ION HEATING WITH RF FIELDS NEAR THE ION CYCLOTRON FREQUENCY

by

J. D. Barter, J. C. Sprott

November 1973

PLP 538

Plasma Studies

University of Wisconsin

For several years we have been heating ions in the original small supported toroidal octupole at Wisconsin, using rf fields at the ion cyclotron frequency. Our experiments of the past year, however, indicate that ion cyclotron resonance heating is not the dominant mechanism. In fact the observed heating is about 100 times greater than predicted by single particle ICRH theory. Although the heating tends to produce distributions with energetic tails, the average energy can be raised from $\lesssim$ 3eV to ~ 30 eV.

Figure 1 shows how the rf is coupled to the plasma. A fifth hoop coaxial to the four main hoops is mounted 1 inch from the floor. The hoop was driven at frequencies in the range of 1-4MHz with amplitudes up to 4kv zero to peak, and 144 μsec duration in the heating mode. The hoop could also be connected as the unknown impedance of an rf bridge at low driving amplitudes ~ 1v for plasma loading measurements.

A 127° electrostatic analyzer was used to measure the ion distribution functions before and after heating. Plasmas studies included gun injected plasmas (kT_i ~ 30eV) and μwave plasmas ($kT_i \lesssim$ 3eV).

The $\dot{B}$ profile produced by the 5^{th} hoop and the plasma density profile were measured on the vertical mid-cylinder and are plotted in Fig. 2. Notice that over most of the volume the density remains within a factor of ~ 2. Also note that this $\dot{B}$ profile is an overlay of the vacuum field (circles) and the field in the presence of the plasma (crosses), and that the fields penetrate the plasma despite the fact that $\omega << \omega_{pe}$. This is true because the penetration depth is large compared to the plasma dimensions. These facts make application of ICRH theory relatively simple. The position of the fifth hoop is indicated by the hashed area.

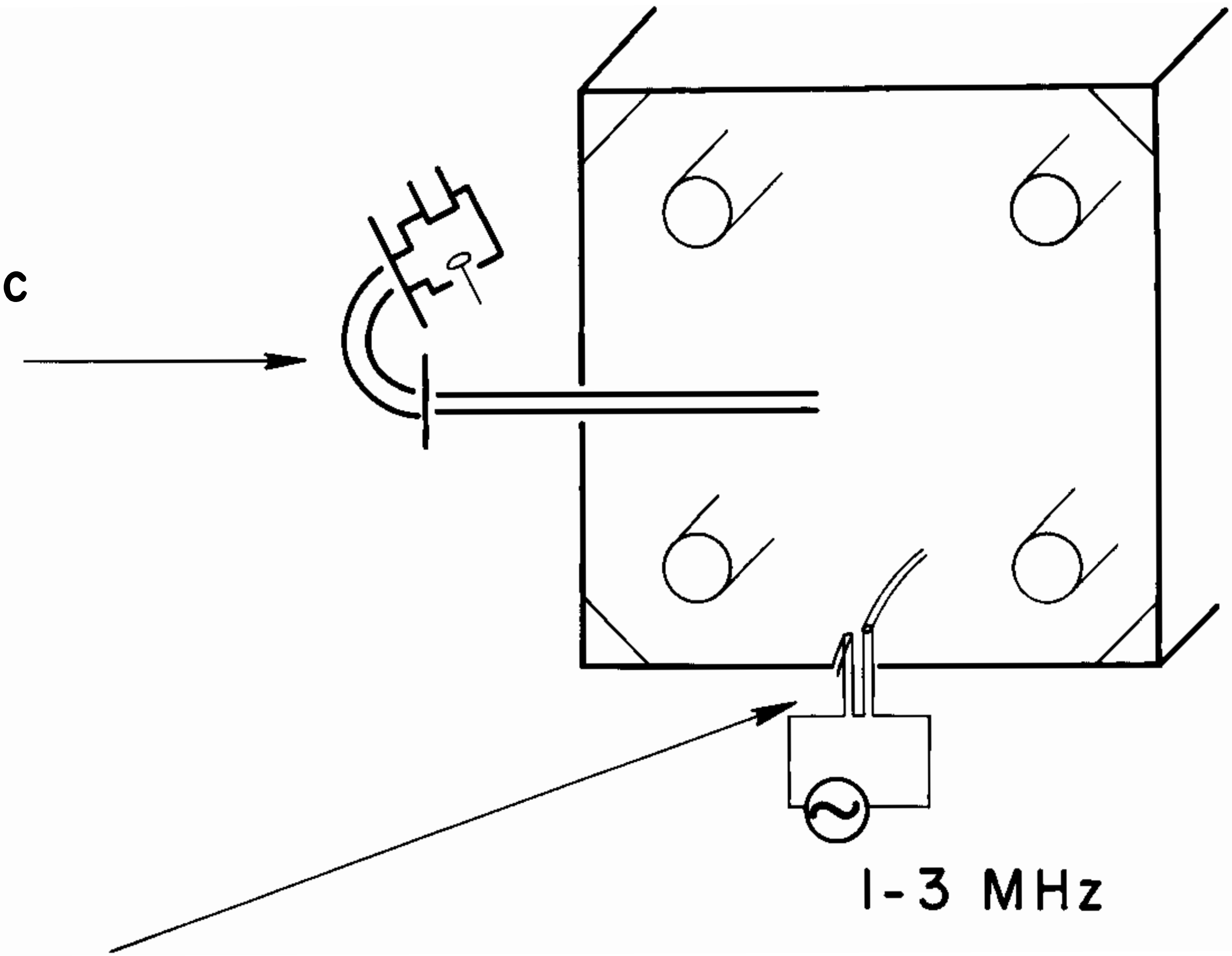
In Fig. 3, a representative heated ion distribution is presented. The hoop was driven at 1MHz at 2kv zero to peak, in pulses of 144 μsec duration. $f(\vec{v})$ is plotted on semilog vs. the energy in eV. With this technique, increases of average energy up to 40eV were observed. Neglecting cooling mechanisms, a change in energy of 30 eV as in Fig. 3 gives a heating rate 2 orders of magnitude higher than ICRH theory predicts.

