OBSERVATION OF DENSITY LIMIT IN A MICROWAVE PLASMA

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This report describes experiments done recently in the small toroidal octupole in which electron density was measured as a function of microwave power for an ECRH microwave-produced plasma. It has long been known that at low values of power the density increases linearly with power.[1] The plateau region where density ceases to increase with increasing microwave power was observed and the forward and reflected power were measured in order to see whether the observed density limit was due to an impedance mismatch between the microwave system and the plasma-filled cavity.

A block diagram of the experimental setup is shown in Fig. 1. A 2450 MHz magnetron capable of up to about 5 kW CW output power is used to produce the plasma; earlier experiments with a 1.5 kW magnetron had indicated that more power was needed to reach maximum density. The magnetron was isolated from the cavity and plasma by a pre-terminator claimed to attenuate reflected power by 35 dB; this was intended to eliminate the coupling of the plasma back to the magnetron seen when using an 8.5 dB isolator. A variable attenuator was used in conjunction with a variable current regulator supplying the magnetron to vary the rf power to the plasma. A directional coupler located after the attenuator samples the forward and reflected power. The forward and reflected power are measured using matched 1N21 diode detectors. The microwaves are fed into the octupole cavity through an E-H stub tuner which allows the impedance of the cavity to be matched so that reflected power from the empty cavity is only a few percent of the forward power. Power is coupled into the cavity through a window located in the midcylinder in the upper lid.

The weighted line-average Langmuir probe developed by E. Strait[2] was used to monitor the plasma. It was located between the lower outer hoop and the outer wall.

Fig. 2 shows a typical succession of shots at increasing power levels. The microwave power waveform is roughly a square wave starting about .5 msec after the rise of the magnetic field and lasting about 4 msec. Measurements of the forward power, reflected power, and ion saturation current were made at the arbitrarily chosen time of 2.5 msec after the start of the magnetic field rise; this is approximately peak magnetic field. Note that as in b, c, and d of Fig. 2, the shape of the ion saturation current signal from 0 to 2.5 msec is still changing with increasing input R.F. power, while the value at 2.5 msec, which was used to derive the subsequent plots, and later times is almost constant as the input power level is increased. The decay in the ion saturation current as microwave power continues to be pumped in c, d is perhaps due to some spatial shifting of the plasma; no attempt has been made to spatially resolve the density profile. The $<\eta_e>$ shown is a volume-averaged density.

Fig. 3 and the center curve in Fig. 4 show the dependence of $<\eta_e>$ on the input microwave power at $t = 2.5$ msec. The error bars shown are typical and represent variations within a few hundred microseconds of the measurements. The electron temperature was measured at several points in the plateau region on the right of Figs. 3 and 4 by sweeping Strait's probe from - 40 V to + 60 V in 100 μsec; it was found to be constant to within measurement accuracy at 8-10 eV. A value of 8 eV was assumed in deriving the densities shown in Figs. 3, 4 from the ion saturation current with the probe biased to - 45 V.

The three density curves in Figs. 3 and 4 were obtained at three different voltages on the capacitor bank that supplies the magnetic field energy. In each case the density reaches a plateau beyond which further increase in microwave power produces no further density increase. One might expect this plateau to be reached around a density given by

$$f = 2450 \text{ MHz} = f_p = 9 \quad n(\text{cm}^{-3}) \times 10^3$$

or

$$n \cong 7.4 \times 10^{10} \text{ cm}^{-3}$$

whereas the experimentally determined densities are roughly a factor of two or three below this in the plateau region. The measured densities are also somewhat below what other people have measured recently, so the discrepancy may be partly due to probe contamination or some other effect.

The reflected power measurements for a bank voltage of 2.0 kV are also plotted in Fig. 4 vs. microwave input power; similar results were obtained at 1.5 and 2.5 kV bank voltages. The fluctuations in the reflected power were fairly high (see Fig. 5) but there is no obvious dependence of P_{refl} on the plasma density. The reflected power is in general small compared to the forward power, and is fairly constant as the input power is varied.

