

ION CYCLOTRON HEATING IN A TOROIDAL OCTUPOLE

J. D. Barter and J. C. Sprott

November 1974

PLP 590

Plasma Studies

University of Wisconsin

These PLP Reports are informal and preliminary and as such may contain errors not yet eliminated. They are for private circulation only and are not to be further transmitted without consent of the authors and major professor.

A fifth hoop mounted near the wall of the Wisconsin Supported Toroidal Octupole has been used to heat ions at the cyclotron frequency. Fig. 1 shows the coupling hoop mounted coaxial to the main  $B_p$  current hoops, near the lower wall which produces an rf electric field in the toroidal direction appropriate to cyclotron heating in the poloidal octupole field. The octupole is normally run without a toroidal field but a toroidal field of variable strength can be added, thus varying the relative strengths of  $E_{\parallel}$  and  $E_{\perp}$ . This versatility is an important advantage of a multipole over a tokamak for ICRH studies. The coupling hoop forms the inductive element of the oscillator tank circuit enabling the oscillator to track in frequency in the presence of reactive plasma loading of the hoop. The resistive loading of the hoop is used to infer power delivered to the plasma by the hoop. The oscillator is operated near 1MHz corresponding to an approximately circular cross section resonance surface centered about the minor axis. The oscillator is capable of supplying 500kW of rf to sufficiently dense plasmas ( $> \text{a few} \times 10^{12} \text{cm}^{-3}$  with the present hoop). The impedance match of the plasma to the oscillator is determined by the density. Since the oscillator may be regarded as a voltage source, the hoop has been made flat to increase the induced field in the plasma. Similarly, the hoop has been mounted as far from the wall as practical to increase the Q, increasing the voltage applied to the hoop and the induced field in the plasma. Faraday shielding modeled after the Princeton design in conjunction with a stainless limiter prevents electrostatic fields from reaching the plasma.

Plasmas are produced either by gun injection or by ECRH at 2.45GHz. Gun injected plasmas ( $n < 4 \times 10^{12} \text{cm}^{-3}$ ) include a very high neutral density ( $\sim 10^{14} \text{cm}^{-3}$ ) limiting attainable ion temperatures and were used primarily for loading measurements. ECRH plasmas ( $n < 10^{11} \text{cm}^{-3}$ ) can be produced with

H<sub>2</sub> filling pressures of  $1.5 \times 10^{-6}$  torr and were used for the temperature scaling measurements.

Ion temperatures are sampled at the B = 0 axis by extracting ions through a ferromagnetic pipe to an electrostatic curved plate analyzer.

The induced rf electric field is measured in the vertical midplane and is plotted in Fig. 2. The  $\Delta$ 's represent the vacuum field without plasma. The o's demonstrate penetration of the field as far as the near portion of the resonance zone in  $4 \times 10^{12} \text{cm}^{-3}$  plasmas. The solid line is the prediction of a simple calculation of the vacuum field.

A heated ion distribution function obtained in an ECRH produced plasma ( $\approx 7 \times 10^{10} \text{cm}^{-3}$ ) is shown in Fig. 3. This distribution shows two components, heated and unheated, of comparable densities, of which the unheated portion probably represents the large amounts of reflux contaminants from the limiter at high rf powers. The high energy component is reasonably Maxwellian.

In Fig. 4 we compare single particle heating theory to measured power supplied to the plasma (loading measurements) and to ion temperature rise (energy analyzer data), plotted against density. The agreement is as good as can be expected considering the approximations that are made. The capability of determining the scaling of ICRH with density is another advantage of an octupole over a Tokamak, since the density in an octupole can be continuously varied from zero up to values typical of Tokamak experiments.

The ion temperature of a heated ECRH plasma is plotted in Fig. 5 against the H<sub>2</sub> filling pressure and compared to a computer simulation, which takes charge exchange and obstacle losses into account. Again the agreement is reasonably good.

Another evidence of this cooling effect can be seen in Fig. 6. Here  $T_i$  is plotted against rf voltage on the hoop. The departure from a linear relation in  $V^2$  may be attributed to two causes: First the same computer code gives the solid line as shown, which rises more slowly than  $V^2$  because charge exchange and obstacle losses increase with increasing ion temperature. Also the plasma bombardment of the limiter can release large amounts of neutrals and impurities into the plasma particularly at the higher power levels contributing to the cooling. We are developing a technique for inductively baking out the coupling hoop and stainless steel limiter by running the ICRH oscillator cw at  $\sim 500$  watts. Extended application of this procedure has been shown to reduce impurity effects.

