASE
        ICOND=1
        IIMAX=1000
        PO=1000.0
        DEA=0.001
        TWALL=0.025
        AL=270.0
        A=18.0
        AO=90.0
        PRES=2.5
        BO=0.88
        F=2.45
        Q=2000.0
        S=100.0
        TMAX=0.005
        TOFF=0.0035
C                        SPECIFY INITIAL CONDITIONS
        TEA=TWALL
        TIA=TWALL
        IPRINT=IIMAX/100
        DT=TMAX/FLOAT(IIMAX)
        B=1.0E-5
        II=0
        TIME=0.0
        DDENS=0.0
        DTE=0.0
        DTI=0.0
        DNWR=0.0
        DNI=322.0*PRES
        DFC=12.88*PRES
        DNEUT=DNI+DFC
        DEMAX=DEA
        TEMAX=TEA
        TIMAX=TIA
        DNMIN=335.0*PRES
        PRMAX=0.1*PO
        BPMAX=0.1*BO
        SJMAX=0.104*DEA*SQRT(TEA)
        QNMAX=0.0
        SD(2)='RD'
        SD(3)='OL'
        SD(4)='FD'
        SD(5)='GR'
        STE(2)='IC'
        STE(3)='EX'
        STE(4)='BR'
        STE(5)='SR'
        STE(6)='TC'
        STI(1)='EC'
        STI(2)='CX'
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      STI(3)='TC'
      STI(4)='NC'
      IOHMIC=MOD(ICOND,2)
      IHICRH=MOD(ICOND/2,2)
      IHECRH=MOD(ICOND/4,2)
C                        RECORD VALUES
      WRITE(6,300)
  300 FORMAT(1H1,'AUXILIARY HEATING:')
      IF(ICOND.EQ.0) WRITE(6,310)
  310 FORMAT(1H+,19X,'NONE')
      IF(IOHMIC.EQ.1) WRITE(6,320)
  320 FORMAT(1H+,19X,'OHMIC')
      IF(IHICRH.EQ.1) WRITE(6,330)
  330 FORMAT(1H+,26X,'ICRH')
      IF(IHECRH.EQ.1) WRITE(6,340)
  340 FORMAT(1H+,32X,'ECRH')
      IF(NCASE.GT.1) WRITE(6,390) ICASE
  390 FORMAT(1H+,116X,'CASE',I3)
      WRITE(6,400)
  400 FORMAT(1H0,2X,'STEP',9X,'TIME',6X,'DENSITY',10X,'TE',11X,'TI',6X,'
     2DNEUTRAL',8X,'FIELD',7X,'POWER',10X,'JSAT',5X,'DE TE TI')
      WRITE(6,440)
  440 FORMAT(1H ,14X,'(SEC)',3X,'(10**9/CC)',9X,'(EV)',9X,'(EV)',3X,'(10
     2**9/CC)',5X,'(KGAUSS)',6X,'(WATTS)',4X,'(MA/SQCM)')
  450 CONTINUE
      BOLD=B
      B=BO*SIN(3.14159*TIME/TMAX)*EXP(-0.5*TIME/TMAX)/0.7887+1.0E-5
      BR=0.34*F/B
      IF(BR.GT.8.77) G=0.0
      IF(BR.LE.2.3511) G=0.25744*BR**0.6666667
      IF(BR.GT.2.3511.AND.BR.LE.8.77) G=2.7*EXP(.45/(BR-8.78))/BR/BR
      DEAF=0.03*A*DEA/F
      IF(DEAF.LT.80.0) G=G/EXP(DEAF)
      IF(DEAF.GE.80.0) G=0.0
      DEAF=0.06*A*SQRT(AMAX1(DEA-12.35*F*F,0.0))
      IF(DEAF.LT.80.)G=G+(2.8E-8*DNEUT+9.15E-6*DEA/TEA**1.5)/F/EXP(DEAF)
      P=PO*AMIN1(1.0,AMAX1(0.0,11.0*TIME*BO**0.6/TMAX-1.7))
      IF(TIME.GT.TOFF) P=0.0
      SJI=0.104*DEA*SQRT(AMAX1(TEA,TIA))*(1.0-EXP(-45.0/TEA))
      DNTO=DNT
      DFCO=DFC
      DNT=DNT+DNWR+318.0*S*DT*(322.0*PRES-DNT)/A/A/AL
