Admittance Probe Measurements of Electron Temperature in the Octupole

by

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The difficulty of measuring the electron temperature with single probes in the toroidal octupole was discussed in PLP 175. This note describes a new method of measuring electron temperature using an admittance probe.

The admittance probe is discussed in PLP 74. Briefly, it consists of placing the probe-to-plasma (sheath) impedance across one leg of a capacitance bridge. The bridge is driven by a low voltage sine wave and balanced to give zero output in the absence of plasma. For a driving frequency well below the ion plasma frequency, the sheath is purely resistive, and for driving voltages much less than kT_e/e, it has been shown theoretically (PLP 88) and experimentally (PLP 167) that the admittance is accurately given by

$$Y = \frac{1}{R_s} = \left.\frac{di}{dV}\right|_{V_f} = \frac{eI_{oi}}{kT_e} \qquad (1)$$

where T_e is the electron temperature and I_{oi} is the ion saturation current drawn by the probe when biased strongly negative.

The temperature measurement consists essentially of measuring Y with an admittance probe circuit and measuring I_{oi} using the same probe as a single Langmuir probe on subsequent shots. The electron temperature is then calculated from equation (1). Alternately, two identical probes could be used to measure Y and I_{oi} simultaneously.

The admittance probe method is closely akin to the double probe method of measuring T_e in that it involves a measurement of both ion saturation current and the slope of the V-i curve at the floating potential. Like the double probe, the admittance probe suffers from the disadvantage that, for a Maxwellian electron velocity distribution, only the most energetic 2% of the electrons are sampled, and hence, for a non-Maxwellian distribution, the temperature inferred from these probes may not be representative of the bulk of the electrons. The admittance probe has several advantages over the double probe, however:

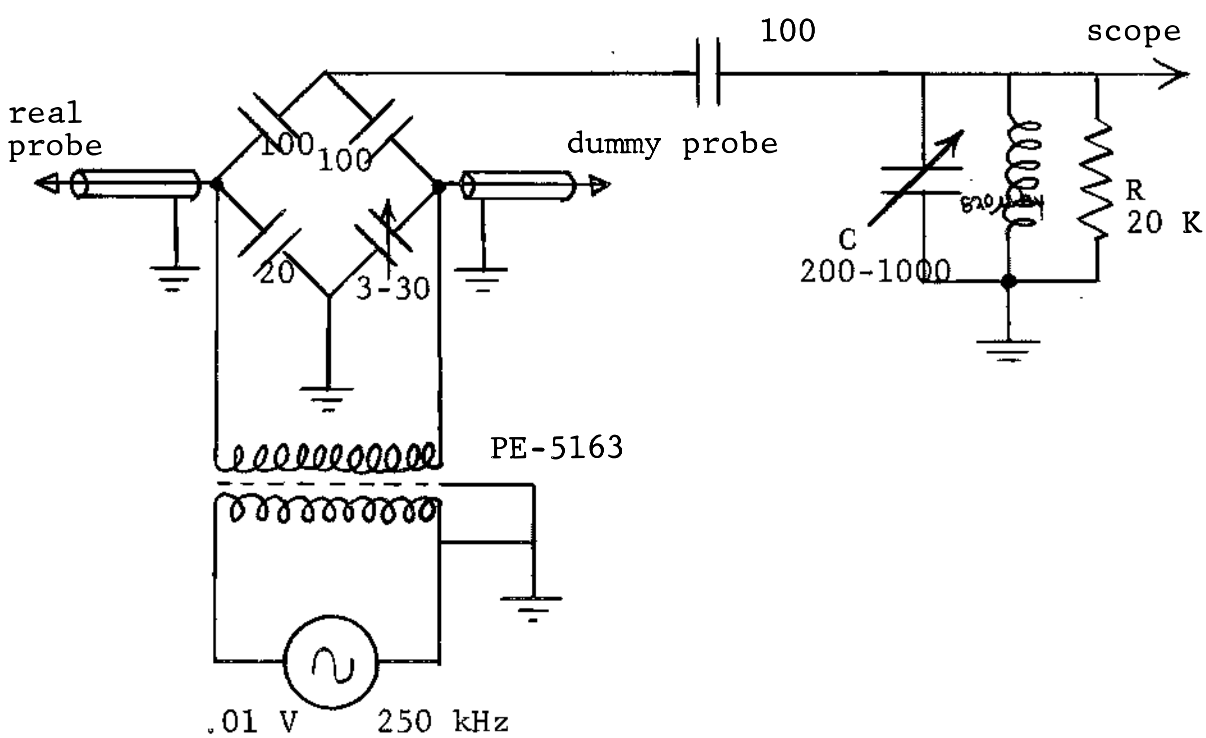
1) Data reduction is easier since it is not necessary to plot out a V-i characteristic.