In Fig. 7, power input to the plasma is plotted with an added toroidal field. In this case the ICRH resonance zone should retreat to the minor axis of the machine and disappear from the machine at the indicated point. In the absence of ohmic heating of the electrons one would expect the power input to drop to zero there. We, however, see the power increase slightly with  $B_T$ . In fact the ohmic heating would greatly increase the hoop loading but the small skin depth for fields parallel to the magnetic field limits the loading observed. Ion temperature measurements in the presence of a toroidal field are not reliable because the method of extracting the ions with a ferromagnetic pipe requires a low magnetic field at the entrance to the pipe. We therefore do not yet know whether the absorption at large toroidal fields results in ion or electron heating. But we expect the energy to appear in the electrons since the mechanism is presumably ohmic heating. We do intend to make electron temperature measurements in the near future.

In conclusion we have demonstrated that ion cyclotron heating can raise the ion temperature by at least a factor of 100 (from  $< 1$  eV to  $\sim 100$  eV) without seriously affecting the confinement in a toroidal octupole. There is some

evidence that neutral reflux from the walls and limiter limit the ion temperatures that can be achieved. In the future we hope to make more detailed quantitative comparisons between the measured heating and theoretical calculations which include all the known loss mechanisms. We also hope to understand and to eventually control the effects of the reflux neutrals.

