SIMULT PREDICTIONS FOR TOKAPOLE II

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The zero-dimensional, time dependent computer code, SIMULT (PLP 607), has recently been refined by Etzweiler (Ph.D. Thesis) to model ohmically heated plasmas in a toroidal octupole with toroidal field. In this note, evidence will be presented to show that SIMULT agrees reasonably well with experiments on Tokapole I (PLP 712). The comparison lends credence to the predictions of SIMULT for the Tokapole II device which is scheduled to begin operation in March, 1978 (PLP 730).

Figure 1 shows the peak value of the plasma current in Tokapole I as measured experimentally and as predicted by SIMULT as a function of poloidal and toroidal field strength. The fields at 5 kV on the capacitor banks are 2.2 kG at the outer wall midplane for B-poloidal and 3.0 kG on axis for B-toroidal. The agreement, especially at high fields, is reasonably close.

Table I shows the time dependence of various plasma parameters in the experiment and in the simulation. Again, the results are reasonably close except that the plasma current in the simulation peaks some 600 μsec. earlier than in the experiment. This may be evidence of a skin effect as expected for fast rising fields in a high conductivity plasma. Measurements of this field penetration are under way. Additional comparisons of Tokapole I experiments with SIMULT can be found in Etzweiler's thesis.

Also shown in Table I is the prediction of SIMULT for an unoptimized Tokapole II plasma. The toroidal field is assumed to be a half sine wave of 12.34 msec. duration with a peak value of 4.4 kG on axis. The poloidal field is a 5.5 msec. half sine wave that begins 5 msec. after the toroidal field and reaches a peak of 2.0 kG at the outside wall midplane. The octupole flux plot is assumed identical to Tokapole I except scaled up in size, and to be unperturbed by the plasma current. The wall reflux is assumed the same as that measured for Tokapole I, and so the predictions are probably conservative in terms of the temperatures and densities we are likely to achieve. Nevertheless, the prediction is for a 70% increase in plasma current, a four times higher electron temperature, a doubling of the energy confinement time, and a slightly higher density. Table II summarizes the results for the two devices at the peak of the plasma current.

At each time-step of its execution, SIMULT calculates the rate at which energy is being added to the plasma and the rates by which energy leaves the plasma through various loss mechanisms. Figure 2 shows the power flow to and from the electrons for the Tokapole I simulation while Figure 3 shows the same data for a Tokapole II simulation. Power balance for the ions has not been considered, since in the simulation and presumably in the experiment they are not nearly so hot as the electrons during much of the discharge.

P_{OHMIC} is the ohmic heating power given to the electrons and is essentially the only way in which electrons receive power in a tokapole discharge. The mechanisms for electron power loss are P_{EXCIT}, P_{IONS}, and $P_{TRANSPORT}$. P_{EXCIT} is the rate at which electrons lose energy in collisions with neutral hydrogen. The electrons lose energy by causing atomic transitions or by ionizing the atoms. Excitation of impurities is not included in the code. P_{IONS} is the rate at which electrons heat the ions by electron-ion collisions, and $P_{TRANSPORT}$ is the rate at which electron flow transports energy from the plasma. The dominant contribution to $P_{TRANSPORT}$ comes from the loss of particles to supports; there is no term for electron loss by anomalous diffusion.

In the Tokapole I simulation (Fig. 2), it can be seen that P_{OHMIC} peaks early in the discharge. This is because at that time the poloidal gap voltage and toroidal current are both very large. P_{OHMIC} has another peak later in the discharge, and this is due to the falling toroidal field which induces a large toroidal gap voltage and drives a poloidal plasma current. Throughout most of the discharge, P_{EXCIT} is the dominant power loss term. As the electron density and temperature increase early in the discharge, P_{EXCIT} rapidly increases and then it drops as the neutrals are ionized and can no longer be excited. Then P_{EXCIT} starts to gradually increase during the remainder of the discharge. This happens because as the ion temperature climbs, an increasingly larger number of neutrals is desorbed by the ions at each time step. These neutrals are presumed to be hydrogen and are available for excitation. Additionally, the electron density is increasing during the discharge. P_{IONS} and $P_{TRANSPORT}$ are seen to be relatively small and comparable loss terms. It might be noted that P_{IONS} results in an increasing ion temperature which peaks at 900 μs at 13.2 eV and which is comparable to T_e by 1300 μs at 10 eV.

