NUMERICAL SIMULATION

OF MULTIPOLE CONFINEMENT (Examples)

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ABSTRACT

Some examples of numerical simulations of multipole confinement, generated by program SIMULT,[1] are presented and discussed. Where possible, comparisons with experimental results are made. The agreement between the calculations and the plasma parameters from experiments, is surprisingly good in spite of the approximations inherent in a zero-dimensional calculation.

[1]"Numerical Simulation of Multipole Confinement," J. R. Patau and J. C. Sprott, PLP 556. This PLP is an expanded version of the examples portion of a talk given at the Philadelphia APS meeting on 2 Nov. 73. See PLP 556 for the first part of that talk.

This PLP demonstrates usage of program SIMULT discussed in detail in PLP 556. Examples 1a, 2, 4 and 5 were shown at the Philadelphia APS meeting in November 1973. All cases are for neutral H_2 background.

The excitation energy loss term (PE3 in SIMULT) used in calculating these results is different from the one in PLP 556. PE3 was changed to the new version after the calculations discussed here were done; in this paper, PE3 is given by

$$PE3 = 10.44T_e^{1.085}[\exp(5.912T_e^{-1.08}) - 1.036] .$$

However, the new PE3 would make little difference in these results.

The first two examples simulate the PSL octupole with supports, and show results of two simulations differing only in the microwave input power. For both examples, background pressure is 10^{-6} Torr, magnetic field is 1 Kgauss maximum and plasma is an ECRH plasma, formed by 2.45 GHz CW microwaves. Example 1a is for 100 W microwaves, while 1b is for .5 W.

For 1a, the 100 W input power initially all goes into heating the low density ($10^6/\text{cm}^3$) electrons, which get quite hot (80 eV) and become quite efficient at ionizing the neutrals. This ionization raises the charged particle density and thus lowers the heating rate per particle, shown by the rapidly decreasing electron temperature.

Until just after peak field, particle loss is mainly to obstacles. Then, when the field starts to decay, field decay becomes the dominant particle loss mechanism, and the density drops. For most of the run, the main electron energy loss is to neutral excitation.

Ion temperature rises like the density as the ions are heated by electron-ion collisions. At late times, field decay particle loss is the dominant ion energy loss. The high T_i spike at very late times in both examples 1a and 1b are not physical - they result from failure of the numerical method when the magnetic field gets too low.

In example 1b, the power input is lowered to .5 W. The resulting density and temperature profiles change noticeably. Again, we see the electron temperature spike - but this time it is much lower, indicating that most electrons are cooler than the neutral ionization threshhold energy, so that little ionization occurs. As a result, the density builds steadily to a maximum at late times, when field decay again dominates the particle loss.

The T_e spike at early times has been experimentally observed.

Example 2 is an extension of examples 1a and 1b. Here we plot ion saturation current to a .5 cm^2 Langmuir probe versus CW microwave power, for the PSL octupole operated supported. Background pressure is 10^{-6} Torr H_2. The lower solid curve is computer prediction; the individual points are the corresponding experimental results.[2] The upper curve is for the levitated case. Agreement is very good between experiment and simulation.

This graph can be understood in terms of examples 1a and 1b. For the conditions described here, ion saturation current measured primarily the density. For high powers, the density peaks near max field and is quite large; for low powers T_e is too low to cause much ionization and the density peaks very late, when the field decay starts to dominate particle loss. Neutral excitation dominates the electron energy losses; excitation and obstacle losses combine to almost cancel out the electron energy gain due to microwaves.

The upper curve for the levitated case is in general agreement with observation. With levitation, a steady state is never reached and the density continues to build up until a large particle loss, due to field decay, results. Again the primary electron energy loss is to neutral excitation, and the knee around 1 Watt reflects the strong temperature dependence of the ionization rate.

Example 3 gives the predicted maximum ion saturation current to a Langmuir probe on the small octupole versus CW microwave power for four different neutral pressures: 1, 2, 5 and 10 x 10^{-5} Torr. This time the simulations are carried out to find the maximum power levels at which plasma is produced. The cutoff in each case is very sharp - for instance the 10^{-4} Torr case goes from much plasma to no plasma by increasing power by 10 W.

The same comments for case 2 apply to this graph. However near the upper cutoffs the density doesn't rise as fast as the saturation current - the hot electrons determine the value of J^+. Above the cutoff power levels, runaway electrons occur which cause breakdown of the program method.