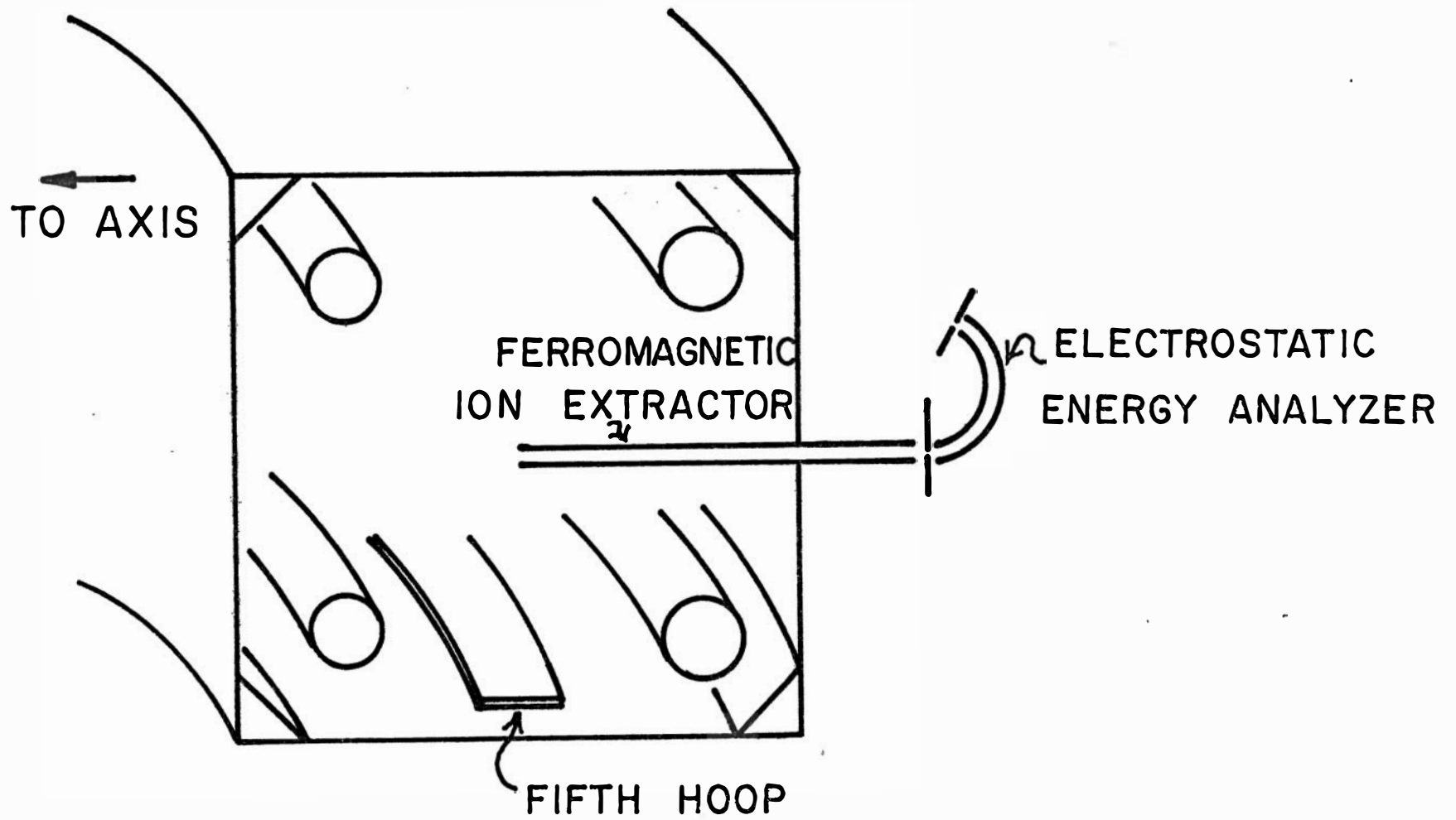