One reproducible effect observed in the reflected power is the peak at the end of the microwave forward power pulse, shown in Fig. 5. The fact that it shifts to later times as the bank voltage is increased suggests it is connected with a fixed value of magnetic field, e.g. the resonance zone sweeping by the microwave window might cause a momentarily high reflection. The magnetic field values corresponding to the time at which the peak in reflected power occurs for the various bank voltages are within 15% of one another. Also, at high power levels as in d), Fig. 5, a peak in the reflected power occurs at the beginning of the microwave pulse (about 1.1 msec in Fig. 5d) at the same magnetic field value as the second peak.

Some dependence of maximum obtainable density on bank voltage (corresponding to magnetic field strength) can be seen in Figs. 3 and 4. Fig. 6 shows this dependence explicitly. The microwave input power levels in this case were presumably high enough so that the density was in the plateau region: there appears to be a fairly well-marked transition from low-field, low density plateau region to a region with a higher density plateau at a bank voltage of about 2.5 kV. This transition occurs approximately at the point where the resonance zone sweeps by the microwave window during the initial breakdown, and suggests that the heating at high densities is better when the microwaves are incident on the resonance from the high field side. A similar conclusion was reached by Wong.[3]

The observed saturation of density as the input microwave power is increased, suggests a pronounced drop in heating at high densities. In fact, Wong[3] has measured that the normalized ECRH rate (G) falls sharply in accordance with the theoretical prediction

$$G = G_o \exp\left(- 4\pi^2 B_o \omega_p^2 / \lambda |\nabla_\parallel B|_o \omega^2\right) .$$

In order to test this prediction, program SIMULT[4] was modified to include a term

$$G = G_o \exp\left(- 0.03\, an/f\right) ,$$

where a is the plasma minor radius (cm), n is the average plasma density (cm^{-3}), and f is the microwave frequency (Hz). The result of the simulation is shown in Fig. 4 and agrees quite well (factor of 2) with the observed values of density.

We are therefore inclined to conclude that a density limit exists for ECRH plasmas at a density the order of the critical density ($\omega_p = \omega$), but at a value that depends on the magnetic field shape and cavity Q, and that in sufficiently large cavities, the power not absorbed by the plasma is absorbed by the cavity walls and is not reflected back to the microwave source. It would then appear ineffective to attempt to improve the impedance match between the source and the plasma, but some improvement might be obtained by a different location of the microwave input (i.e., in the bridge region).

FOOTNOTES

1. J. C. Sprott, Phys. Fluids 14, 1795 (1971).
2. This probe is a modified version of the one designed for the large octupole, described in PLP 566, averaging probe for the large octupole. E. Strait (May 1974).
3. K. L. Wong, Ph.D. thesis, University of Wisconsin (PLP 601).
4. PLP 556. Numerical Simulation of Multipole Confinement. (Revised). J. R. Patau and J. C. Sprott (March 1974).