      DFC=DFC+0.04*DNWR+318.0*S*DT*(12.88*PRES-DFC)/A/A/AL
      DNTA=AMIN1(DNT,DNT+(DNTO-DNT)*EXP(-1.2E6*DT*SQRT(TWALL)/A))
     2*EXP(-4.1E-7*A*D1(DEA,DNEUT,TEA)/DNEUT/SQRT(TWALL))
      DFCA=AMIN1(DFC,DFC+(DFCO-DFC)*EXP(-3.4E6*DT/A))
     2*EXP(-1.1E-7*A*D1(DEA,DNEUT,TEA)/DNEUT)
      DNEUT=DNTA+DFCA
      GLC=0.0083*SQRT(TEA)+0.28*SQRT(TIA)
      DNWR=GLC*(D2(DEA,TEA)+D3(DEA,TEA)+D4(DEA)+D5(DEA,TIA))*DT
     2-0.5*D1(DEA,DNEUT,TEA)*DT
      DEMAX=AMAX1(DEMAX,DEA)
      TEMAX=AMAX1(TEMAX,TEA)
      TIMAX=AMAX1(TIMAX,TIA)
      DNMIN=AMIN1(DNMIN,DNEUT)
      BPMAX=AMAX1(BPMAX,B)
      PPMAX=AMAX1(PPMAX,P)
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      SJMAX=AMAX1(SJMAX,SJI)
      QNMAX=AMAX1(QNMAX,DEA/DNEUT)
      IF(MOD(II+1,IPRINT).NE.1) GO TO 480
      D(2)=D2(DEA,TEA)
      D(3)=D3(DEA,TEA)
      D(4)=D4(DEA)
      D(5)=D5(DEA,TIA)
      PE(2)=AMAX1(0.0,PE2(DEA,TEA,TIA))
      PE(3)=PE3(DEA,DNEUT,TEA)
      PE(4)=PE4(DEA,TEA)
      PE(5)=PE5(DEA,TEA)
      PE(6)=AMAX1(0.0,PE6(DEA,TEA))
      PI(1)=AMAX1(0.0,-PE(2))
      PI(2)=AMAX1(0.0,PI1(DEA,DNEUT,TIA))
      PI(3)=AMAX1(0.0,PI6(DEA,TEA,TIA))
      PI(4)=AMAX1(0.0,PI8(DEA,DNEUT,TIA))
      DM=0.
      DO 453 I=2,5
      IF(DM.GT.D(I)) GO TO 453
      DM=D(I)
      MD=I
  453 CONTINUE
      EM=0.
      DO 455 I=2,6
      IF(EM.GT.PE(I)) GO TO 455
      EM=PE(I)
      ME=I
  455 CONTINUE
      TIM=0.
      DO 457 I=1,4
      IF(TIM.GT.PI(I)) GO TO 457
      TIM=PI(I)
      MTI=I
  457 CONTINUE
      WRITE(6,460)II,TIME,DEA,TEA,TIA,DNEUT,B,P,SJI,SD(MD),STE(ME),
     2STI(MTI)
  460 FORMAT(1H ,I6,8F13.4,5X,3A3)
      I=II/IPRINT+1
      T(I)=TIME
      DE(I)=DEA
      TE(I)=TEA
      TI(I)=TIA
      DN(I)=DNEUT
      BP(I)=B
      PP(I)=P
      SJ(I)=SJI
  480 CONTINUE
      IF(II.GE.IIMAX) GO TO 640
      DEAT=DEA
      TEAT=TEA
      TIAT=TIA
      DEA=DEA+0.5*DDENS
      TEA=TEA+0.5*DTE
      TIA=TIA+0.5*DTI
C                     INCREMENT DENSITY
      DDENS=D1(DEA,DNEUT,TEA)*DT
     2-D2(DEA,TEA)*DT
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     3-D3(DEA,TEA)*DT
     4-D4(DEA)*DT
     5-D5(DEA,TIA)*DT
      IF(ABS(DDENS).GT.0.5*DEA) DDENS=SIGN(0.5*DEA,DDENS)
      DEA=DEAT+0.5*DDENS
C                     INCREMENT ELECTRON TEMPERATURE
      DUE=PE1(P)*DT
     2-PE2(DEA,TEA,TIA)*DT
     3-PE3(DEA,DNEUT,TEA)*DT
     4-PE4(DEA,TEA)*DT
     5-PE5(DEA,TEA)*DT
     6-PE6(DEA,TEA)*DT
      IF(IOHMIC.EQ.1) DUE=DUE+OHMIC(B,BOLD,DT,TIME,DEA,TEA,DNEUT)*DT
      IF(IHECRH.EQ.1) DUE=DUE+HECRH(B,TIME,DEA,DNEUT,TEA,A,AL)*DT
      DTE=(0.66667*DUE-TEA*DDENS)/DEA
      IF(ABS(DTE).GT.0.5*TEA) DTE=SIGN(0.5*TEA,DTE)