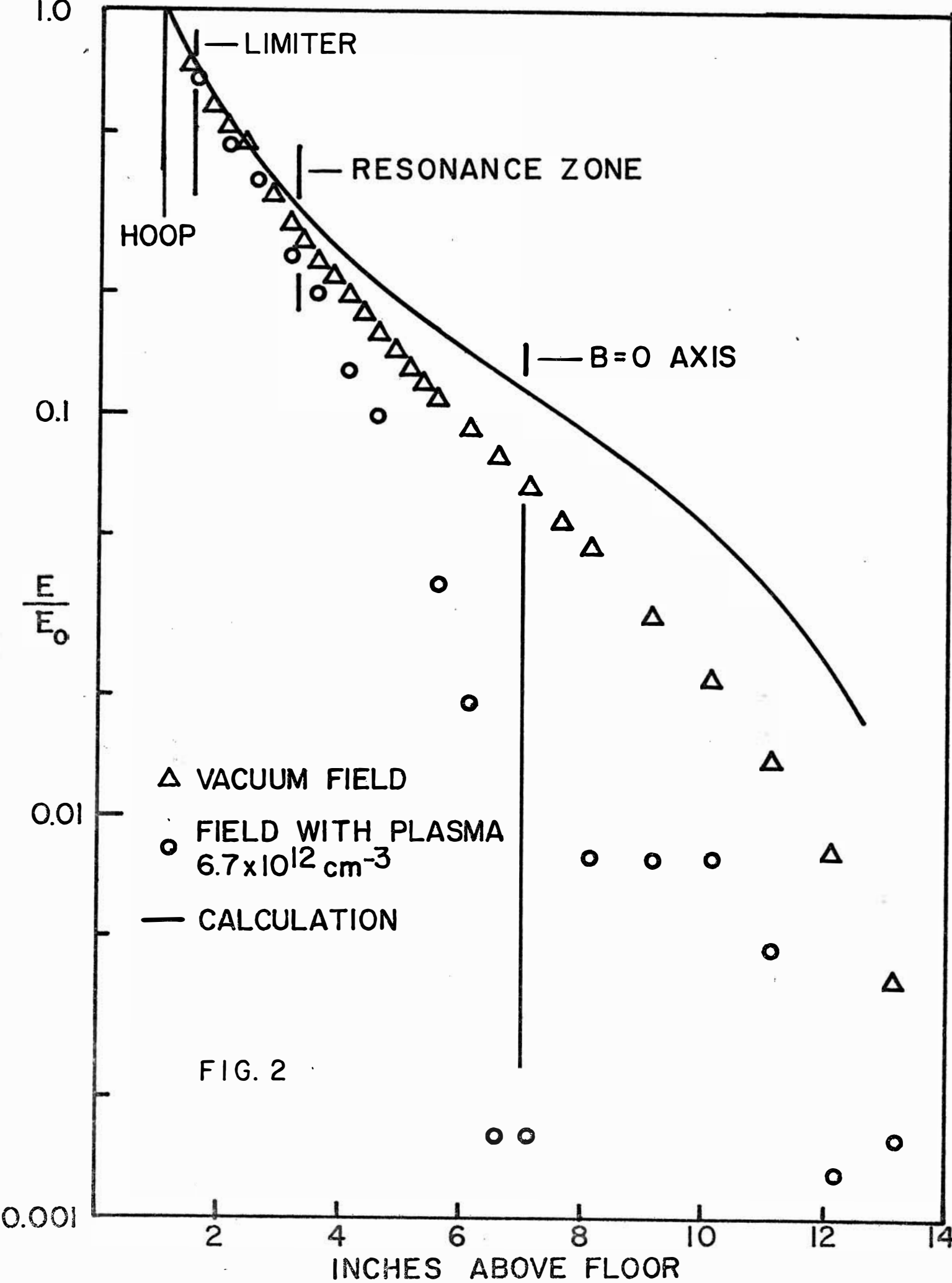