2) Probe construction is simpler since only one electrode is required.

3) The probe radius can more easily be made large compared with a Debye length giving better ion saturation.

4) High common mode rejection is not necessary since no differential amplifier

The circuit used with the admittance probe is shown below:



The dummy probe consists of a length of microdot cable equal to the length of the cable on the real probe. The rf source is a 250 kHz crystal oscillator with a peak-to-peak output of 10 mV. This frequency was chosen so as to be much less than the ion plasma frequency at the lowest density anticipated. (f_{pi} = 2.1 MHz at n = 10^8 cm^{-3}). The resonant circuit eliminates interference from floating potential variations. The load resistor is required to damp the resonance in order to achieve a satisfactory frequency response. The response time of the admittance probe is approximately

$$\tau = \frac{Q}{2\pi f} = RC \approx 10 \ \mu sec \tag{2}$$

which is adequate for measurements in the octupole during the quiescent decay. The probe is calibrated by connecting various resistors between the probe tip and ground and measuring the output signal. The output is proportional to admittance for $R_s > 10$ K although the probe is useful down to $\sim$1 K if a suitable calibration curve is prepared.

The above described method has been applied to measurement of electron temperature for the gun and microwave plasma in the octupole. A 1/8" x 1/8" cylindrical probe was used. Ion saturation current was determined by measuring the current to the probe for -45 volts and -22.5 volts bias, and linearly extrapolating the result to zero bias. Admittance measurements gave values of R_s in the 10 K-300 K ohm range.

Fig. 1 shows the result for three cases. The gun plasma at a background pressure of 10^{-6} torr has an electron temperature which is initially ~ 10 eV and decays with a time constant of ~ 800 μsec. These observations are in good agreement with those of Meade (PLP 163) using a swept single probe. The microwave plasma with a background pressure of 5×10^{-5} torr has an electron temperature which is considerably lower and which decays somewhat faster than the gun plasma in rough agreement with measurements made by the much cruder method described in PLP 165. When the background pressure is raised to 5×10^{-5} torr for the gun plasma, the temperature decay closely resembles that of the microwave plasma. Since the microwave plasma is produced 700 μsec earlier than the gun plasma with respect to the confining magnetic field pulse, we expect magnetic compression to reduce the decay rate of the microwave plasma temperature. Assuming $\delta T_e/T_e \propto \delta B/B$, the difference after 2 msec should amount to a factor of two, in good agreement with the observation.

The admittance probe also allows one to calculate the density for plasmas with $T_i < T_e$ since the sheath criterion requires that the ion saturation current be given by

$$I_{oi} = neA\sqrt{\frac{kT_e}{2\pi M}} \qquad (3)$$

where n is the density, A is the probe area and M is the ion mass. Applying this method to the microwave plasma gives a density decay as shown in Fig. 2. This local density measurement strongly resembles the average density measurements of PLP 165. Note particularly the 3 msec lifetime at $\sim 1000\ \mu$sec. The increased decay after 1500 μsec is probably caused by the magnetic field expansion which moves the density peak off the separatrix.