      TEA=TEAT+0.5*DTE
C                     INCREMENT ION TEMPERATURE
      DUI=PE2(DEA,TEA,TIA)*DT
     2-PI3(DEA,DNEUT,TIA)*DT
     3-PI6(DEA,TEA,TIA)*DT
     4+PI7(DEA,DNEUT,TEA)*DT
     5-PI8(DEA,DNEUT,TIA)*DT
      IF(IHICRH.EQ.1) DUI=DUI+HICRH(B,TIME,DEA,A,AL)*DT
      DTI=(0.66667*DUI-TIA*DDENS)/DEA
      IF(ABS(DTI).GT.0.5*TIA) DTI=SIGN(0.5*TIA,DTI)
C                     INCREMENT TIME
      DEA=DEAT+DDENS
      TEA=TEAT+DTE
      TIA=TIAT+DTI
      II=II+1
      TIME=DT*FLOAT(II)
      GO TO 450
  640 CONTINUE
      WRITE(6,700) DEMAX,TEMAX,TIMAX,DNMIN,BPMAX,PPMAX,SJMAX
  700 FORMAT(1H0,'     MAXIMUM  VALUES',7F13.4)
      FDP=100.0*(DNEUT/334.88-PRES)/PRES
      WRITE(6,750) FDP
  750 FORMAT(1H0,14X,'FRACTIONAL  CHANGE  IN  NEUTRAL  PRESSURE  =',F13.
     24,'  PER CENT')
      WRITE(6,760) QNMAX
  760 FORMAT(1H0,28X,'MAXIMUM  RATIO  OF  NE / NO  =',F13.4)
  800 CONTINUE
C                     GRAPH OUTPUT
      DO 820 I=1,101
      T(I)=6.0*T(I)/TMAX
      DE(I)=6.0*DE(I)/DEMAX
      TE(I)=6.0*TE(I)/TEMAX
      TI(I)=6.0*TI(I)/TIMAX
      DN(I)=6.0*DN(I)/DNEUT
      BP(I)=6.0*BP(I)/BPMAX
      PP(I)=6.0*PP(I)/PPMAX
  820 SJ(I)=6.0*SJ(I)/SJMAX
      CALL GRAPH2(T,'R',DE,'R',101,'6X6','NONE','MULTIPOLE SIMULATION..'
     2,'TIME..','DENSITY AND TEMP (NORMALIZED)..','D')
      CALL GRPH2V(T,'R',TE,'R',101,'NONE','E')
      CALL GRPH2V(T,'R',TI,'R',101,'NONE','I')
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              CALL GRPH2V(T,'R',DN,'R',101,'NONE','N')
              CALL GRAPH2(T,'R',BP,'R',101,'6X6','NONE','MULTIPOLE SIMULATION..'
             2,'TIME..','FIELD AND POWER (NORMALIZED)..','B')
              CALL GRPH2V(T,'R',PP,'R',101,'NONE','P')
              CALL GRPH2V(T,'R',SJ,'R',101,'NONE','J')
              CALL GRPHND
              END

 END OF COMPILATION:          NO  DIAGNOSTICS.
$   ,OHMIC
N-MACC 1.17S-06/08/76-14:44:19              OHMIC
              FUNCTION OHMIC(B,BOLD,DT,T,DENS,TE,DNEUT)
              BT(T)=0.177*BTMAX*SIN(1571.0*(T-TON))/EXP(654.0*(T-TON))
              OHMIC=0.0
              TON=0.0035
              IF(T.LE.TON) RETURN
              BTMAX=1.25
              ZEFF=1.0
              DBPO=0.1*(B-BOLD)/DT
              DBT=0.708*(BT(T+0.5*DT)-BT(T-0.5*DT))/DT
              ALF=0.141*B/BT(T)
              OHMIC=(6.51*ALF**2*DBT**2/(0.591+ALF**2)-12.6*ALF*DBT*DBPO/(0.663+
             2ALF**2)+8.79*DBPO**2/(0.962+ALF**2))
             3/(ZEFF/1600.0/TE**1.5+6.29E-6*DNEUT/DENS+0.025*SQRT(TE)/DENS)
              OHMIC=AMAX1(OHMIC,0.0)
              RETURN
              END

 END OF COMPILATION:          NO  DIAGNOSTICS.