FIG. 1



HEATED ECRH PLASMA

$6.7 \times 10^{10} \text{ cm}^{-3}$

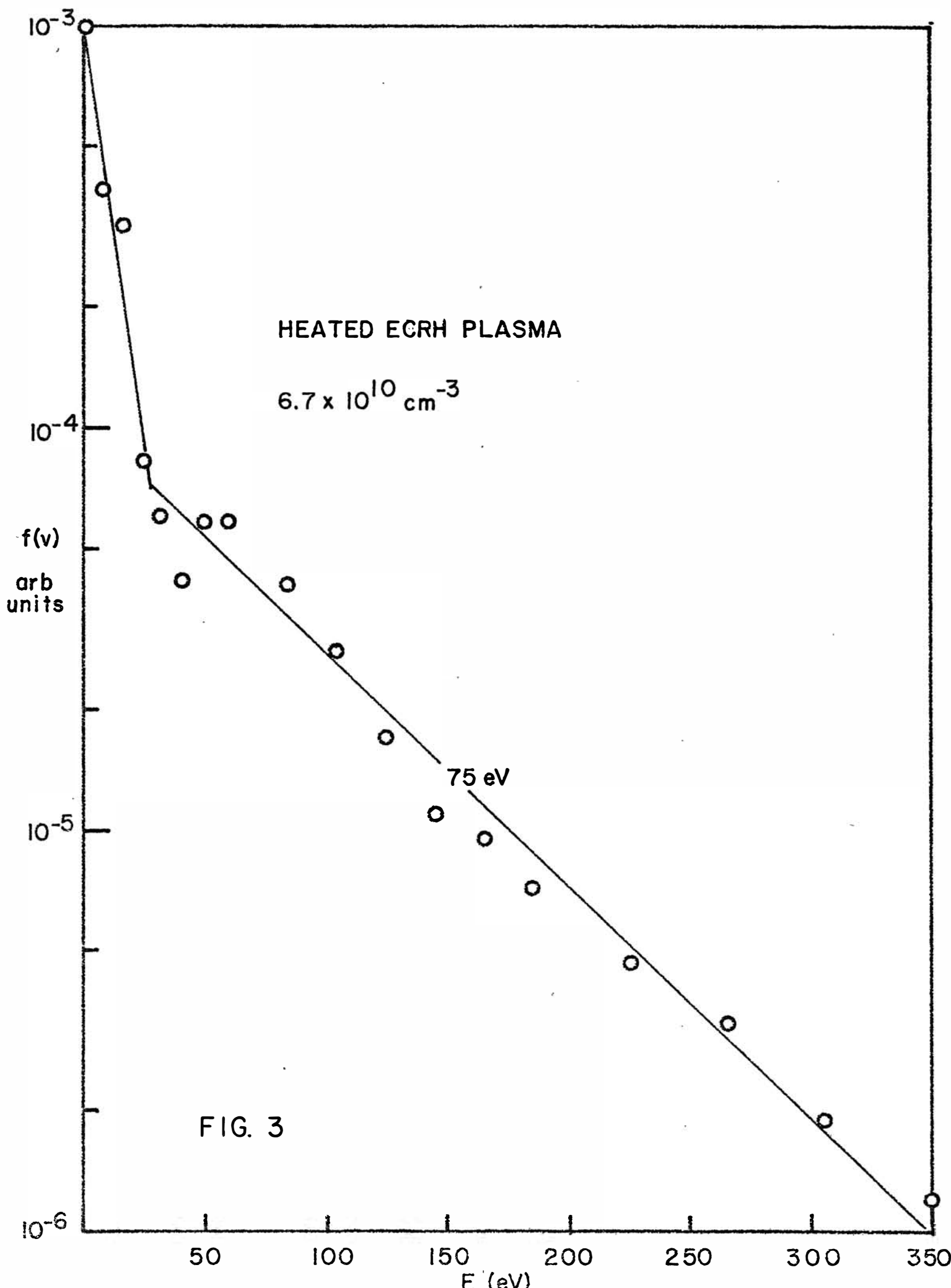


FIG. 3



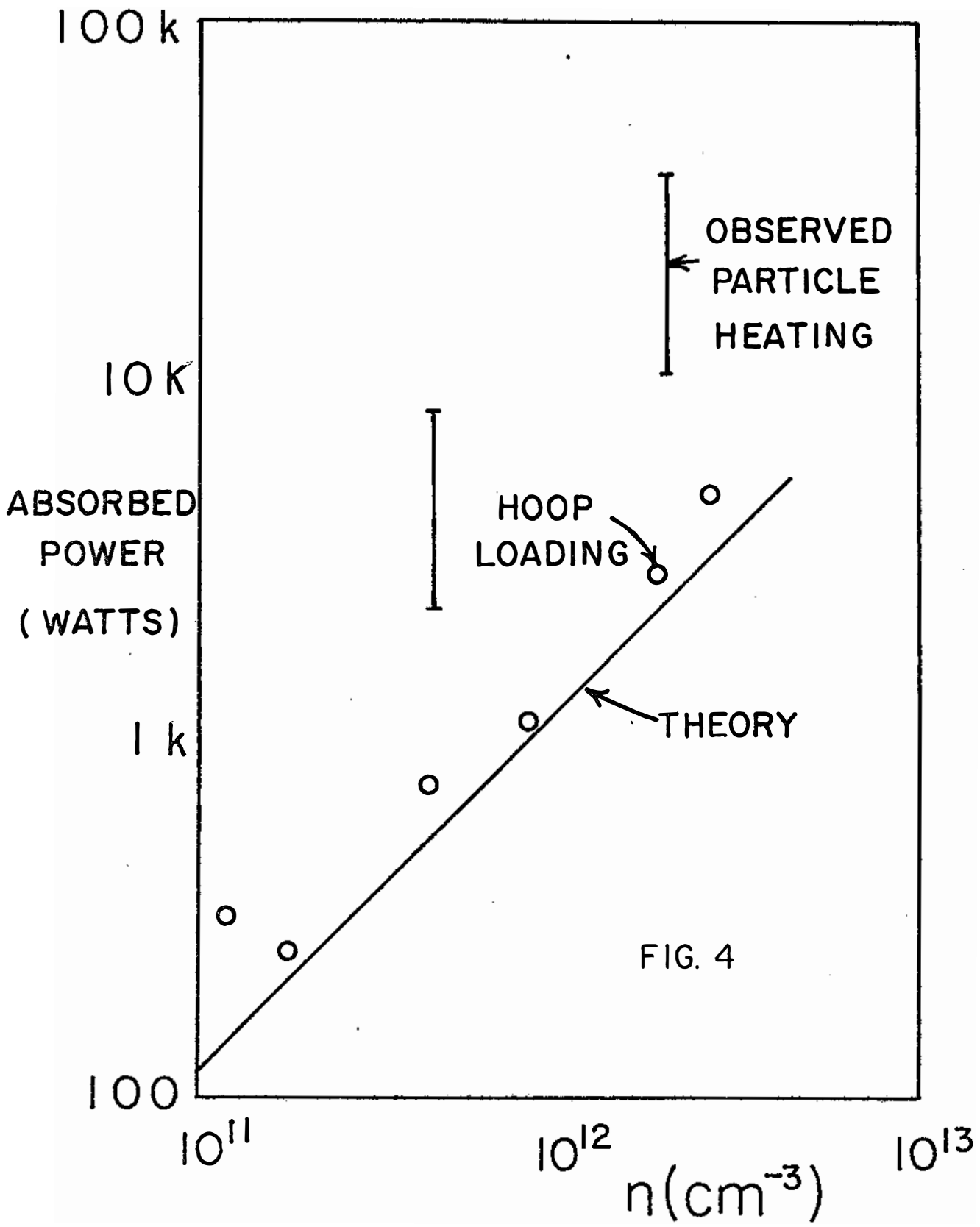