Figure 3 indicates that in the Tokapole II simulation, P_{OHMIC} peaks very early in the discharge at 886 kW and then drops continuously as the plasma current and poloidal gap voltage drop. During the ionization phase, P_{EXCIT} is again the dominant power loss term. Later in the discharge P_{EXCIT} increases for the same reasons as it increases in the Tokapole I simulation. (The oscillations in P_{EXCIT} are probably due to the fact that the time steps in this simulation were large and may have caused strange behavior in some of the terms used to calculate P_{EXCIT}.) Through most of the discharge, $P_{TRANSPORT}$ is the dominant energy loss mechanism, and it reaches 200 kW at 400 μs. This term is large because electron losses to the internal ring supports increase rapidly with T_e, which is about 100 eV in this case. (However, if a true tokapole discharge is initiated in Tokapole II so that a well-defined current channel is formed, electron losses to the supports should be much smaller than in the simulation.) P_{IONS} is relatively small as it reaches 72 kW at 1000 μs. T_i peaks at 19.6 eV at 1300 μs and is equal to T_e by about 1600 μs.

A number of interest in the Tokapole I experiment has been TAU, the energy confinement time. In the experiment, a computer is programmed to print out TAU at the peak of the plasma current. The program assumes that the plasma is in a steady state so that the rates of power flow to and from the plasma are equal. Thus,

$$P_{OHMIC} = \frac{U}{\tau}$$

where U is the energy in the plasma and τ is TAU. Experimentally, TAU has always been about 10 μs, independently of any other plasma parameter. Using this formula for TAU, SIMULT predicts that in the Tokapole I case, TAU should be ∿12 μs (Table 1), while in the Tokapole II case, TAU should be ∿22 μs. The agreement between the experiment and the simulation for the Tokapole I case is remarkable.

We thought, however, that the assumption that the plasma is in a steady state might not be correct, so we redefined TAU and had SIMULT calculate the new TAU at each time step. The formulation for the definition of TAU is as follows. By power balance,

$$\text{OHMIC HEATING POWER} = \text{RATE AT WHICH STORED PLASMA ENERGY INCREASES} + \text{RATE AT WHICH PLASMA LOSES ENERGY}$$

or

$$P_{OHMIC} = \dot{U} + \frac{U}{\tau} .$$

U is the plasma energy and

$$U = nk(T_i + T_e)\ V$$

where V is the plasma volume. TAU, as defined in this sense, is also plotted in Figures 2 and 3. It can be seen both in the Tokapole I and Tokapole II simulations that when the ohmic power peaks (which is the time that the current peaks), TAU is indeed very low. However, in both cases, TAU rapidly climbs and is about an order of magnitude higher for most of the discharge. (It is about 180 μs and 330 μs for the Tokapole I and II cases, respectively.) These results suggest that the experimental energy confinement time for Tokapole I may be better than 10 μs and the subject needs closer attention.

In conclusion, we have shown that Tokapole II ought to produce plasmas with $kT_e \gtrsim 100$ eV and $n \sim 10^{13}$ cm^{-3}. The dominant losses are neutral excitation and obstacles. The first can be minimized by careful vacuum practices and discharge cleaning, and the second by careful design of the octupole field topology in order to insure the formation of a current channel.

TABLE I

EXPERIMENT

```
         14
IP=   22.330000   AT     760
TE=   23.304976
NE=    .48585372E 13
A=   9.2484648
Q=   1.1322118
   TIME          IP       JSAT        BT       VPG     IHOOP       TE         NE

    200           1         17      2864        69        89        5         74
    400           9        329      3010        66       171       13        971
    600          18       1375      2854        62       247       20       8803
    800          22       1038      2443        57       319       24       4090
   1000          14        867      1827        52       386       23       2940
   1200           7        823      1085        46       446       21       2688
   1400           4        559       303        41       499       19       1611
```

SIMULT

TOKAPOLE I

```
IP=   21.981079   AT     160
TE=   16.563461
NE=     .76220777+13
A=   13.235129
Q=     .7448062
TAU=   11.833782
PO=       13    DP=      25
   TIME          IP       JSAT        BT       VPG     IHOOP       TE         NE

    200          19       3395      2845        70        89       26       7909
    400          10       4156      3000        65       173       34       9341
    600           8       5169      2854        59       251       26      11841
    800           6       6335      2449        54       322       21      15113
   1000           4       7568      1848        47       386       17      19081
   1200           2       8516      1128        41       440       13      23634
   1400           0       8478       369        33       486        9      27673
```

SIMULT

TOKAPOLE II

```
        SIMULT   -  TOKAPOLE II
IP=   36.804194   AT     145
TE=   64.452435
NE=     .91394249+13
A=   16.169946
Q=   3.6149739
TAU=   22.186454
PO=       13    DP=      45
   TIME          IP       JSAT        BT       VPG     IHOOP       TE         NE

    200          27       3720      4382       104        74       96       9740
    400          11       3722      4397        98       144      131      10751
    600           8       4605      4400        91       210      103      12303
    800           7       5801      4391        82       270       74      14232
   1000           7       7529      4371        73       325       48      17185
   1200           6       8929      4340        63       374       31      20139
   1400           6      10009      4298        58       416       21      23838
   1600           5      10548      4245        47       451       15      27570
   1800           4      10394      4181        36       479       11      30278
   2000           3       9344      4108        25       500        7      32738
```

TABLE II.