$   ,HICRH
N-MACC 1.17S-06/08/76-14:44:30              HICRH
              FUNCTION HICRH(B,TIME,DEA,A,AL)
        C   SEE BK. 6 PG. 118 FOR EXPLANATIONS AND REFERENCES
              HICRH=0.0
              TON=0.0045
              TOFF=0.006
              IF(TIME.LT.TON.OR.TIME.GT.TOFF) RETURN
              VOPO=6.5
              RPAR=800.0
              RO=200.
              FREQ=2.0
              DRDT=2.0E4
              TRISE=5.E-5
              BO=.626*FREQ/B
              IF(BO.LT.0.51198402) GI=.027*BO**1.03
              IF(BO.GE.0.51198402.AND.BO.LT.0.82973281) GI=.051*BO**1.98
              IF(BO.GE.0.82973281.AND.BO.LT.1.01377) GI=.019/BO**3.31
              IF(BO.GE.1.01377) GI=.0185/BO**1.36
              RLOAD=1.32E4*FREQ*AL/DEA/A/A/GI
              REQ=RPAR*RLOAD/(RPAR+RLOAD)
              VOP=VOPO*(1.87*REQ+RO)/(1.87*REQ+RO+DRDT*(TIME-TON))
              XP=(TIME-TON)/TRISE
              IF(XP.LT.88.) VOP=VOP*(1.0-EXP(-XP))
              HICRH=7.62E10*DEA*VOP*VOP*GI/AL/AL/FREQ
              RETURN
              END
```

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END OF COMPILATION:          NO  DIAGNOSTICS.
S  ,HECRH
N=MACC 1.178-06/08/76-14:44:41                  HECRH
              FUNCTION HECRH(B,TIME,DEA,DNEUT,TEA,A,AL)
              TON=0.003
              TOFF=0.004
              HECRH=0.0
              IF(TIME.LT.TON.OR.TIME.GT.TOFF) RETURN
              F=9.0
              DEAF=0.03*A*DEA/F
              P=2.0E4
              Q=3000.0
              BO=0.34*F/B
              IF(BO.GT.8.77) G=0.0
              IF(BO.LE.2.3511) G=0.25744*BO**0.66666667
              IF(BO.GT.2.3511.AND.BO.LE.8.77) G=2.7*EXP(.45/(BO-8.78))/BO/BO
              IF(DEAF.LT.80.0) G=G/EXP(DEAF)
              IF(DEAF.GE.80.0) G=0.0
              DEAF=0.06*A*SQRT(AMAX1(DEA-12.35*F*F,0.0))
              IF(DEAF.LT.80.)G=G+(2.8E-8*DNEUT+9.15E-6*DEA/TEA**1.5)/F/EXP(DEAF)
              HECRH=2.0E9*P*G*DEA/(G*DEA+12.35*F*F/Q)/A/A/AL
              RETURN
              END

END OF COMPILATION:          NO  DIAGNOSTICS.