FIG. 4

○ COMPUTER SIMULATION  
△ ENERGY ANALYZER DATA

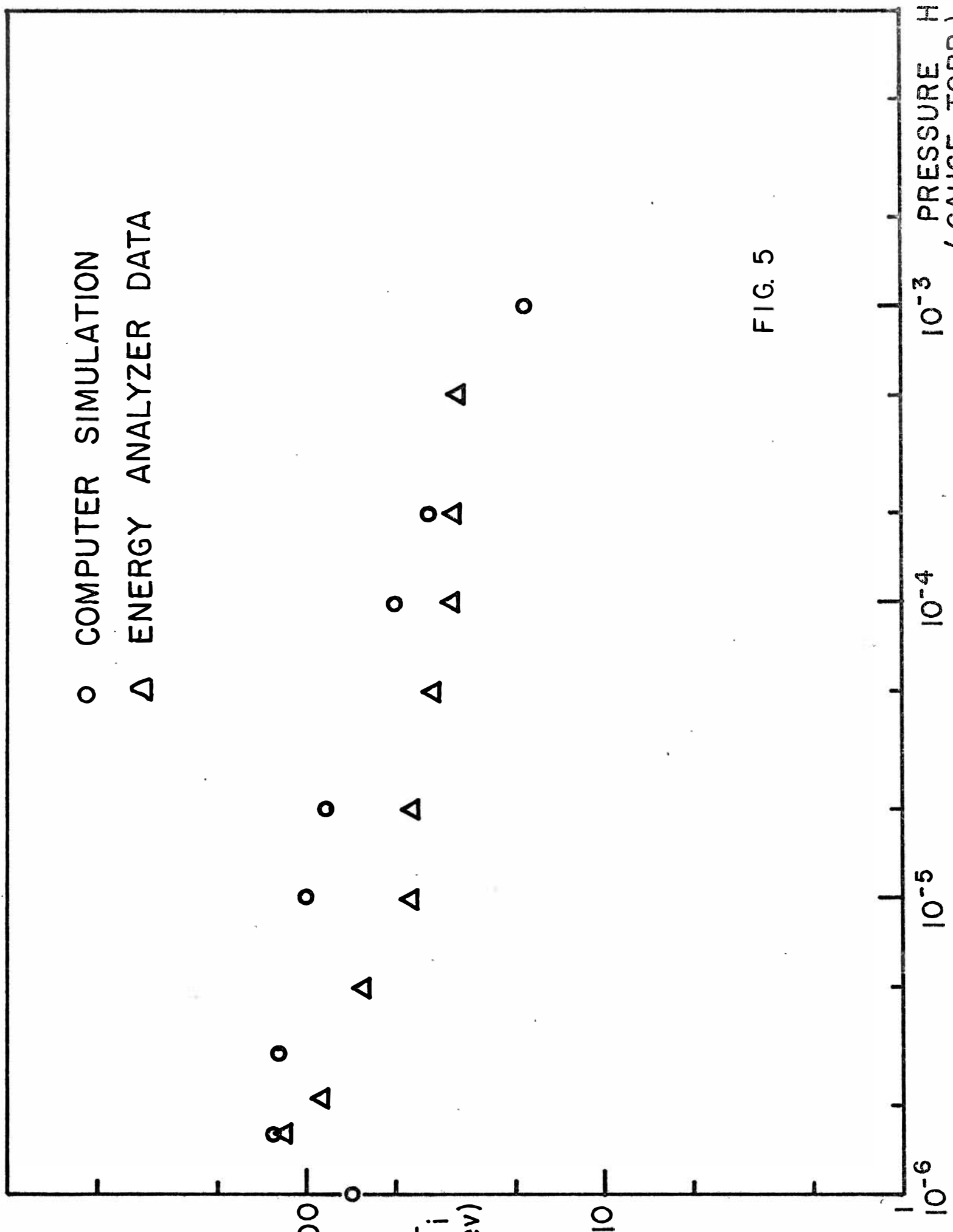


FIG. 5

PRESSURE  $H_2$   
(GAUGE TORR)