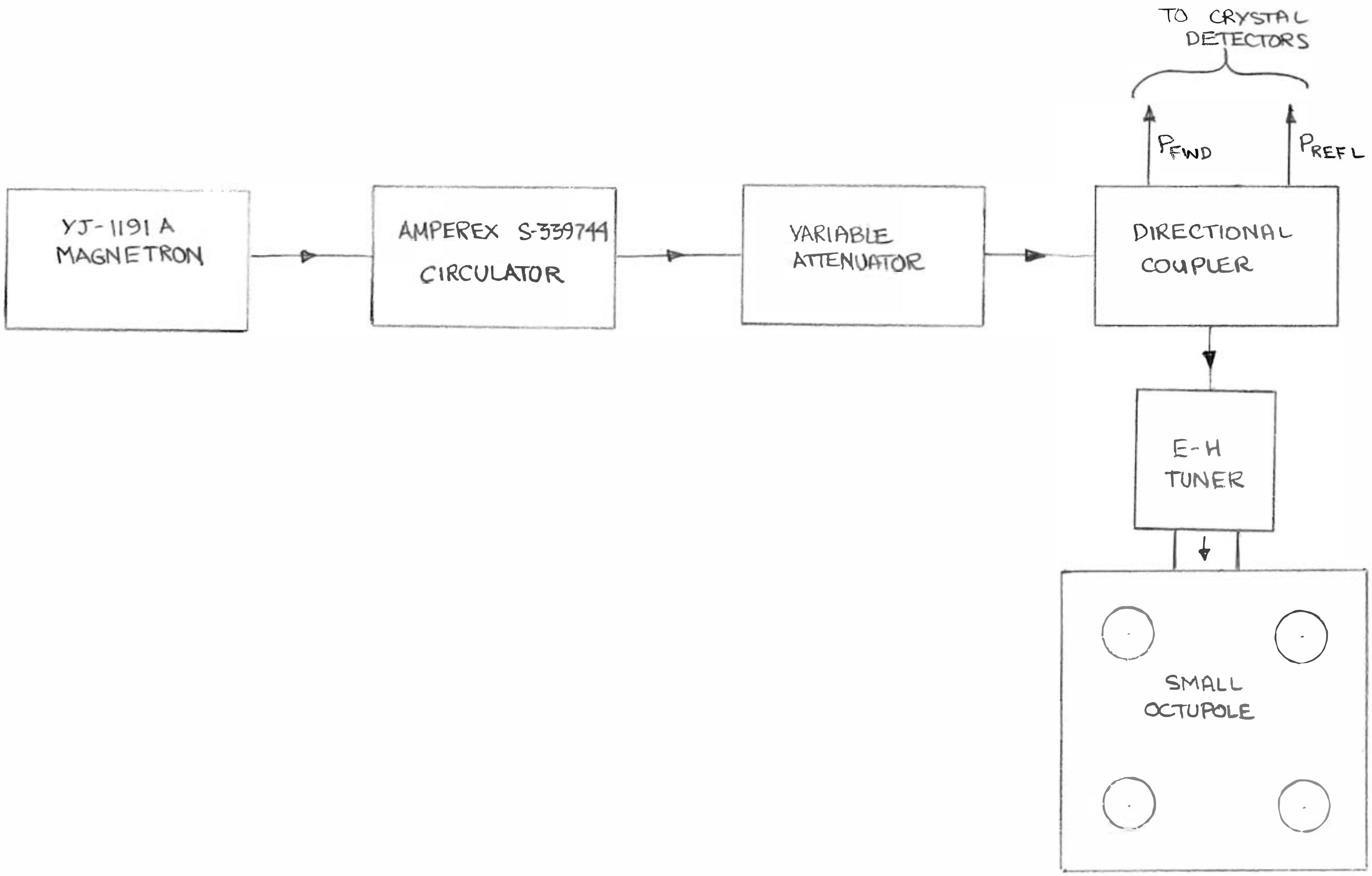
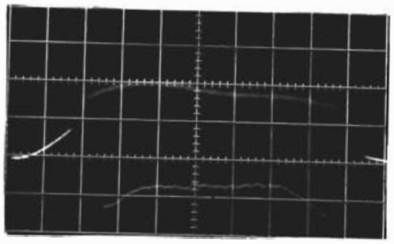
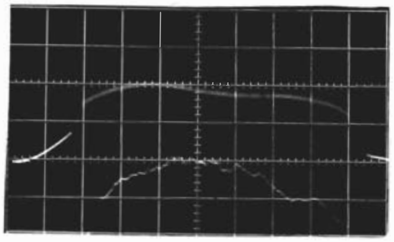


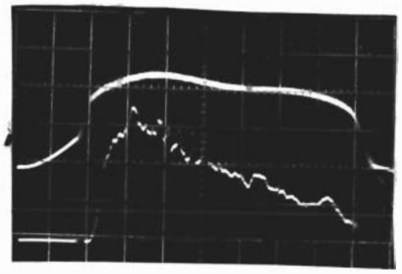
FIG. 1. BLOCK DIAGRAM OF SETUP.