XN
4 RLIB64 06/08-14:45:09
P
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AUXYLIARY HEATING: OHMIC

STEP	TIME (SEC)	DENSITY (10**9/CC)	TE (EV)	TI (EV)	DNEUTRAL (10**9/CC)
0	.0000	.0010	.0250	.0250	837.2000
10	.0000	.0005	.0375	.0370	837.2040
20	.0001	.0005	.0376	.0366	837.2040
30	.0001	.0005	.0377	.0361	837.2040
40	.0002	.0005	.0377	.0357	837.2040
50	.0002	.0005	.0378	.0353	837.2040
60	.0003	.0005	.0378	.0349	837.2040
70	.0003	.0005	.0379	.0349	837.2040
80	.0004	.0005	.0380	.0342	837.2040
90	.0004	.0005	.0380	.0339	837.2040
100	.0005	.0005	.0381	.0339	837.2040
110	.0005	.0005	.0381	.0332	837.2040
120	.0006	.0005	.0382	.0329	837.2040
130	.0006	.0005	.0382	.0326	837.2040
140	.0007	.0005	.0383	.0323	837.2040
150	.0007	.0005	.0383	.0321	837.2040
160	.0008	.0005	.0384	.0318	837.2040
170	.0008	.0005	.1453	.0318	837.2040
180	.0009	.0005	15.3014	.0316	837.2036
190	.0009	.0050	401.1626	.0277	837.1897
200	.0010	.0496	586.7402	.0279	837.0671
210	.0010	.5171	309.5417	.0276	835.6402
220	.0011	6.9511	46.2284	.0272	819.7187
230	.0011	21.6655	11.3768	.0325	815.8335
240	.0012	27.6215	6.7719	.0466	818.2517
250	.0012	30.0193	5.5981	.0649	818.1283
260	.0013	31.4678	5.1550	.0844	817.5303
270	.0013	32.5384	4.8914	.1039	816.9216
280	.0014	33.3032	4.6215	.1234	816.4829
290	.0014	33.8226	4.4306	.1428	816.0901
300	.0015	34.1858	4.3017	.1617	815.7215
310	.0015	34.4475	4.2118	.1799	815.3743
320	.0016	34.6396	4.1467	.1972	815.0459
330	.0016	34.7818	4.0983	.2137	814.7334
340	.0017	34.8873	4.0617	.2292	814.4342
350	.0017	34.9650	4.0338	.2438	814.1459
360	.0018	35.0215	4.0125	.2575	813.8666
370	.0018	35.0618	3.9962	.2703	813.5947
380	.0019	35.0895	3.9838	.2822	813.3288
390	.0019	35.1076	3.9746	.2933	813.0678
400	.0020	35.1184	3.9679	.3036	812.8108
410	.0020	35.1238	3.9633	.3132	812.5569
420	.0021	35.1252	3.9603	.3221	812.3055
430	.0021	35.1239	3.9587	.3303	812.0560
440	.0022	35.1208	3.9582	.3379	811.8079
450	.0022	35.1169	3.9586	.3449	811.5608
460	.0023	35.1054	3.9603	.3513	811.3154
470	.0023	35.0779	3.9652	.3572	811.0715
480	.0024	35.0375	3.9736	.3626	810.8271
490	.0024	34.9868	3.9852	.3675	810.5812
500	.0025	34.9283	3.9994	.3718	810.3326
510	.0025	34.8642	4.0158	.3755	810.0805
520	.0026	34.7963	4.0341	.3788	809.8240