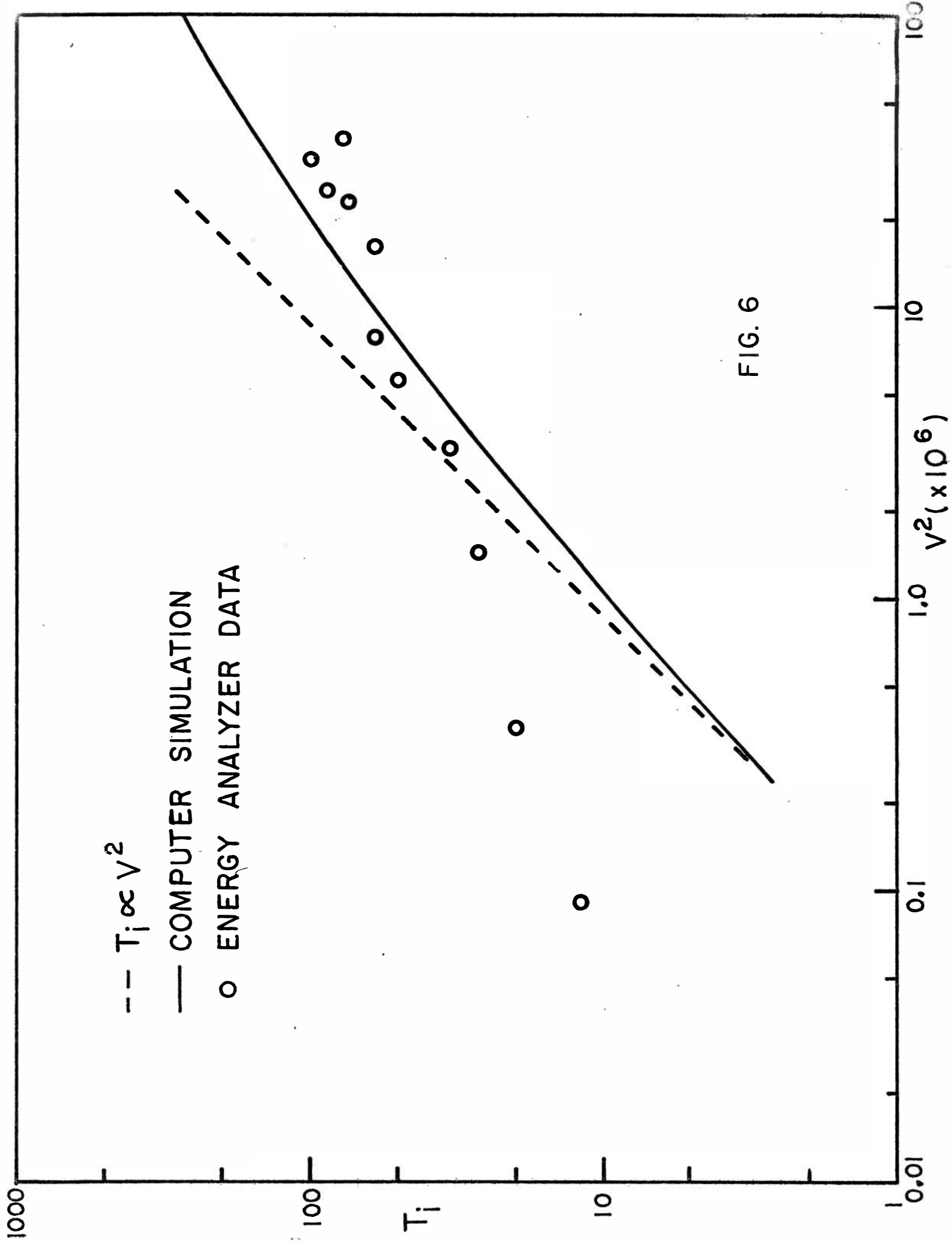
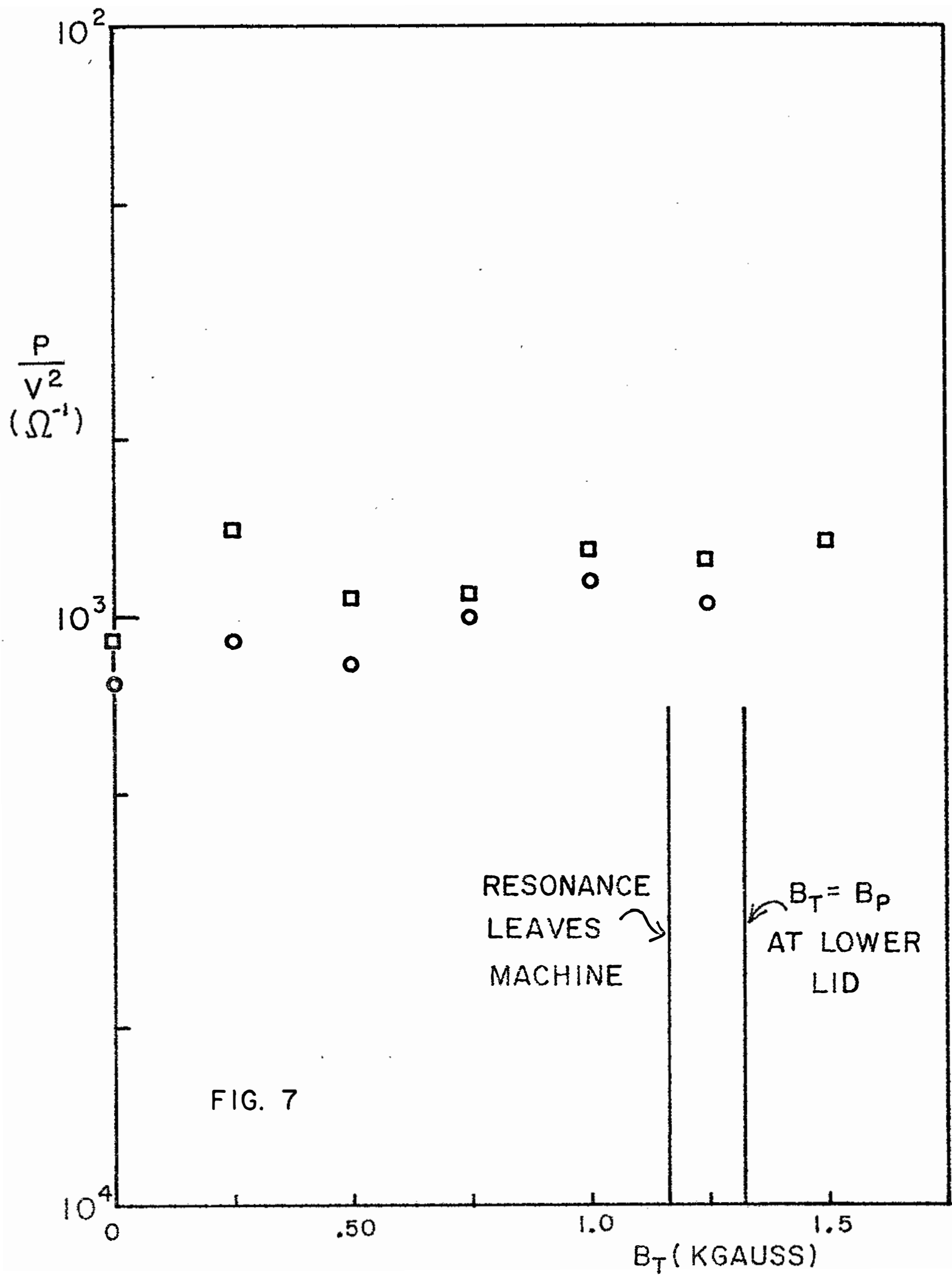