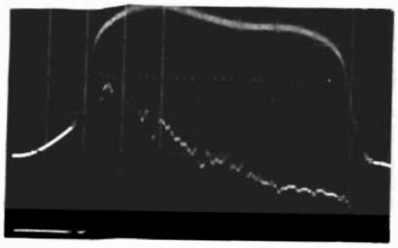
(a) MICROWAVE POWER .5 kW



(b) MICROWAVE POWER .8 kW



(c) MICROWAVE POWER 1.2 kW



(d) MICROWAVE POWER 2.5 kW

FIG. 2. TOP: MAGNETRON CURRENT, .2 A / DIVISION

BOTTOM: ION SATURATION CURRENT TO 2.13 cm^2 PROBE, 5 ma / DIVISION

HORIZONTAL SCALE .5 msec/ DIVISION. BANK VOLTAGE 2.0 kV.

THE MICROWAVE INPUT POWER IS NOT PROPORTIONAL TO THE MAGNETRON CURRENT BECAUSE A VARIABLE ATTENUATOR WAS USED TO REGULATE THE MICROWAVE POWER.

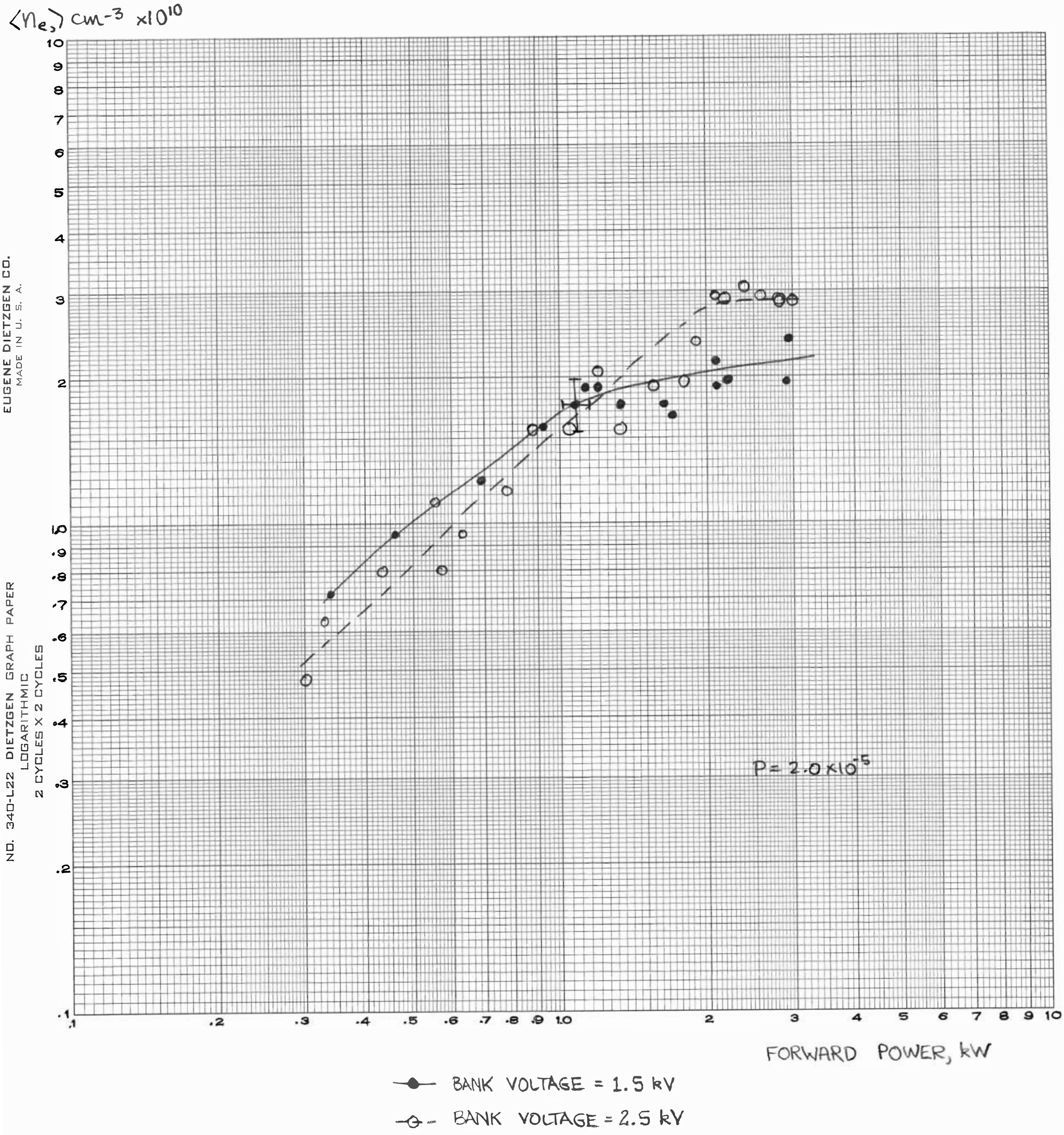

⟨n_e⟩ cm^-3 ×10^10
10
9
8
7
6
5
4
3
2
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
2
3
4
5
6
7
8
9
10
FORWARD POWER, kW
P= 2.0×10^-5
BANK VOLTAGE = 1.5 kV
BANK VOLTAGE = 2.5 kV

FIG. 3

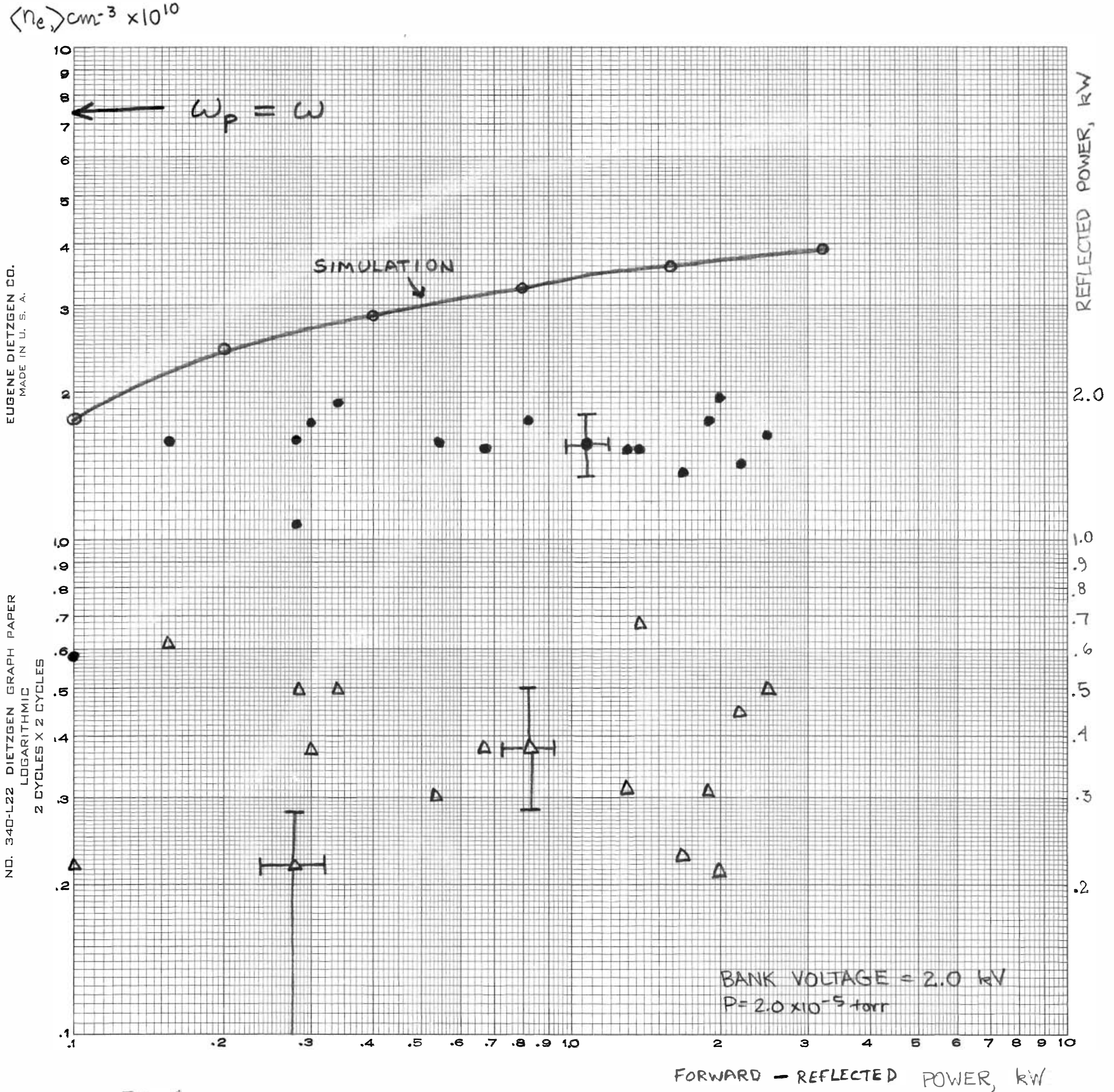
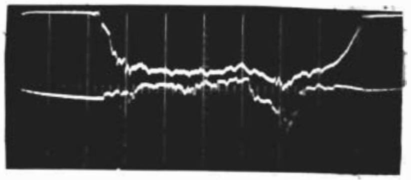