We then turned to rf bridge measurements to obtain scaling laws of the resistive loading of the plasma at low powers. With this method we found the plasma resistance to be relatively insensitive to variations of the resonance position and bulk plasma density as shown in Fig. 4. Note this is a log-log plot, with ICRH theory plotted as shown. R_p is the equivalent series resistive loading of the plasma. So the loading measurements would predict a heating 5 orders of magnitude higher than ICRH. Noticing that the features of the plasma resistance followed the time evolution of plasma density on outer field lines more closely, I then began plotting R_p vs. the density at the poloidal gap. An example of such a plot is shown in Fig. 5. This location was chosen because electrostatic fields induced by the fifth hoop appear at the gap. Also definite effects on ion saturation current to a Langmuir probe were seen with power inputs as low as 100 watts, such as enhanced losses to the gap during the rf. Such effects could account for the high loading observed. The gap was then partially shorted to rf with capacitors connected across the gap directly below the fifth hoop. A reduction of the measured resistance was noted, but less than sufficient to bring the resistance measurements into agreement with the observed heating. There are, however, other sources of electrostatic fields. In particular, the gap should be more thoroughly shorted. Also the feed-through to the fifth hoop extends into the plasma inside ψ critical. The poloidal field gap may also be shielded from the plasma by means of poloidal limiters at the gap, which we are presently designing.

In Fig. 6 another bit of evidence is presented that we are not observing ICRH. This is a plot of relative increase of ion saturation current to a langmuir probe measured in the regions near to the hoops. In these regions the ψ lines encircle only one hoop so the particles heated in one such region would not be expected to migrate to another private flux region. With this in mind, I have overlayed $\Delta J^+/J^+$ for upper inner hoop and lower inner hoop. Recalling the $\dot{B}$ profile shown previously (Fig. 2) we should expect cyclotron resonance heating to be down two orders of magnitude at the upper inner hoop. We find they are of the same magnitude. Although the peak in $\Delta J^+/J^+$ at the upper hoop occurs approximately at the resonance zone for this case, it didn't shift with the resonance zone for other cases. Also the largest effect appears in the upper hoop region with the lowest $\dot{B}$.