Finally, it is of interest to measure the gun electron temperature vs. background pressure. Since the gun plasma presumably has an initial temperature which is independent of background pressure (T_e = 10 eV at t = 0), measurements at a later time give an indication of the cooling effect of background neutrals. Fig. 3 shows the electron temperature of the gun plasma at 1 msec for background pressures between 10^{-6} and 10^{-4} torr. The pressure readings were made directly from the Bayard-Alpert ionization gauge on the toroid and probably are somewhat low because the gauge is calibrated for air rather than hydrogen. The temperature is not strongly pressure dependent for pressures below $\sim 10^{-5}$ torr, but for higher pressures, the decay rate becomes quite sensitive to pressure.

Some attempts have been made to understand quantitatively the temperature decay. For example, hanger losses can be estimated by a method suggested by Erickson in PLP 100. In slightly modified form, his prediction for a collision dominated plasma is that the temperature obey the equation

$$T = \frac{T_o}{[1 + .188\ \bar{v}_o\ t/\lambda]^2} \qquad (4)$$

where T_o is the initial temperature, $\bar{v}_o$ is the initial average velocity and λ is the mean free path for collection on hangers. The mean free path is estimated from

$$\lambda = 4 \frac{V}{A} \frac{I_{oe}}{I_{oi}} = 4 \frac{V}{A} \sqrt{\frac{T_e M}{T_i m}} \qquad (5)$$

where V is the volume of the toroid and A is the geometrical area of the hangers. The ratio of electron to ion saturation current I_{oe}/I_{oi} is included to account for the fact that electrons can be collected only as fast as the ions. The prediction of equation (4) is that an initial 10 eV electron distribution should decay to $\sim$ 5.5 eV in 1 msec.

The effect of magnetic field expansion is easily taken into account by using an analytic expression for the multipole field pulse:

$$T_e \; (t) \propto B(t) = B_o e^{-t/10} \sin 2\pi \frac{t}{10} \qquad (6)$$

where t is in milliseconds. For the interval 1800 - 2800 μsec, field expansion would account for only $\sim$ 2% decrease in T_e.