Example 4 shows experiment[3] (circles) and prediction (solid curve), for the time evolution of ion saturation current in a gun injected plasma in the small octupole. J is in arbitrary units; theory was normalized to experiment at about 750 μsec after injection. Computer prediction is that obstacle loss is the dominant loss for both particles and energy. The experimental initial fast drop is probably from turbulence left over from the injection process. The experimental drop at late times comes from densities being measured by a probe on the separatrix, and as the field decays, the density peak moves towards the wall so that the measured density is lower than the average density.

Example 5 shows T_e versus time for the two milliseconds after gun injection for the same case as example 4. There is a noticeable difference between the experimental points[4] (x) and the solid curve prediction. However, this discrepency probably occurs for several reasons:

1. T_e can vary considerably in space,
2. Impurities aren't treated in our program,
3. Treatment of low energy excitation losses is still not perfect.

Again, obstacle loss dominates both particle and electron energy loss.

Example 6 shows charges particle density as a function of time, this time for a pulsed ECRH plasma. Time is measured from the start of the pulse. Experimental measurements[4] are by microwave perturbation (0's) and time integrated particle loss flux to hoops, walls and obstacles (x's). Again there is good agreement between prediction and experiment.

Particle losses are dominated by obstacle loss until near the break around 3 ms, when field decay dominates. These processes also account for energy losses.

REFERENCES

For a description of the computer program used to generate these examples, see:

1 J. R. Patau and J. C. Sprott, PLP 556.

2 J. C. Sprott, Phys. Fluids 14, 1795 (1971). See Fig. 5.

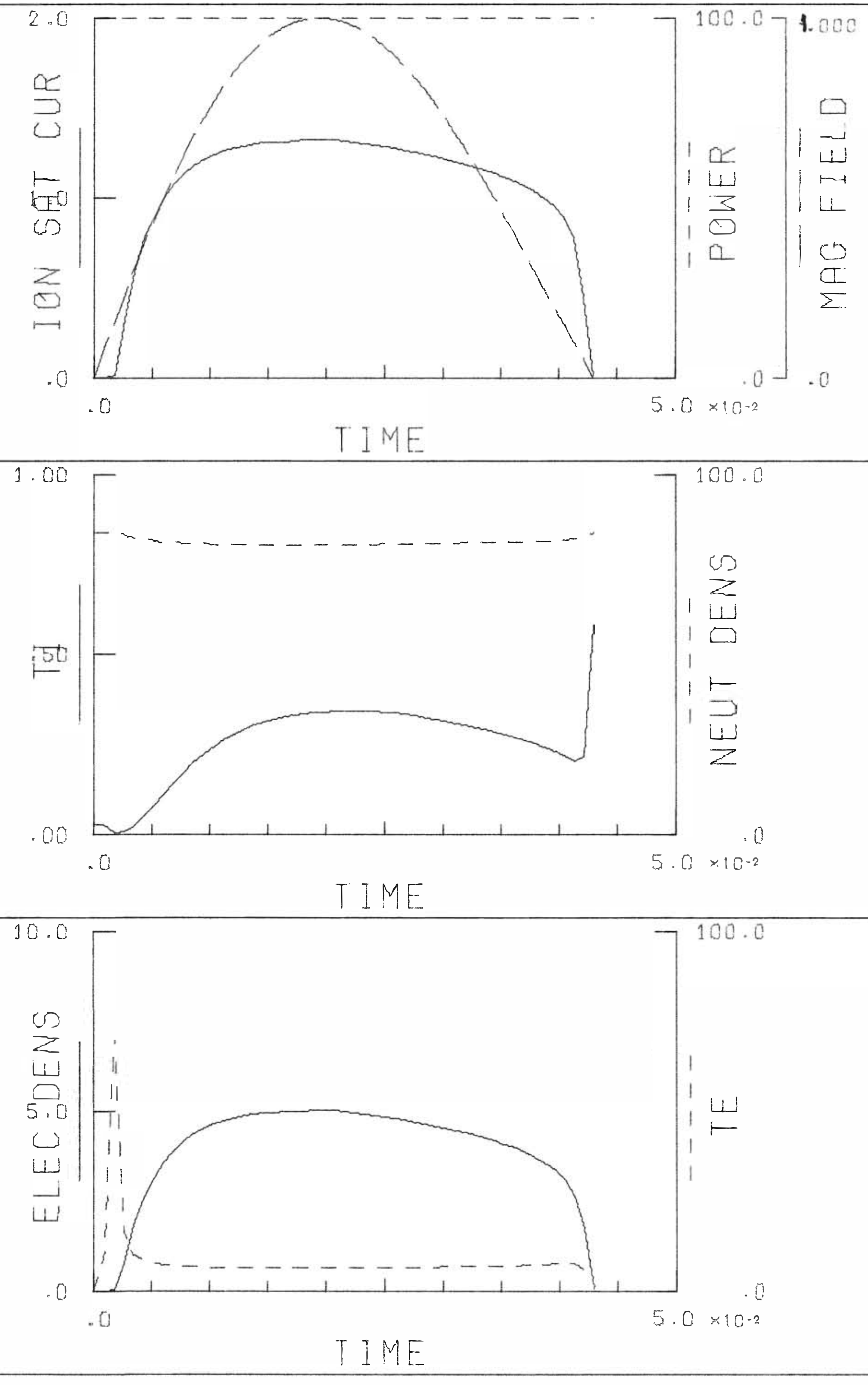
3 D. E. Lencioni, J. W. Poukey, J. A. Schmidt, J. C. Sprott and C. W. Erickson, Phys. Fluids 11, 1115 (1968).

