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ABSTRACT

RF power near the ion cyclotron resonance frequency has been used to produce a hundred-fold increase (from $\lesssim$ 1 eV to ~ 100 eV) in the ion temperature in a toroidal octupole device. The heating produces no noticeable instabilities or other deleterious effects except for a high reflux of neutrals from the walls. The heating rate is consistent with theory and the limiting ion temperature is determined by charge exchange losses.

Ion cyclotron resonance heating has previously been used in the Model C Stellarator[1], in a turbulently heated magnetic mirror[2], and in the S-T Tokamak[3]. We report here the first experiments in which high power ion cyclotron resonance heating has been used to significantly raise the ion temperature (a hundred-fold) in a toroidal multipole device. The ion cyclotron heating rate agrees with theoretical calculations[4], produces no noticeable instabilities or other deleterious effects except for a high reflux of neutrals from the walls, and is limited to ~ 100 eV by losses due to charge exchange with the background neutrals. The advantages of studying ICRH in a toroidal multipole are that density, electron temperature, poloidal field, and toroidal field can all be adjusted independently from zero up to values approaching those used in present Tokamak devices.

The experiments were performed on the small Wisconsin toroidal octupole[5], part of which is shown in Fig. 1. The poloidal magnetic field is produced by the currents in the four solid copper hoops which encircle an iron transformer core (not shown). The poloidal magnetic field pulse is normally a half sine wave of 5 msec duration. In the experiments described here, no toroidal field was used.

The rf power is introduced by means of a single turn, flat copper, electrostatically shielded fifth hoop located near the bottom wall of the device. The fifth hoop is the inductance of a tank circuit of an oscillator tuned to ~ 1 MHz and capable of supplying up to 500 kW of rf for 1 msec. This system produces a toroidal electric field which is everywhere perpendicular to the confining magnetic field and which falls rapidly with distance from the coupling hoop. The resonance zone for protons (~ 700 gauss) is an approximately circular cross-section toroidal surface which comes within ~ 6 cm of the fifth hoop at its closest point.

Plasmas with $kT_e \sim$ 3-5 eV are produced either by ECRH at 2.45 GHz ($n \lesssim 10^{11}$ cm^{-3}) or by gun injection ($n \lesssim 5 \times 10^{12}$ cm^{-3}). Ion distribution functions are measured by an electrostatic energy analyzer[6] which extracts particles from the zero field region near the axis through a ferromagnetic pipe[7]. The rf power absorbed by the plasma can be determined by measuring the change in Q of the oscillator tank circuit. The rf electric field in the plasma is measured using magnetic probes. These probes show that even at the highest densities available (6.7×10^{12} cm^{-3}), the electric field at the resonance zone nearest the hoop is hardly affected by the plasma, whereas the rf field on the $B = 0$ axis is depressed by about a factor of 30.

When the rf power is applied, the ion temperature rises from < 1 eV to ~ 100 eV in ~ 100 μsec and then remains nearly constant until the rf is turned off. Thus an equilibrium is achieved between ICRH and charge exchange losses. The equilibrium value is in good agreement with the value predicted from the measured power absorption and published values of charge exchange cross-sections. Fig. 2 shows that the ion energy distribution function for a typical case is reasonably Maxwellian except for a cold component that may represent impurity ions or ions which never reached a resonance zone.

The power absorbed by the plasma

is plotted in Fig. 3 vs plasma density. Applied voltages on the hoop are typically 3 to 7 kV zero to peak. The absorbed power is determined from the loading of the oscillator tank circuit (x) and by the observed rate of rise of ion temperature (0) when the rf is turned on. The absorbed power is proportional to plasma density in agreement with single particle cyclotron heating theory[4].

The ion temperature is limited by charge exchange losses as can be demonstrated by quantitative calculations based on the measured neutral pressure and by the fact that the ion temperature decreases when the H_2 gas pressure (normally ~ 10^{-6} torr) is raised.

These neutrals are due in part to reflux from the walls as evidenced by an upward kick in ion gauge pressure reading when the machine is pulsed with ICRH. We have succeeded in minimizing the wall reflux by a variety of discharge cleaning techniques.