FIG. 6



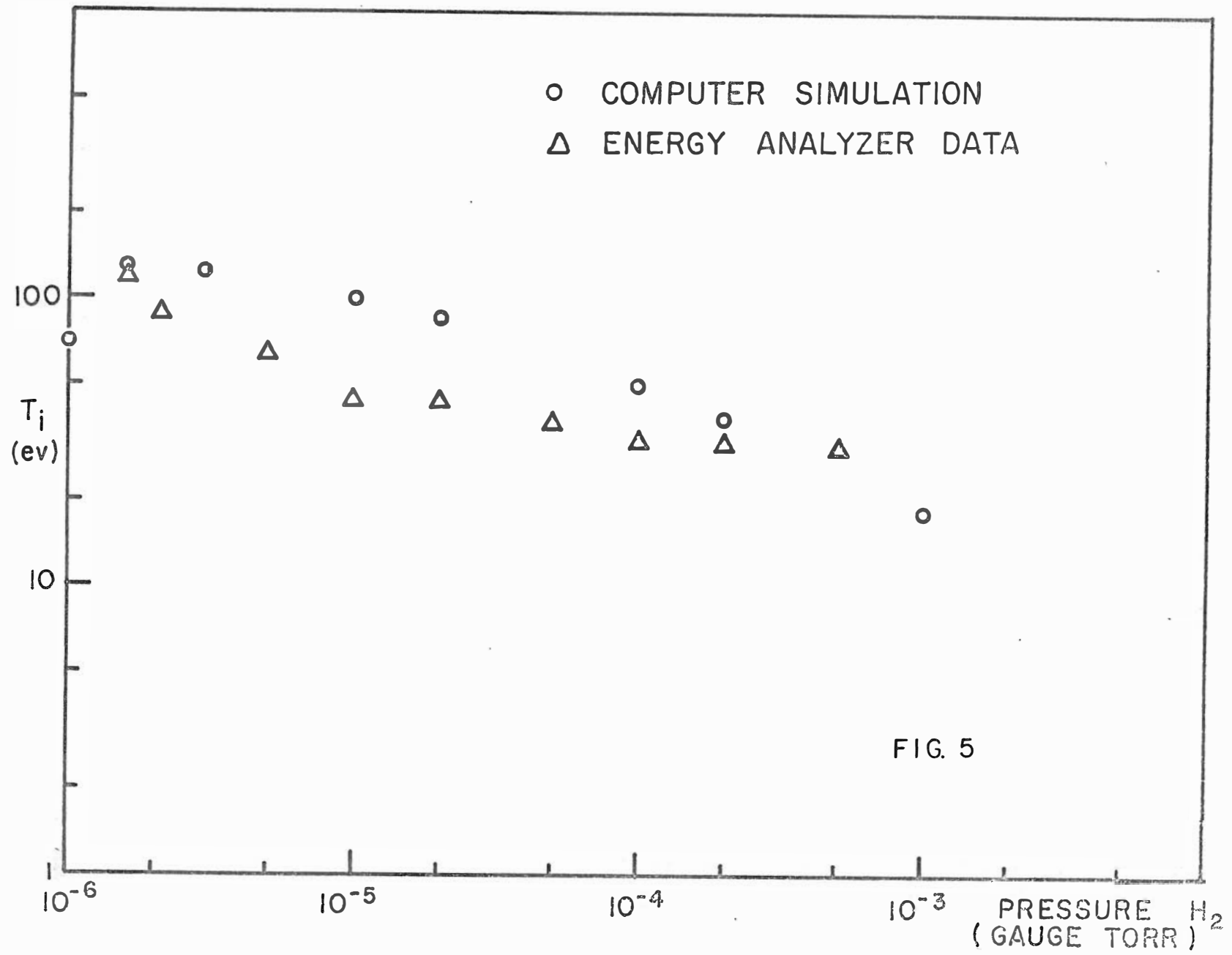


FIG. 5