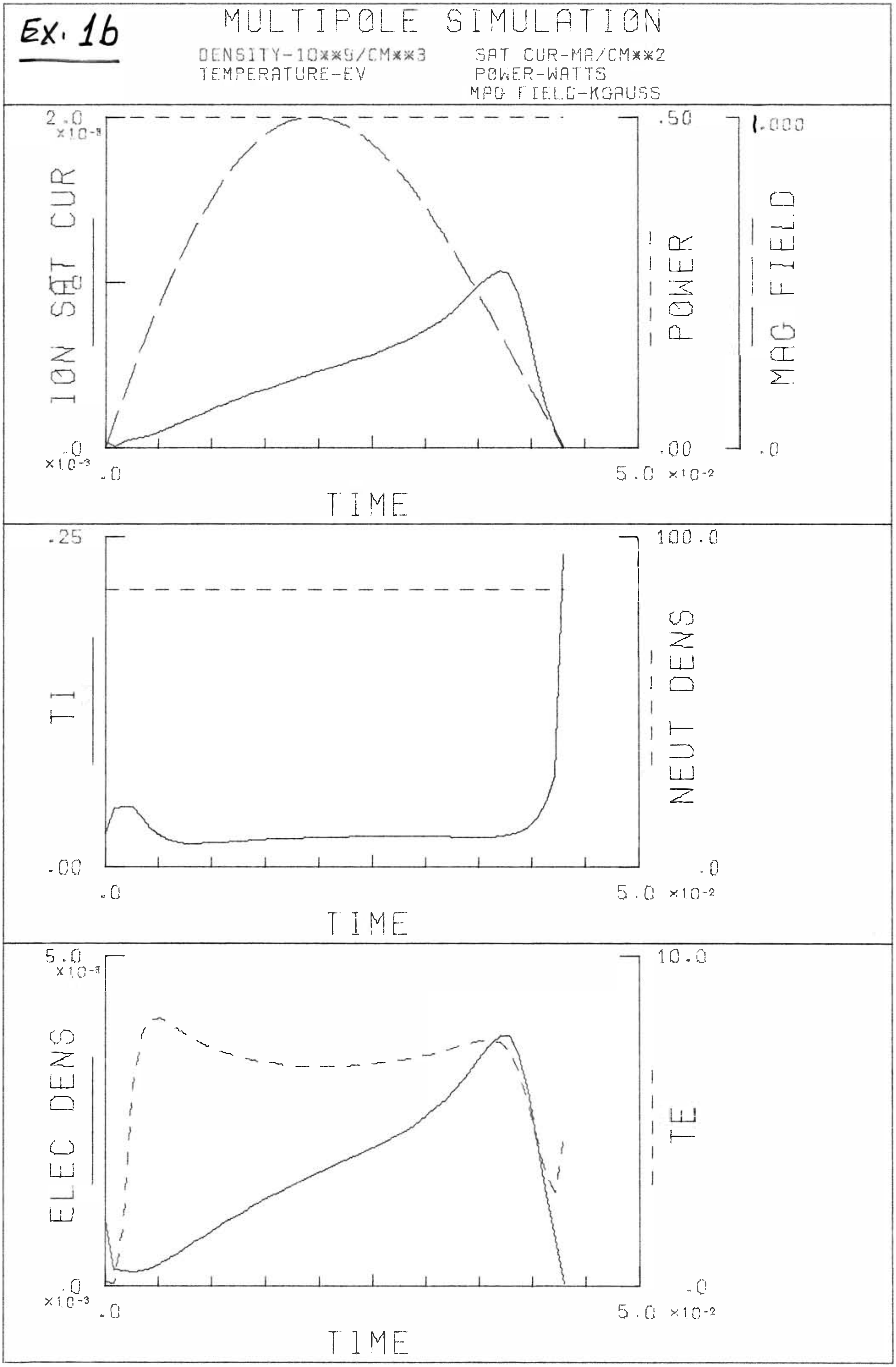
4 J. C. Sprott, Phys. Fluids 13, 1626 (1970). Example 5 - see Fig. 7 - curve labeled GUN - 10^{-6} TORR. Example 6 - see Fig. 6.