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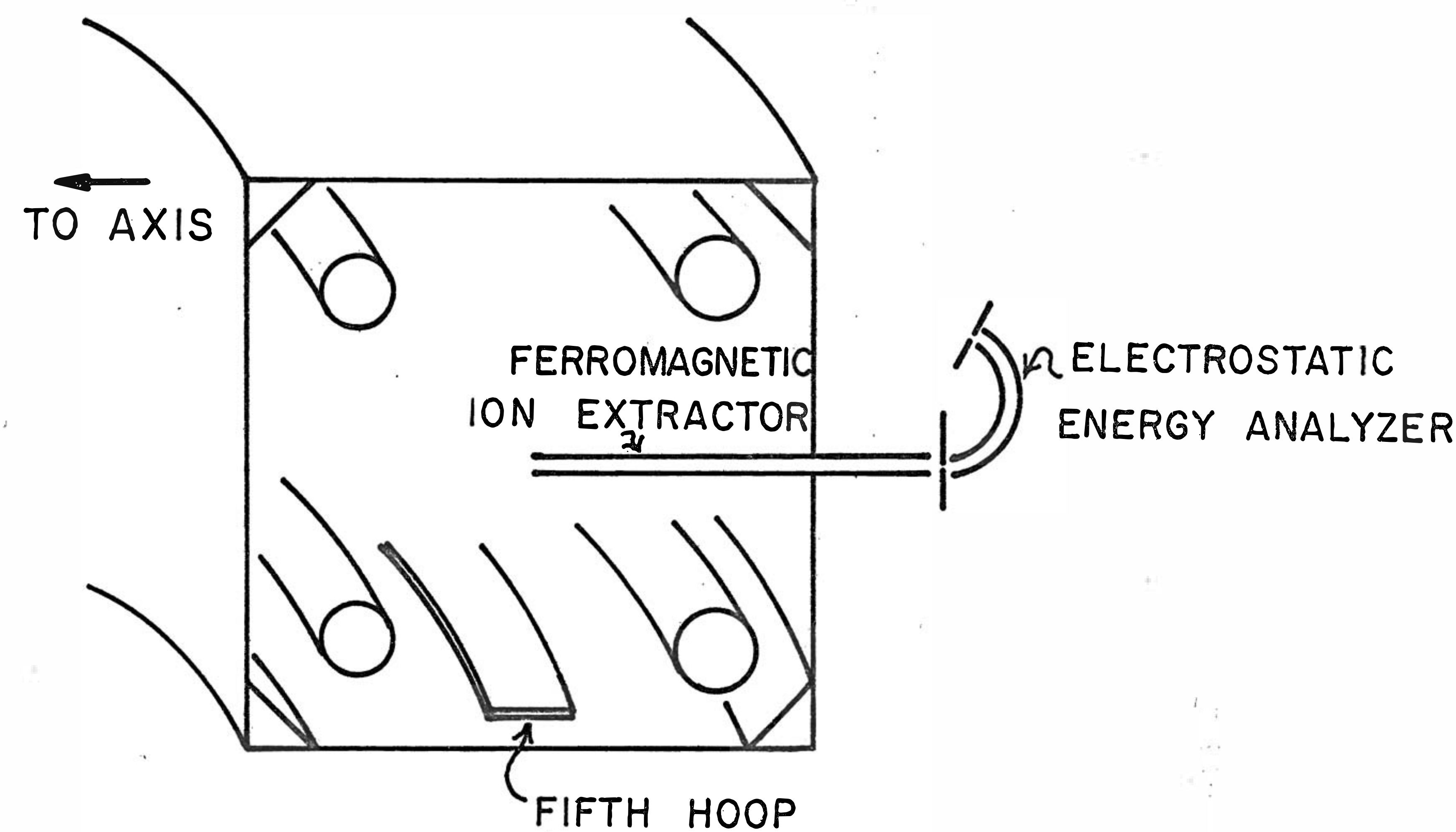