FIG. 4

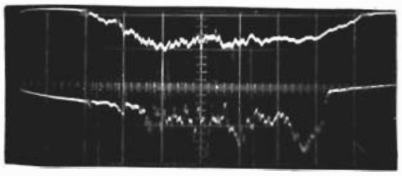
● EXPERIMENTAL DENSITY MEASUREMENTS

○ SIMULT COMPUTER SIMULATION DENSITY

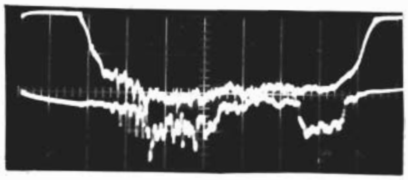
△ EXPERIMENTAL REFLECTED POWER



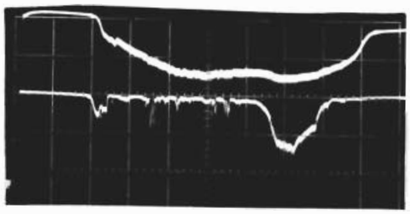
(a) BANK VOLTAGE 1.5 kV
MICROWAVE POWER = 1.7 kW



(b) BANK VOLTAGE 2.0 kV
MICROWAVE POWER = .8 kW



(c) BANK VOLTAGE 2.5 kV