B_{po} FIELD (KGAUSS)	μwave POWER (WATTS)	JSAT (MA/SQCM)	dominating term DE	TE	TI
,0000	,0000	,0000	RD	BR	NC
,0349	,0000	,0000	OL	TC	NC
,0694	,0000	,0000	OL	TC	NC
,1034	,0000	,0000	OL	TC	NC
,1371	,0000	,0000	OL	TC	NC
,1702	,0000	,0000	OL	TC	NC
,2029	,0000	,0000	OL	TC	NC
,2350	,0000	,0000	OL	TC	NC
,2666	,0000	,0000	OL	TC	NC
,2976	,0000	,0000	OL	TC	NC
,3280	,0000	,0000	OL	TC	NC
,3577	,0000	,0000	OL	TC	NC
,3868	,0000	,0000	OL	TC	NC
,4152	,0000	,0000	OL	TC	NC
,4430	,0000	,0000	OL	TC	NC
,4700	,0000	,0000	OL	TC	NC
,4962	,0000	,0000	OL	TC	NC
,5217	31,9335	,0000	OL	TC	NC
,5464	133,8119	,0002	OL	EX	TC
,5703	235,6903	,0011	OL	TC	TC
,5934	337,5688	,0092	OL	TC	TC
,6157	439,4472	,1280	OL	TC	TC
,6371	541,3257	3,0583	OL	EX	TC
,6577	643,2041	7,4544	OL	EX	TC
,6774	745,0825	7,4657	OL	EX	NC
,6963	846,9610	7,3844	OL	EX	NC
,7142	948,8394	7,4293	OL	EX	NC
,7313	1000,0000	7,4835	OL	EX	NC
,7474	1000,0000	7,4454	OL	EX	NC
,7626	1000,0000	7,4038	OL	EX	NC
,7769	1000,0000	7,3737	OL	EX	NC
,7903	1000,0000	7,3521	OL	EX	NC
,8028	1000,0000	7,3358	OL	EX	NC
,8143	1000,0000	7,3228	OL	EX	NC
,8249	1000,0000	7,3122	OL	EX	NC
,8346	1000,0000	7,3033	OL	EX	NC
,8433	1000,0000	7,2957	OL	EX	NC
,8511	1000,0000	7,2893	OL	EX	NC
,8579	1000,0000	7,2838	OL	EX	NC
,8638	1000,0000	7,2791	OL	EX	NC
,8688	1000,0000	7,2752	OL	EX	NC
,8729	1000,0000	7,2721	OL	EX	NC
,8760	1000,0000	7,2696	OL	EX	NC
,8782	1000,0000	7,2679	OL	EX	NC
,8796	1000,0000	7,2668	OL	EX	NC
,8800	1000,0000	7,2663	OL	EX	NC
,8795	1000,0000	7,2655	OL	EX	NC
,8782	1000,0000	7,2643	OL	EX	NC
,8760	1000,0000	7,2636	OL	EX	NC
,8729	1000,0000	7,2636	OL	EX	NC
,8690	1000,0000	7,2644	OL	EX	NC
,8642	1000,0000	7,2660	OL	EX	NC
.8586	1000.0000	7.2683	OL	EX	NC

STEP	TIME (SEC)	N_e^{35-} ($10^9/cm^3$)	T_e (eV)	T_i (eV)	neutral density
530	.0026	34.7261	4.0540	.3815	809.5625
540	.0027	34.6550	4.0752	.3836	809.2953
550	.0027	34.5841	4.0975	.3856	809.0218
560	.0028	34.5144	4.1207	.3870	808.7415
570	.0028	34.4466	4.1445	.3880	808.4540
580	.0029	34.3813	4.1689	.3886	808.1589
590	.0029	34.3192	4.1937	.3888	807.8559
600	.0030	34.2604	4.2189	.3887	807.5446
610	.0030	34.2053	4.2444	.3883	807.2247
620	.0031	34.1541	4.2701	.3876	806.8960
630	.0031	34.1068	4.2960	.3866	806.5581
640	.0032	34.0635	4.3222	.3854	806.2108
650	.0032	34.0243	4.3486	.3840	805.8537