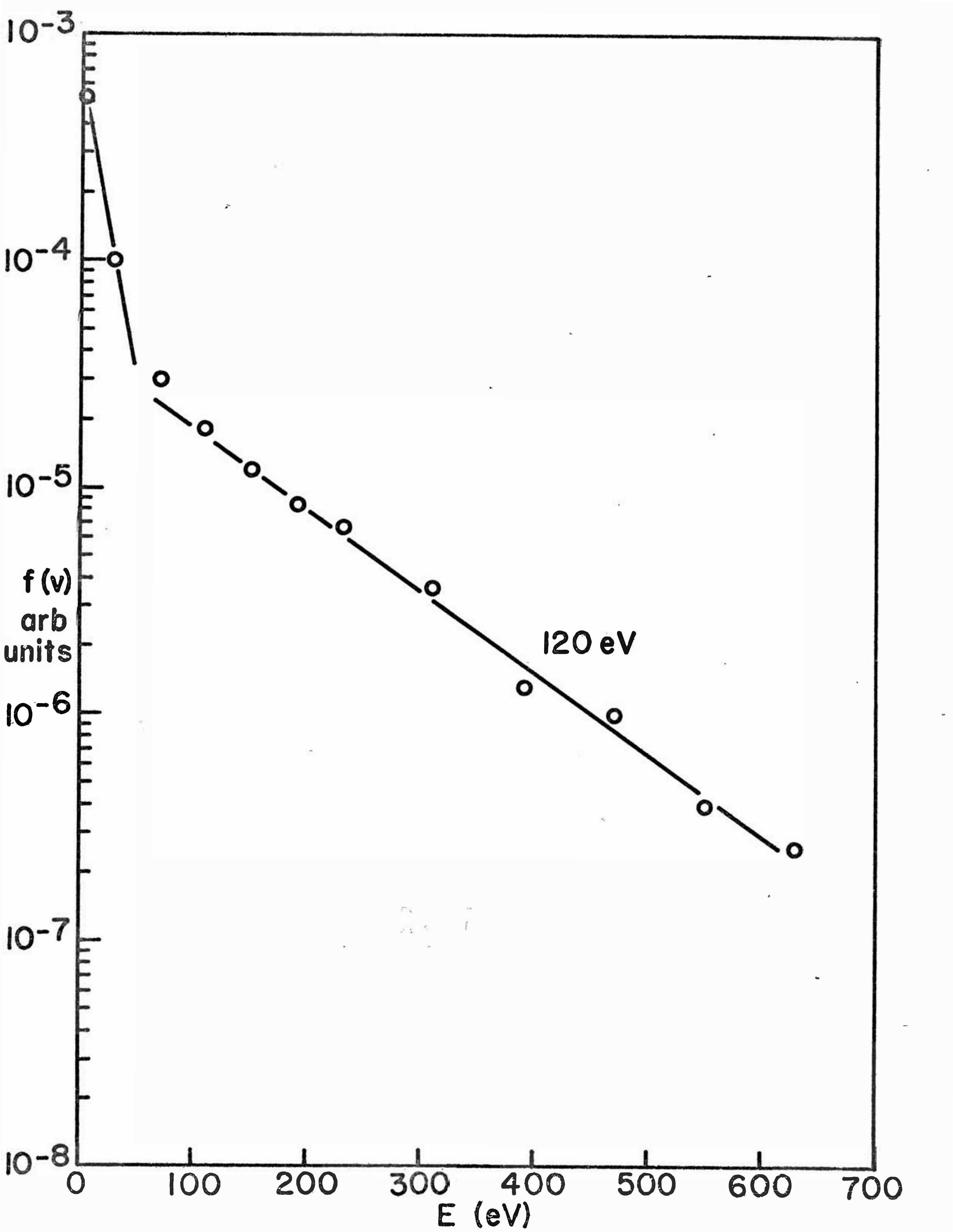
FIGURE CAPTIONS