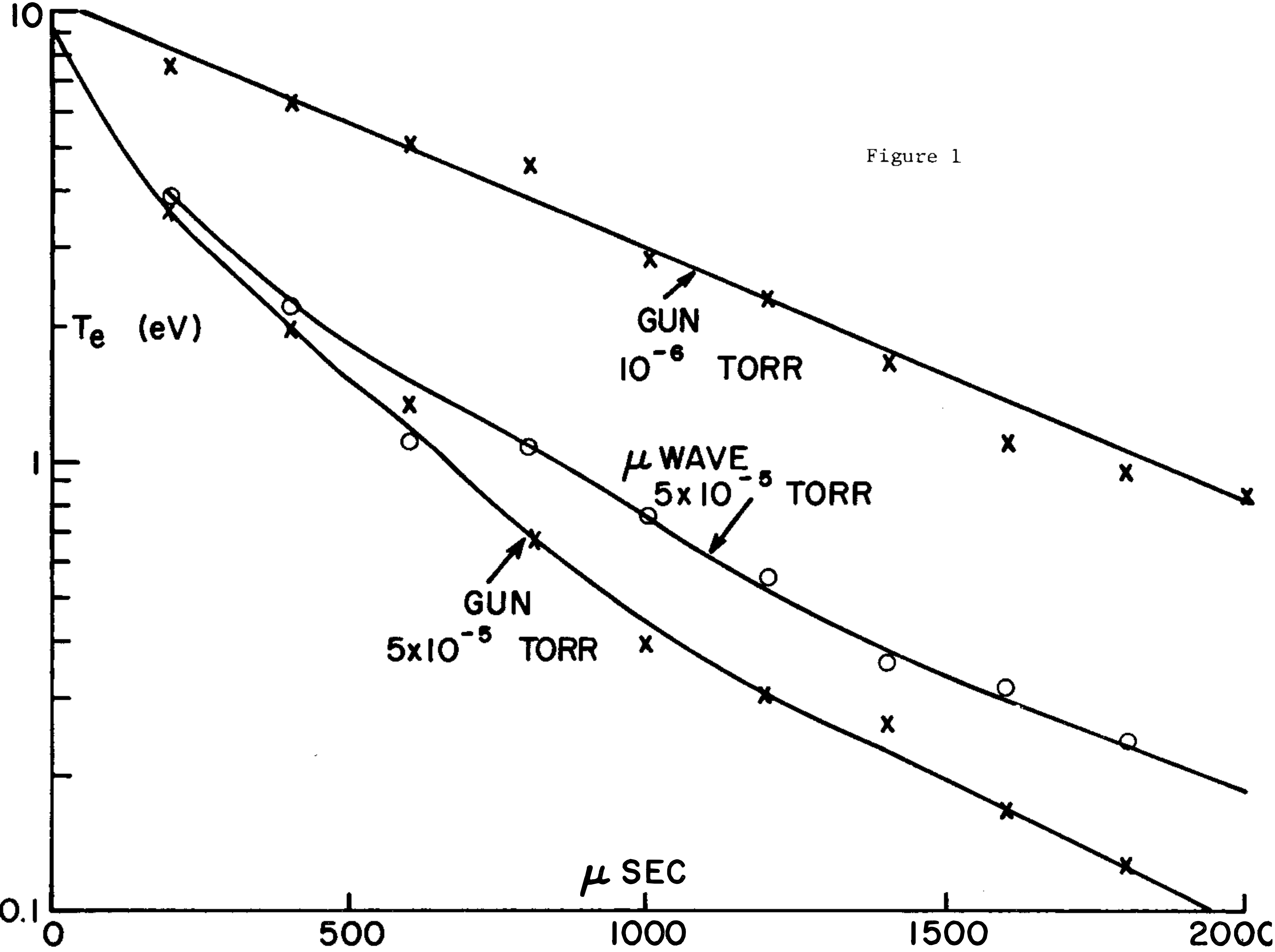
Perhaps the most complicated, and certainly the dominant losses at high pressures, are inelastic collisions with neutrals. Some attempts to calculate ionization losses were made in PLP 142. These results, when applied to the present case, give a temperature decay as indicated in Fig. 3. The calculation was only carried out to a temperature of 3 eV, and seems to account for a large part of the temperature decay. Excitation losses could be calculated in the same way, and certainly must dominate at very low temperatures.

In the foregoing discussion, it has been implicitly assumed that the electron velocity distribution is Maxwellian. Since both hanger and ionization losses are expected to destroy the thermal equilibrium, a knowledge of the electron thermalization time is crucial. This time is given by Spitzer as

$$\tau_{ee} = 0.266 \frac{T_e^{3/2}(°K)}{n(cm^{-3}) \ln \Lambda} \tag{7}$$

where $\ln\Lambda \approx 13$. In the worst case considered here ($kT_e \sim 10$ eV, $n \sim 10^9$ cm^{-3}), $\tau_{ee} \approx 650$ μsec, which is comparable with the decay time. Meade's observations (PLP 163) using a swept probe show $\ln I \propto V$ over 1 1/2 decades indicating that the distribution is probably adequately Maxwellian. For the microwave plasma, the situation is considerably better since T_e is smaller and n larger.