	TOKAPOLE I		TOKAPOLE II	
	SIMULT	*EXPERIMENT*	*SIMULT*	*EXPERIMENT*
B_T (axis)	3.0 kG	3.0 kG	4.4 kG	$\sim$4.4 kG
B_P (OW/MP)	2.2 kG	2.2 kG	2.0 kG	$\lesssim$2.0 kG
I_P	22 kA	25 kA	37 kA	?
t (peak)	160 μsec.	800 μsec.	150 μsec.	?
T_e	17 eV	25 eV	64 eV	?
n_e	8×10^{12}/cc.	5×10^{12}/cc.	9×10^{12}/cc.	?
T_i	3 eV	?	1.4 eV	?
$\Delta p/p$	1.9	1.3	3.5	?
P_{OH}	240 kW	?	890 kW	?
P_{EX}	92 kW	?	121 kW	?
P_{TC}	8 kW	?	60 kW	?

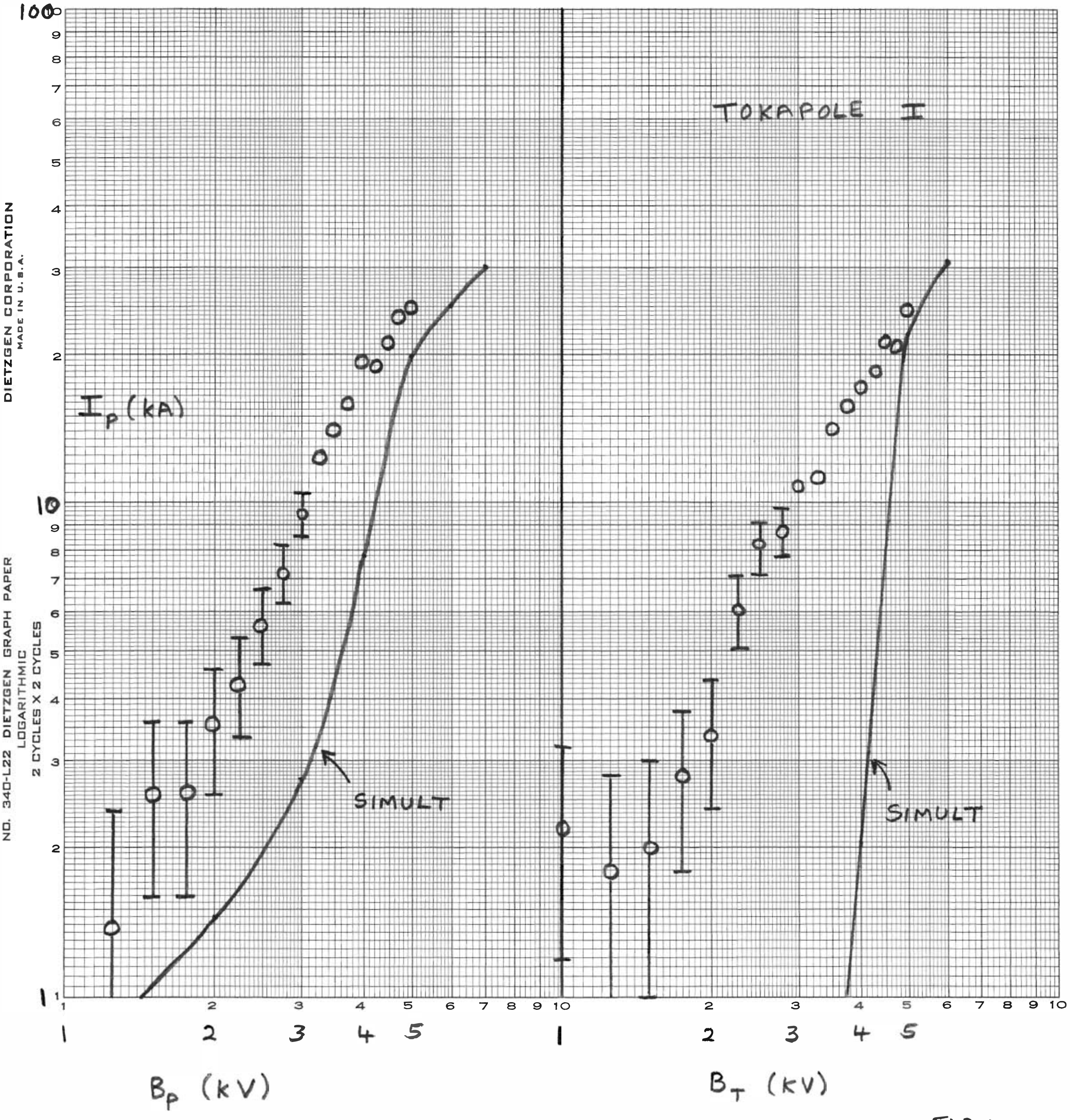
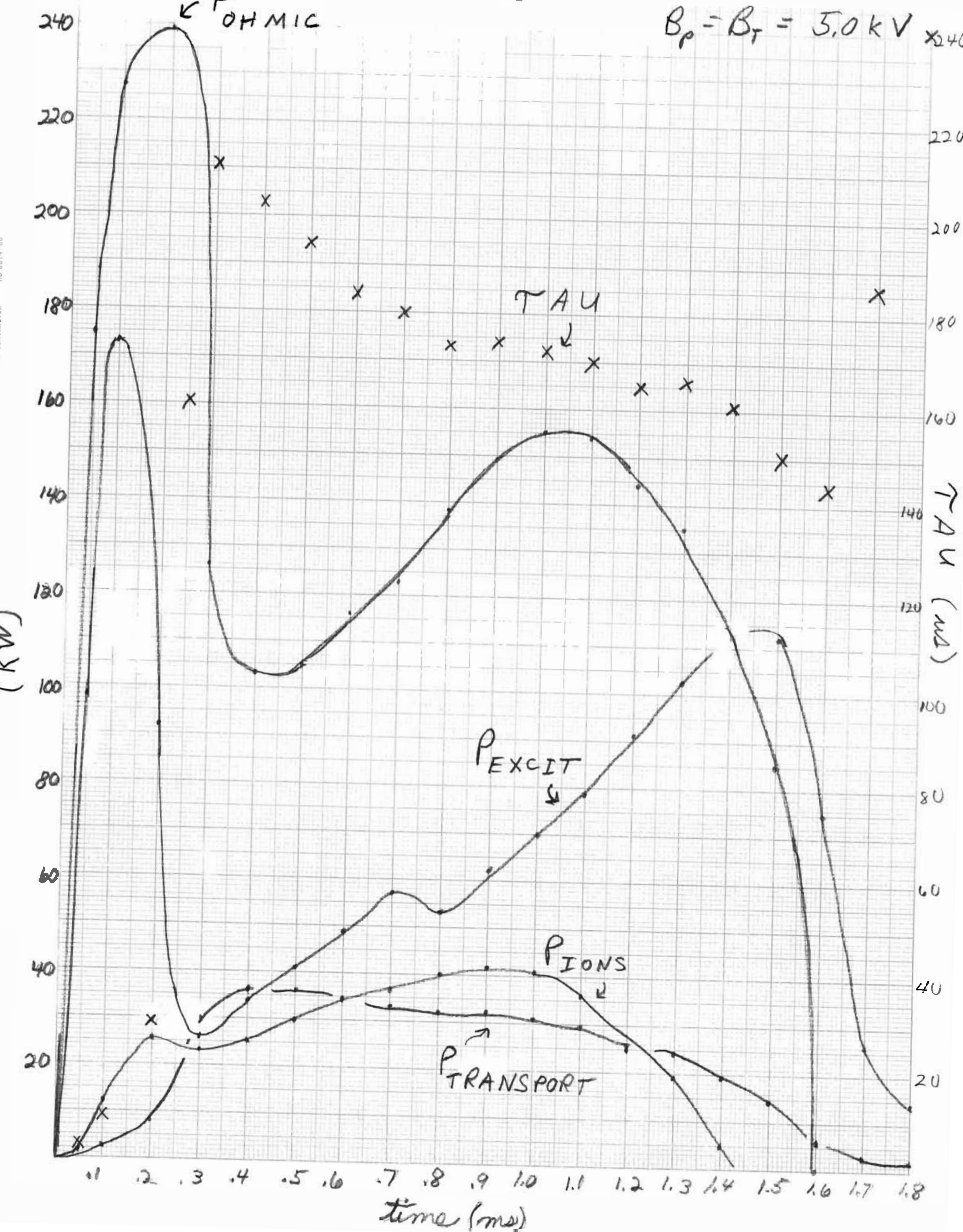

100
10
1
Ip (kA)
TOKAPOLE I
SIMULT
SIMULT
1 2 3 4 5
1 2 3 4 5
Bp (kV)
BT (kV)
DIETZGEN CORPORATION
MADE IN U.S.A.
NO. 340-L22 DIETZGEN GRAPH PAPER
LOGARITHMIC
2 CYCLES X 2 CYCLES

FIG 1

TOKAPOLE I SIMULATION

(Fig. 2)



TOKAPOLE II SIMULATION
(Fig. 3)