Ex. 1a

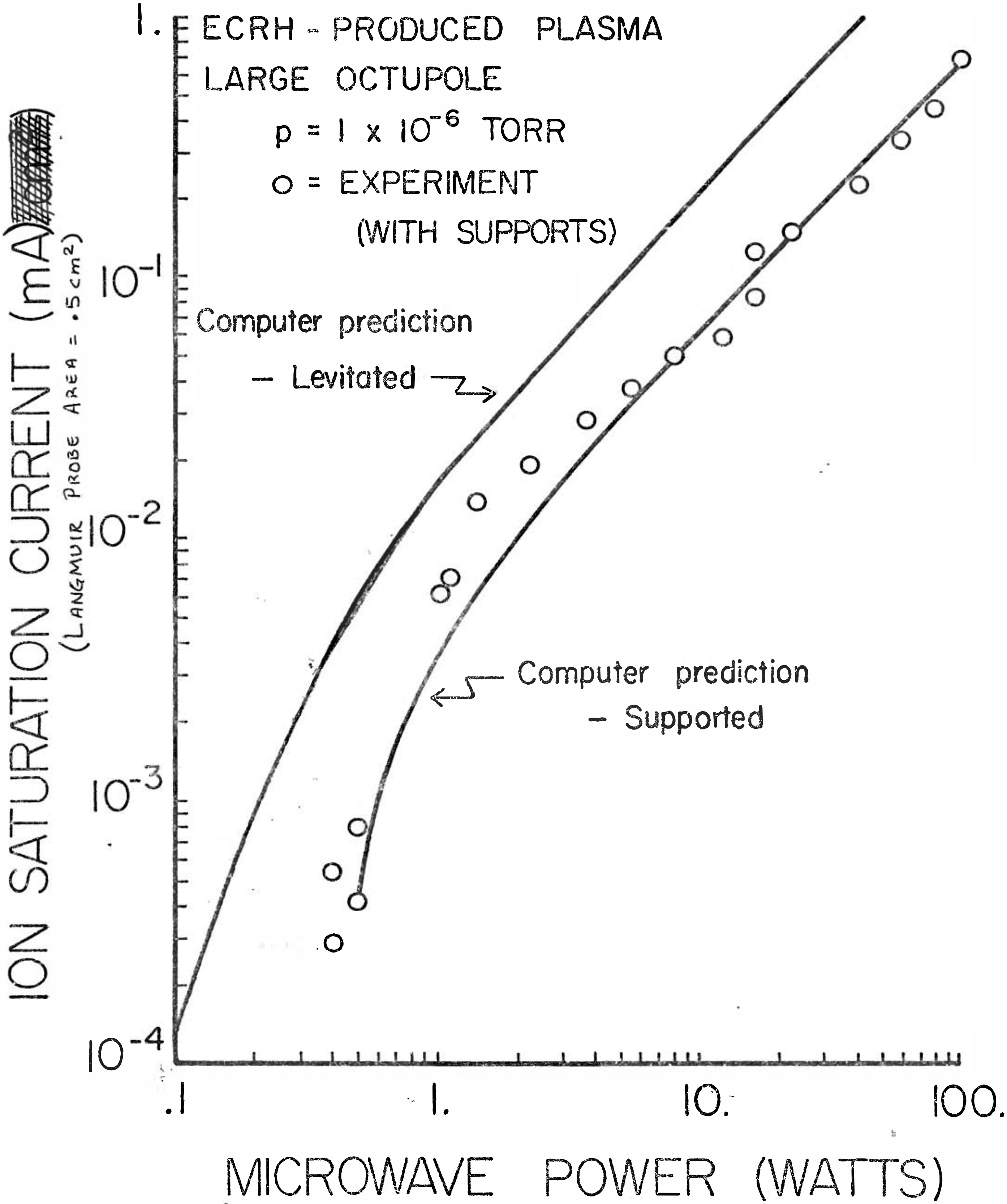
MULTIPOLE SIMULATION

DENSITY-10**9/CM**3 SAT CUR-MA/CM**2
TEMPERATURE-EV POWER-WATTS
MAG FIELD-KGAUSS



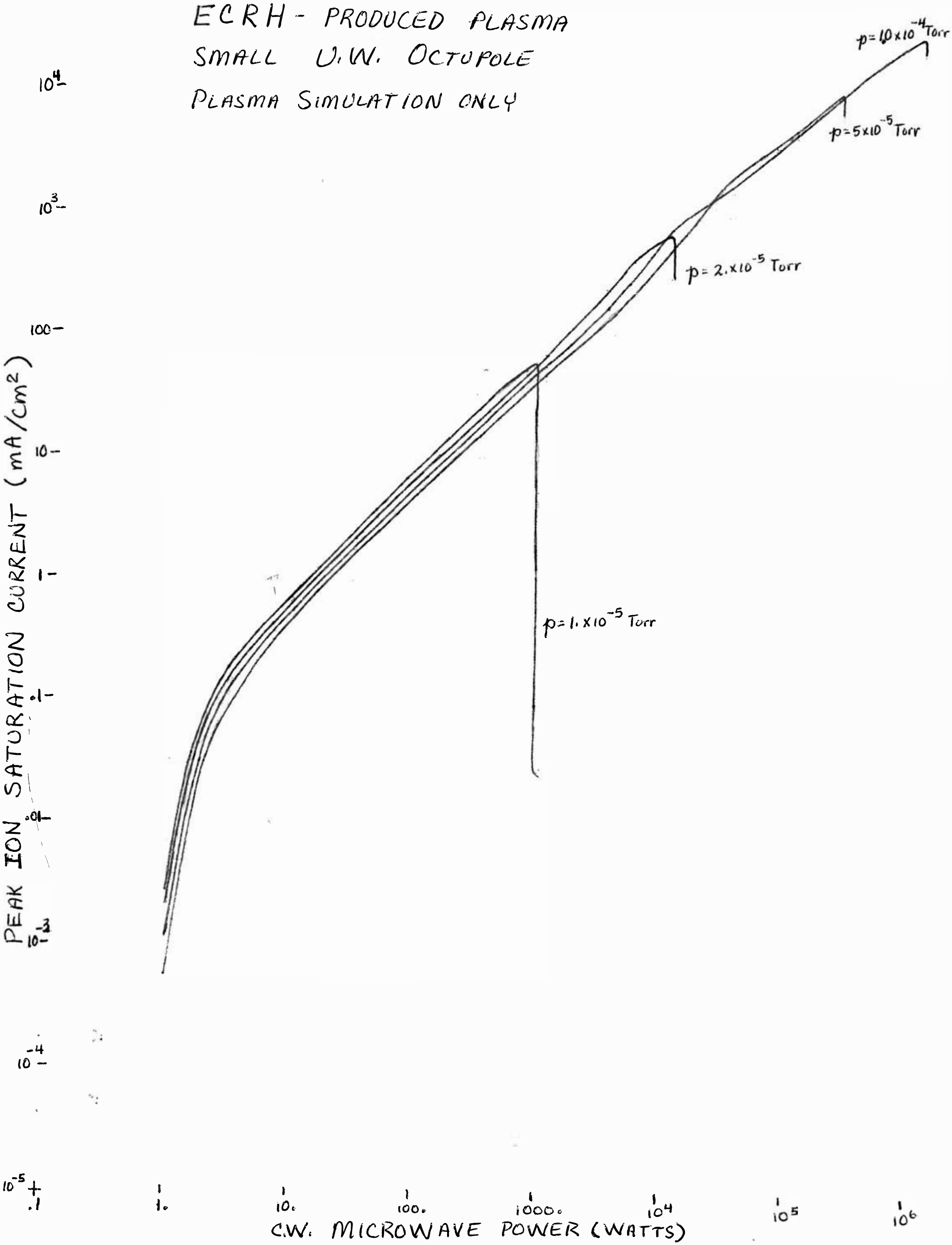

Ex. 1b
MULTIPOLE SIMULATION
DENSITY-10**9/CM**3
TEMPERATURE-EV
SAT CUR-MA/CM**2
POWER-WATTS
MAG FIELD-KGAUSS
2.0 x10-3
.50
1.000
ION SAT CUR
POWER
MAG FIELD
.0 x10-3
.00
.0
.0
5.0 x10-2
TIME
.25
100.0
TI
NEUT DENS
.00
.0
.0
5.0 x10-2
TIME
5.0 x10-3
10.0
ELEC DENS
TE
.0 x10-3
.0
.0
5.0 x10-2
TIME