MICROWAVE POWER = 2 kW



(d) BANK VOLTAGE 1.5 kV
MICROWAVE POWER = 3 kW

FIG. 5

TOP: FORWARD POWER, SCALES VARIABLE
BOTTOM: REFLECTED POWER, SCALES VARIABLE
HORIZONTAL .5 msec/cm

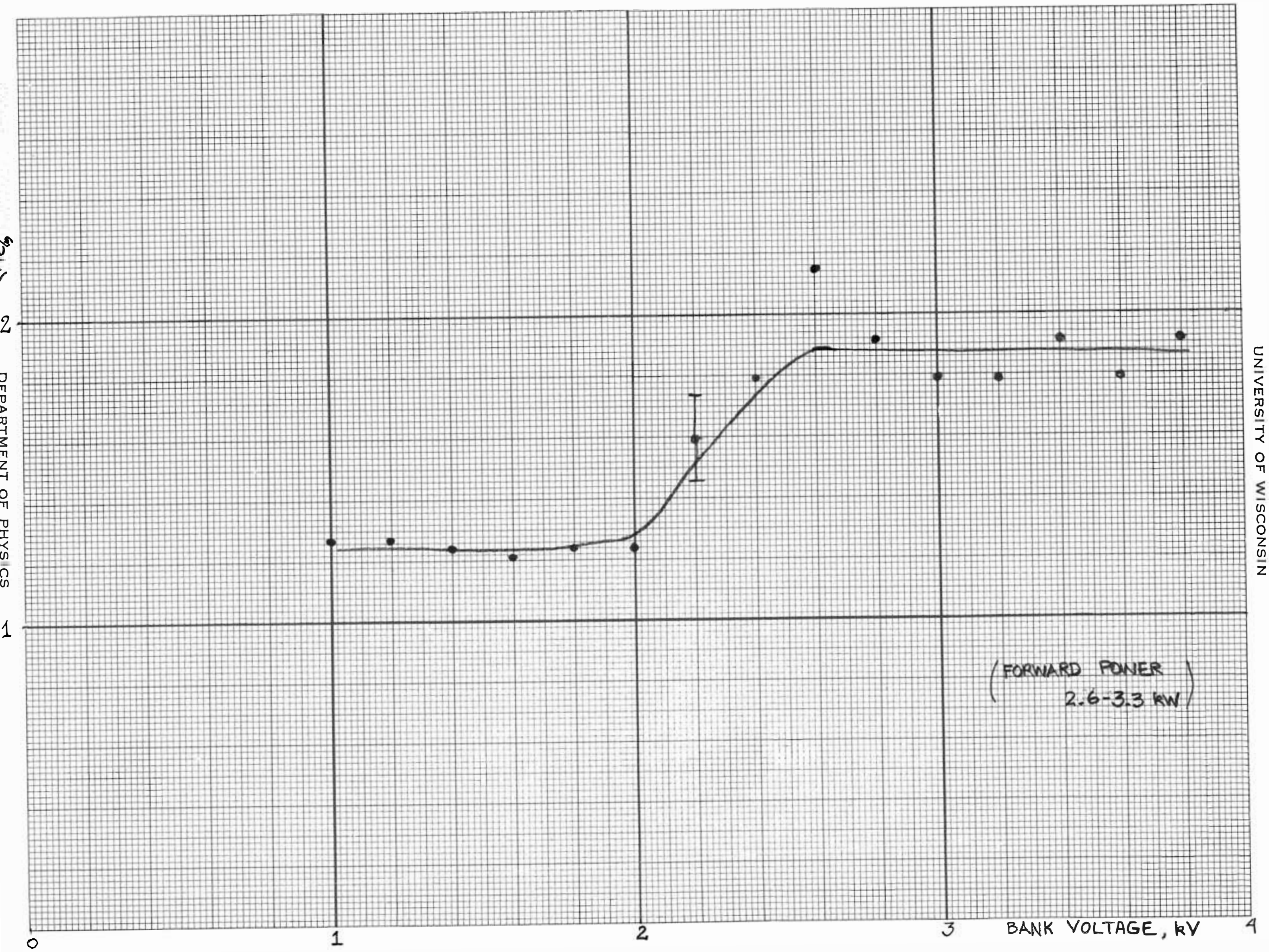

2
1
0
1
2
3
4
BANK VOLTAGE, kV
(FORWARD POWER
2.6-3.3 kW)

FIG. 6. DENSITY AT 2.5 msec vs. BANK VOLTAGE FOR HIGH MICROWAVE POWER INPUTS.