Figure 1



10
1
0.1
Te (eV)
GUN
10^-6 TORR
μ WAVE
5x10^-5 TORR
GUN
5x10^-5 TORR
μ SEC
0
500
1000
1500
2000

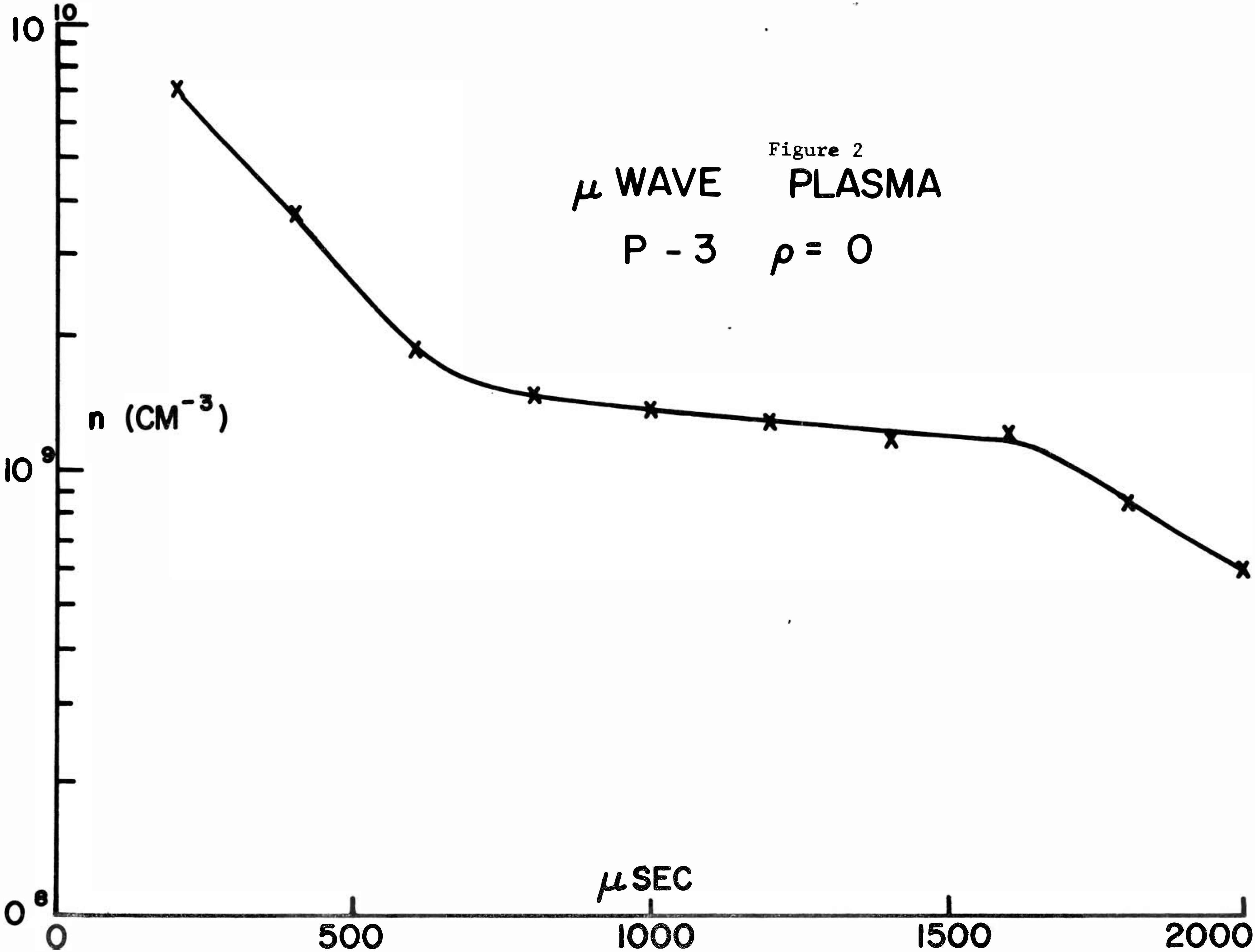