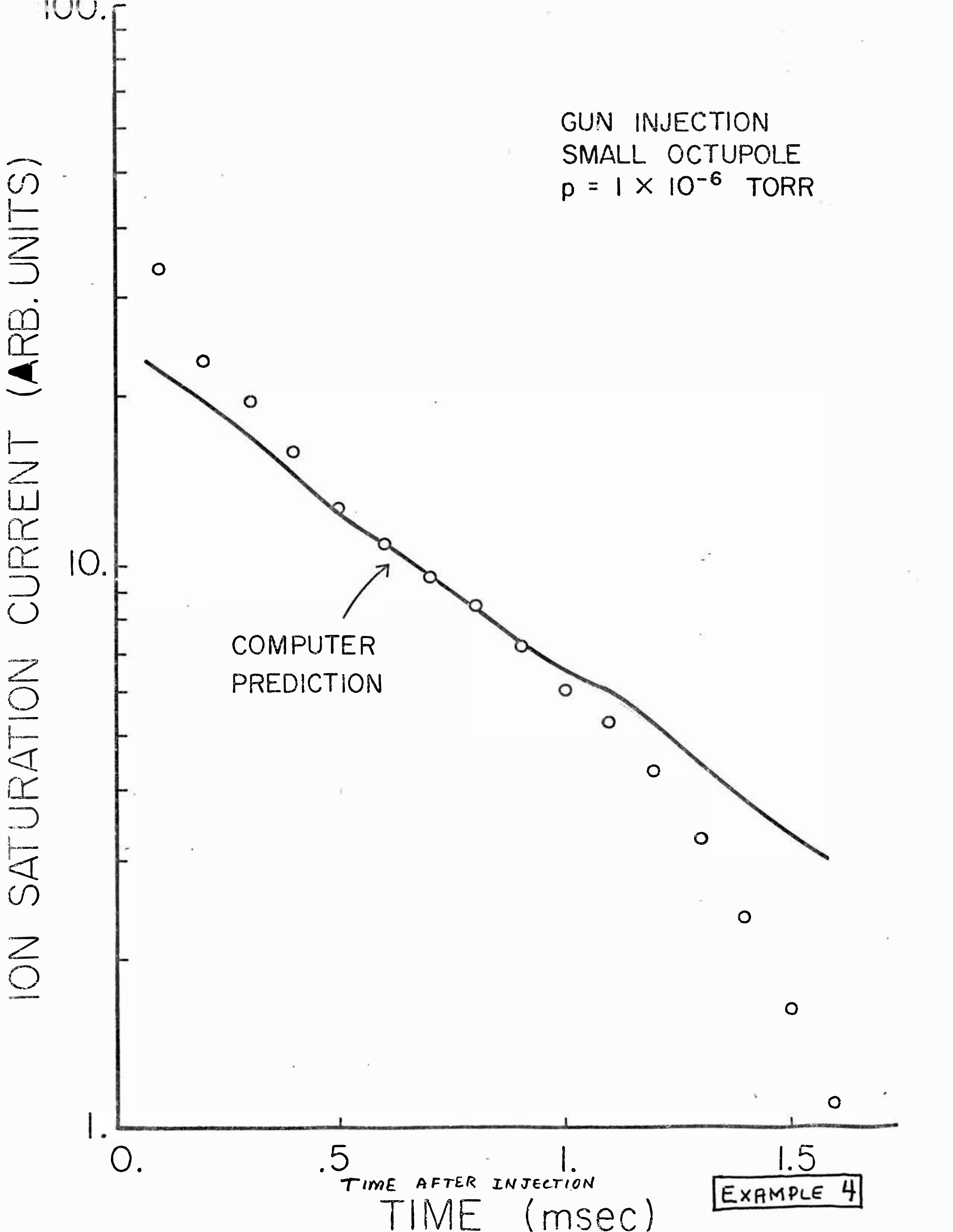
Ex.2

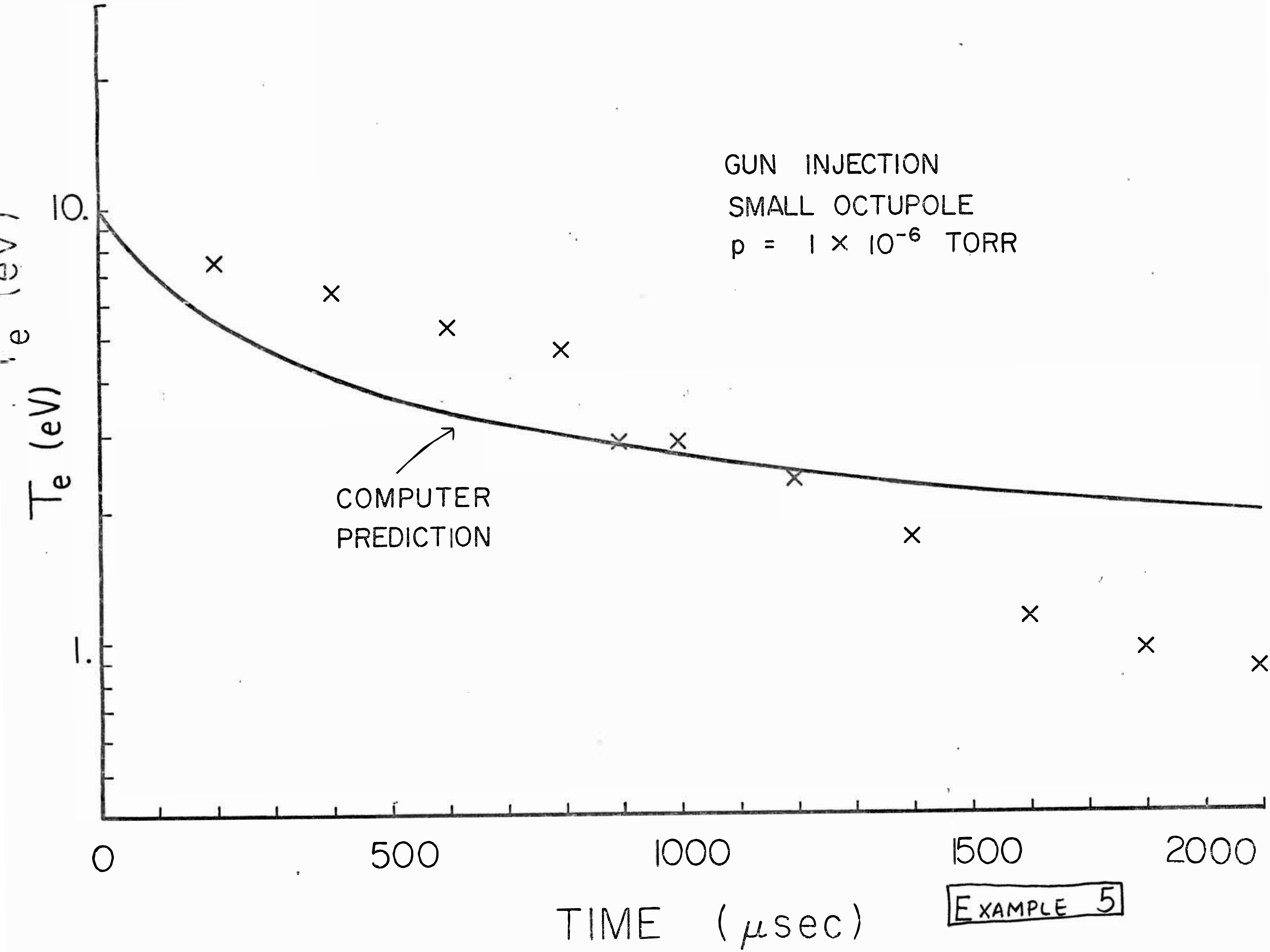


EXAMPLE 2

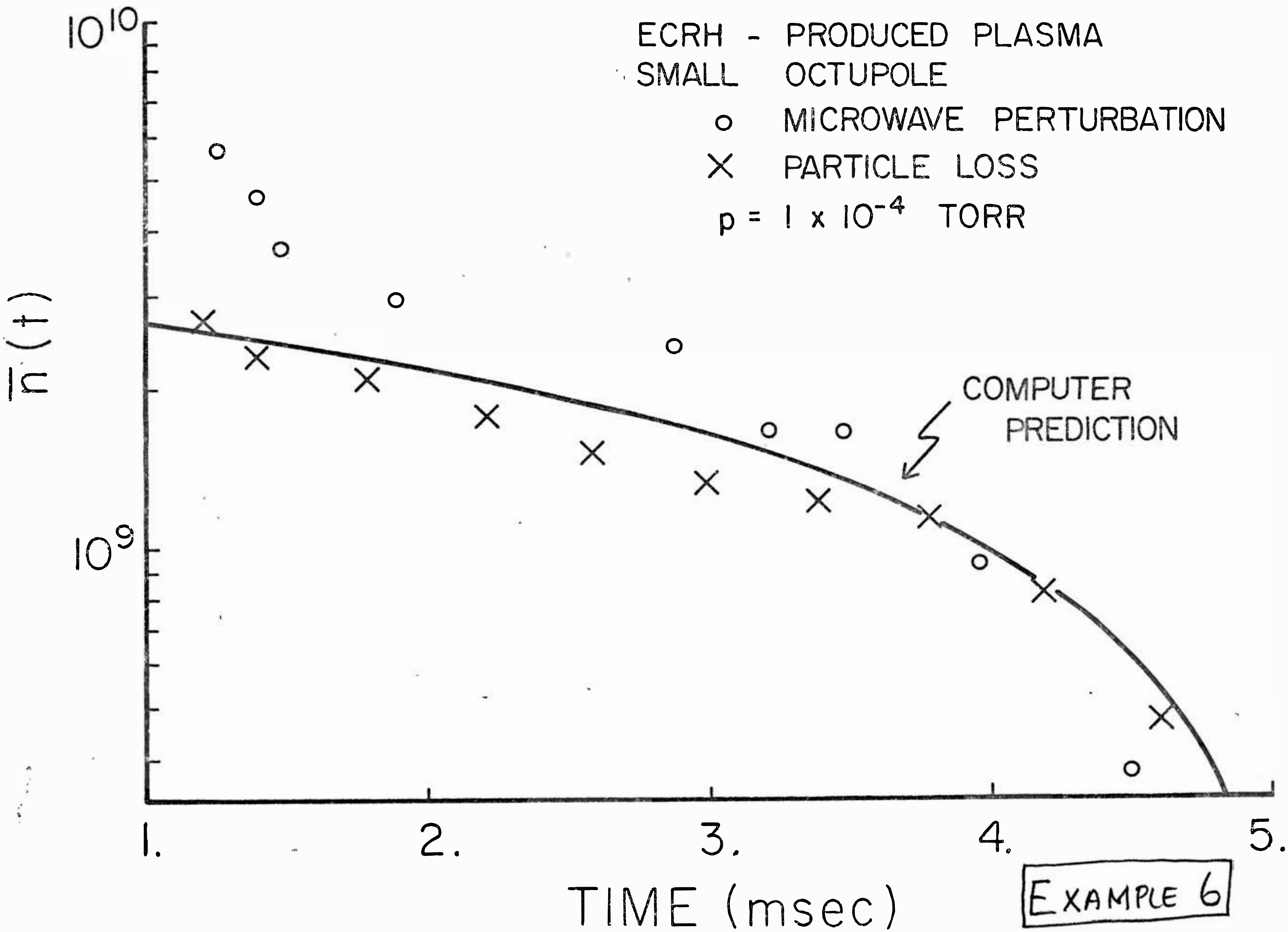
Ex. 3


ECRH - PRODUCED PLASMA
SMALL U.W. OCTUPOLE
PLASMA SIMULATION ONLY
p = 1.0 x 10^-4 Torr
p = 5 x 10^-5 Torr
p = 2. x 10^-5 Torr
p = 1. x 10^-5 Torr
10^4
10^3
100
10
1
.1
.01
10^-3
10^-4
10^-5
PEAK ION SATURATION CURRENT (mA/cm^2)
.1
1.
10.
100.
1000.
10^4
10^5
10^6
C.W. MICROWAVE POWER (WATTS)


GUN INJECTION
SMALL OCTUPOLE
p = 1 × 10⁻⁶ TORR
COMPUTER
PREDICTION
ION SATURATION CURRENT (ARB. UNITS)
100.
10.
1.
0.
.5
1.
1.5
TIME AFTER INJECTION
TIME (msec)
EXAMPLE 4


GUN INJECTION
SMALL OCTUPOLE
p = 1 × 10⁻⁶ TORR
COMPUTER
PREDICTION
10.
1.
T_e (eV)
0
500
1000
1500
2000
TIME (μsec)

EXAMPLE 5



ECRH - PRODUCED PLASMA
SMALL OCTUPOLE
o MICROWAVE PERTURBATION
X PARTICLE LOSS
p = 1 x 10^{-4} TORR
COMPUTER PREDICTION
10^{10}
10^{9}
$\bar{n}(t)$
1.
2.
3.
4.
5.
TIME (msec)

EXAMPLE 6