660	.0033	33.9890	4.3753	.3823	805.4867
670	.0033	33.9576	4.4022	.3805	805.1093
680	.0034	33.9300	4.4296	.3785	804.7211
690	.0034	33.9061	4.4574	.3763	804.3218
700	.0035	33.8858	4.4857	.3740	803.9109
710	.0035	78.3739	30.0963	.1741	677.1127
720	.0036	251.4967	35.5121	.1050	411.6204
730	.0036	484.4878	46.6022	.1555	179.3079
740	.0037	644.5074	59.2427	.2547	89.9616
750	.0037	732.2671	68.5325	.3701	58.7936
760	.0038	778.2108	73.7413	.4872	45.6386
770	.0038	800.6711	75.5579	.6003	39.2032
780	.0039	809.8063	74.8412	.7074	35.8304
790	.0039	811.5023	72.3351	.8082	34.0830
800	.0040	809.2790	68.6289	.9030	33.3086
810	.0040	805.2587	64.1723	.9929	33.1867
820	.0041	800.7044	59.3006	1.0784	33.5598
830	.0041	796.3375	54.2582	1.1620	34.3638
840	.0042	792.5302	49.2189	1.2435	35.5962
850	.0042	789.4208	44.3030	1.3244	37.3026
860	.0043	786.9750	39.5904	1.4058	39.5739
870	.0043	785.0103	35.1326	1.4884	42.5507
880	.0044	783.1856	30.9613	1.5729	46.4337
890	.0044	780.9617	27.0964	1.6598	51.5009
900	.0045	777.5336	23.5519	1.7496	58.1274
910	.0045	771.7416	20.3418	1.8422	66.8034
920	.0046	761.9807	17.4833	1.9370	78.1372
930	.0046	745.7857	15.0001	2.0269	92.7370
940	.0047	715.5908	12.9063	2.0541	112.8447
950	.0047	645.0611	11.1227	1.8504	148.3165
960	.0048	507.0191	9.4948	1.3639	212.4293
970	.0048	327.0318	8.2102	.7998	289.4035
980	.0049	162.7962	7.6599	.3495	346.5477
990	.0049	49.7327	7.7639	.0865	376.8779
1000	.0050	1.3780	8.0308	.0802	390.5984
MAXIMUM	VALUES →	811.5647	586.7402	2.0611	33.1663

FRACTIONAL CHANGE IN NEUTRAL PRESSURE = -53.3447 %

MAXIMUM RATIO OF NE / NO = 24.3365

B_{po} (kG)	μwave Power (watts)	probe ion sat. current (mA/cm^2)	dominating term N_e	T_e	T_i
.8522	1000.0000	7.2715	OL	EX	NC
.8450	1000.0000	7.2756	OL	EX	NC
.8371	1000.0000	7.2805	OL	EX	NC
.8283	1000.0000	7.2863	OL	EX	NC
.8189	1000.0000	7.2930	OL	EX	NC
.8087	1000.0000	7.3006	OL	EX	NC
.7977	1000.0000	7.3090	OL	EX	NC
.7861	1000.0000	7.3184	OL	EX	NC
.7738	1000.0000	7.3286	OL	EX	NC
.7609	1000.0000	7.3398	OL	EX	NC
.7473	1000.0000	7.3518	OL	EX	NC
.7331	1000.0000	7.3648	OL	EX	NC
.7183	1000.0000	7.3788	OL	EX	NC
.7029	1000.0000	7.3937	OL	EX	NC
.6870	1000.0000	7.4095	OL	EX	NC
.6705	1000.0000	7.4265	OL	EX	NC
.6536	1000.0000	7.4445	OL	EX	TC