Fig. 1 Cross-section of toroidal octupole showing fifth hoop (shielding not shown) and electrostatic ion energy analyzer.

Fig. 2 Ion energy distribution with two-temperature Maxwellian fit for $n \simeq 6 \times 10^{10}$ cm^{-3}.

Fig. 3 Absorbed power vs plasma density.


TO AXIS
FERROMAGNETIC
ION EXTRACTOR
ELECTROSTATIC
ENERGY ANALYZER
FIFTH HOOP



10-3
10-4
10-5
10-6
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f (v)
arb
units
120 eV
0
100
200
300
400
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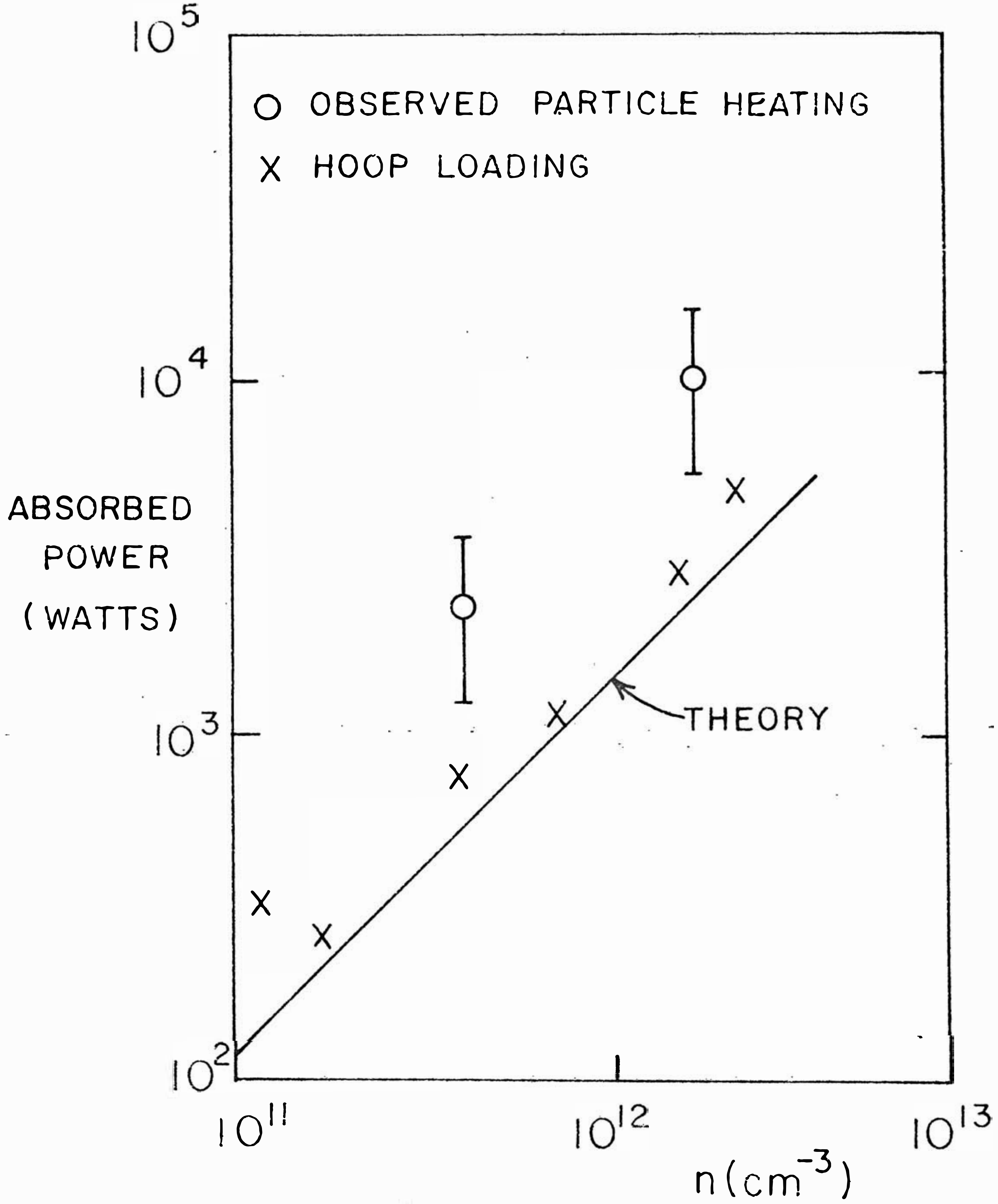
600
700
E (eV)



O OBSERVED PARTICLE HEATING
X HOOP LOADING
THEORY
ABSORBED POWER (WATTS)
10^5
10^4
10^3
10^2
10^{11}
10^{12}
10^{13}
$n(cm^{-3})$