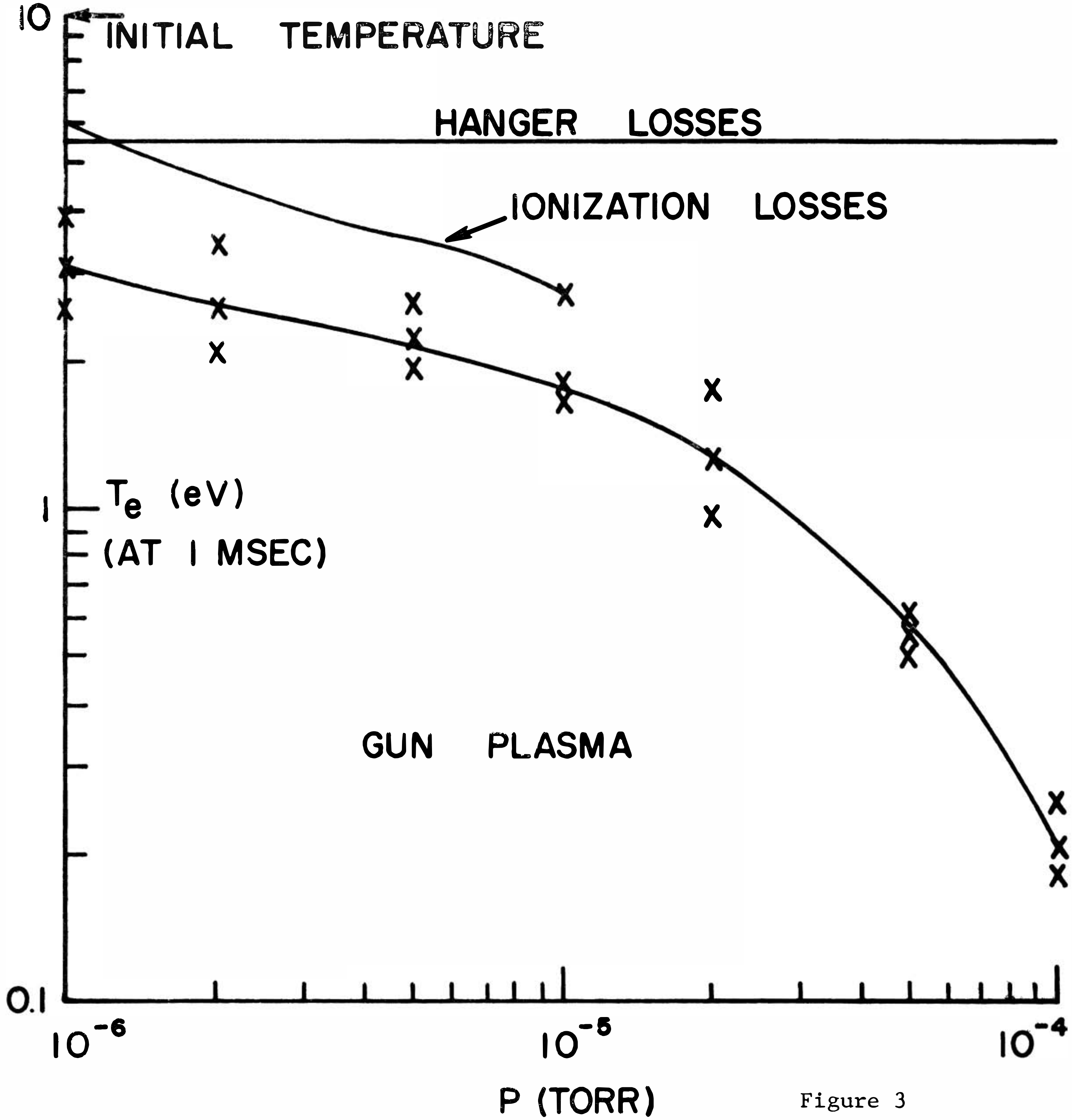


Figure 2



10
INITIAL TEMPERATURE
HANGER LOSSES
IONIZATION LOSSES
T_e (eV)
(AT 1 MSEC)
1
GUN PLASMA
0.1
10^{-6}
10^{-5}
10^{-4}
P (TORR)

Figure 3