.6361	1000.0000	7.4635	OL	EX	TC
.6182	.0000	34.6904	OL	EX	TC
.5998	.0000	111.9706	OL	EX	TC
.5810	.0000	213.0038	OL	EX	TC
.5618	.0000	274.5396	OL	TC	TC
.5423	.0000	303.4991	OL	TC	TC
.5223	.0000	317.4632	OL	TC	TC
.5021	.0000	324.8130	OL	TC	TC
.4815	.0000	329.2412	OL	TC	TC
.4607	.0000	332.4708	OL	TC	TC
.4396	.0000	335.3200	OL	TC	TC
.4183	.0000	338.1810	OL	TC	TC
.3968	.0000	341.0186	OL	TC	TC
.3751	.0000	343.8681	OL	TC	TC
.3532	.0000	346.4847	OL	TC	TC
.3312	.0000	348.5667	OL	TC	TC
.3090	.0000	349.7242	OL	TC	TC
.2868	.0000	349.4802	OL	TC	TC
.2645	.0000	347.2707	OL	TC	TC
.2422	.0000	342.4558	OL	TC	TC
.2199	.0000	334.3605	OL	TC	TC
.1975	.0000	322.3689	FD	EX	TC
.1752	.0000	306.0895	FD	EX	TC
.1529	.0000	285.4403	FD	EX	TC
.1307	.0000	259.1797	FD	EX	TC
.1086	.0000	219.8228	GR	EX	TC
.0865	.0000	161.0594	GR	TC	TC
.0647	.0000	97.0481	GR	TC	TC
.0429	.0000	46.7271	GR	TC	TC
.0214	.0000	14.3678	GR	TC	TC
.0000	.0000	.2042	RD	TC	TC
.8800	1000.0000	349.8245	← MAX VALUES		

PER CENT

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@FIN

    RUNID: C00295   PROJECT: 02980            USER: 4126810219

  ITEM                                AMOUNT     COST(DOLLARS)

CPU TIME                      00:00:14.047        $0.53
FILE I/O REQUESTS                      558        $0.25
FILE I/O WORDS                      471145        $0.21
SWAP REQUESTS                            1        $0.00
SWAP WORDS                            3072        $0.00
MEMORY USAGE                         0.383        $0.24
CARDS IN                               355        $0.09
PAGES PRINTED                           13        $0.18
ER + CC                                 12        $0.12
JOB CHARGE                               1        $0.05

TOTAL COST                                        $1.67

    THE ABOVE DOLLAR AMOUNTS ARE APPROXIMATE AND ARE BASED ON RATES FOR STANDARD RUNS
USER BALANCE                                    $113.46

    INITIATION  TIME:   14:43:15 JUN  8,1976

    TERMINATION TIME:   14:49:21 JUN  8,1976

   PREVIOUS RUN TIME:   14:13:59 MAY 20,1976
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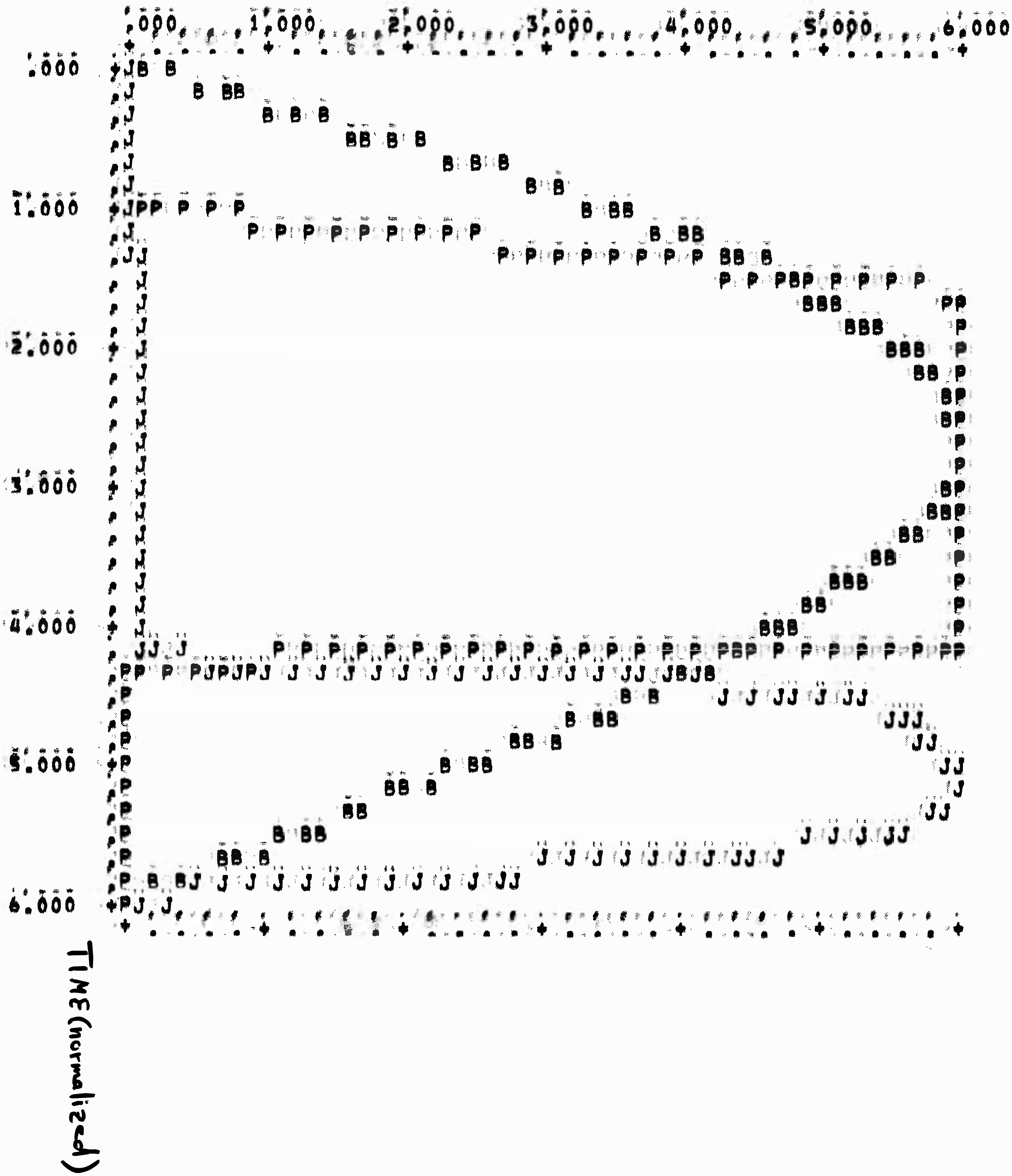
MULTIPOLE SIMULATION

FIELD AND POWER (NORMALIZED)



MULTIPOLE SIMULATION

DENSITY AND TEMP (NORMALIZED)