A test for the presence of cyclotron resonance heating would be to attempt heating ions sufficiently heavy that no cyclotron resonance zone exists in the machine ($m > eB/\Omega$). A limit is imposed on the mass by the gyroradius if the heated ions are to be contained $m < \frac{m_p E_{p\,max}}{E_{max}}$. We used Argon for which the maximum contained energy ~ 10eV heated with rf at 1MHz. The experiment proved difficult for two reasons. First, the low maximum energy would make detection of heating difficult at best, and second, the machine has been run with hydrogen for so many years that hydrogen liberated from the wall by the plasma and heated by the rf obscures the desired effect. The presence of Hydrogen as the only energetic component present in a "heated" argon plasma was demonstrated with an E x B analyzer.

In summary, we have shown that ion heating observed in the toroidal octupole is probably not ion cyclotron resonance heating. It is, however, 2 orders of magnitude more efficient than ICRH. The distribution functions produced by the heating tend to be somewhat non-Maxwellian but still show large increases in average ion energy. Finally we have learned to interpret coil loading measurements as plasma heating rates with caution when voltage gaps are in contact with the plasma.



APPARATUS
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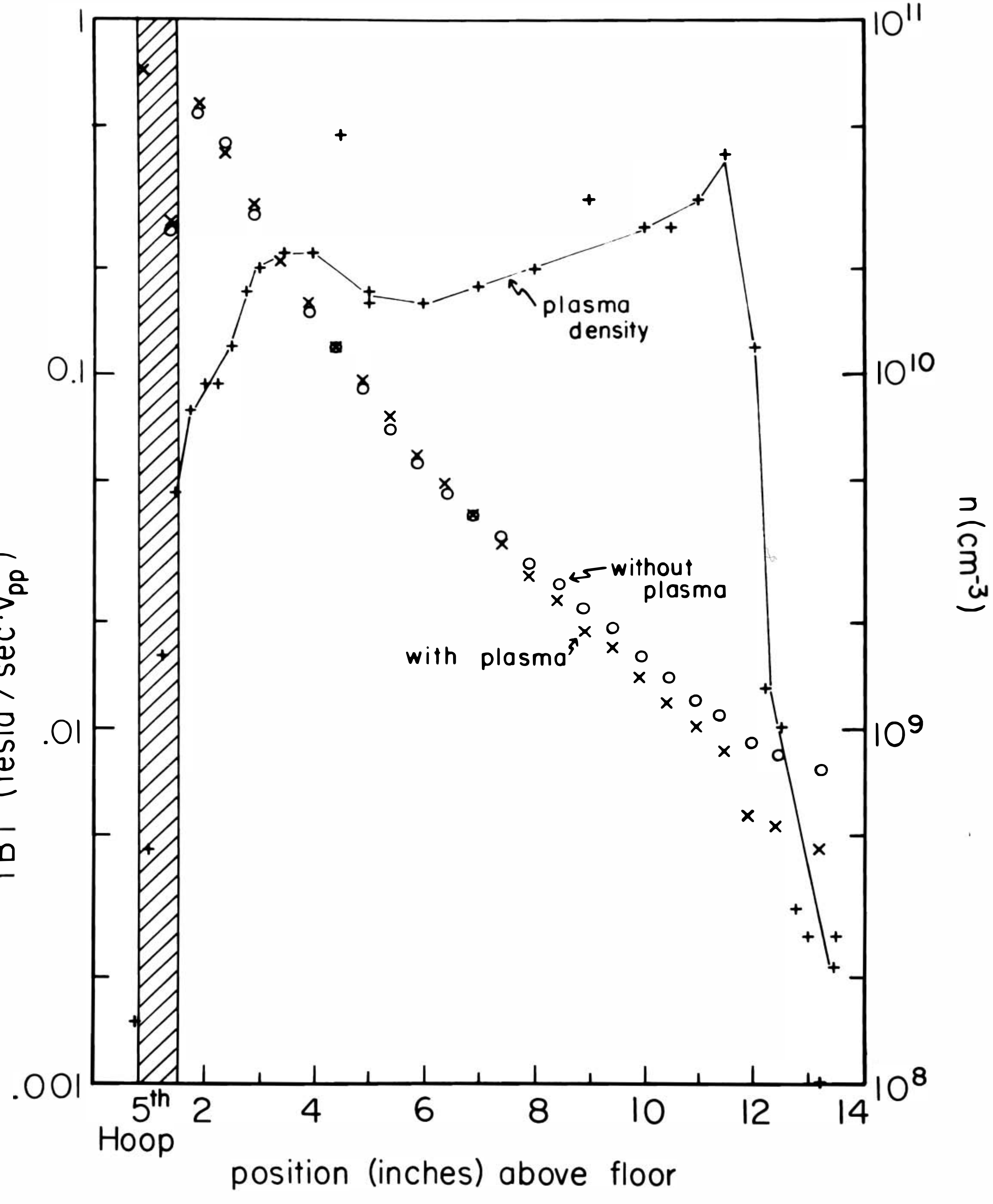
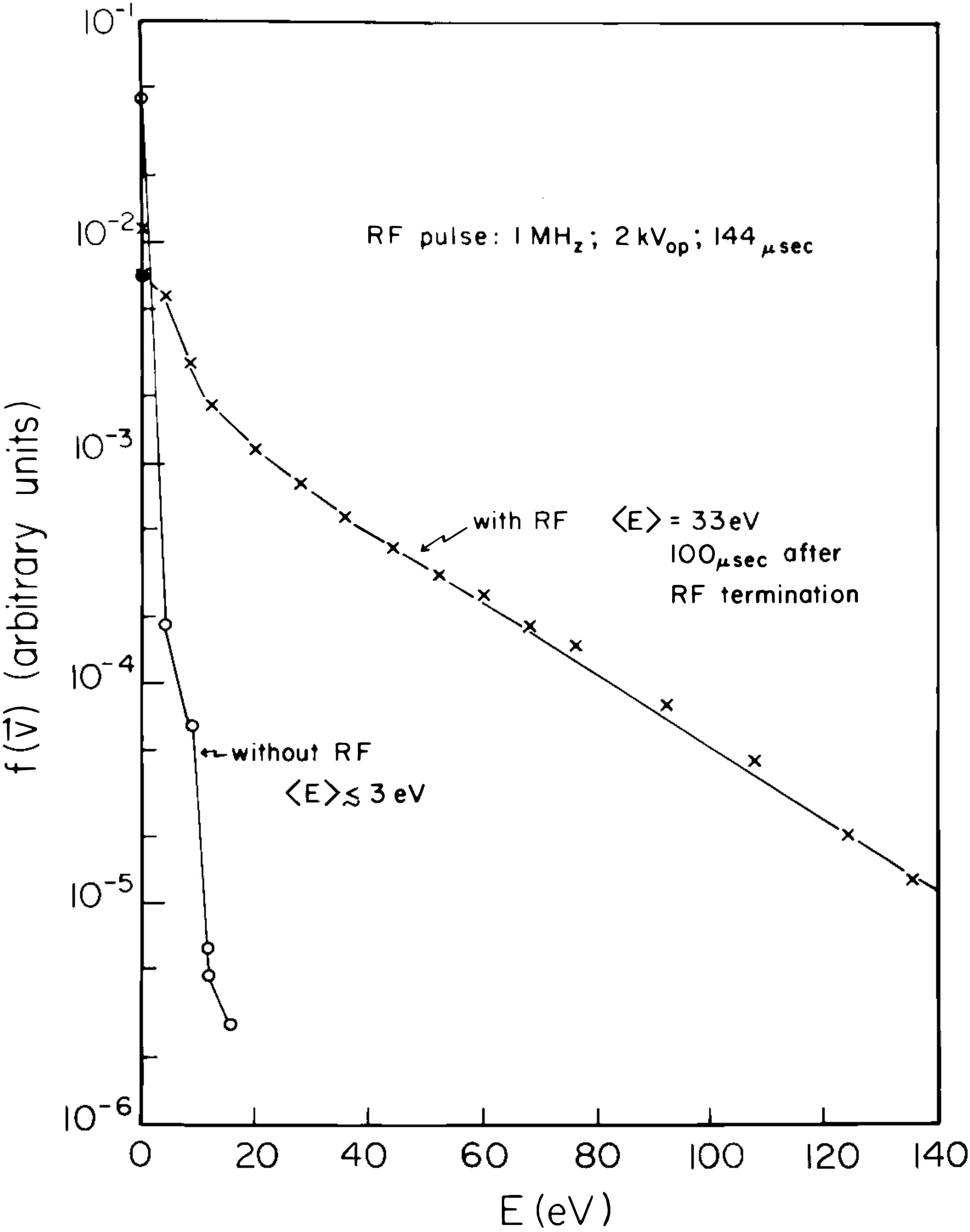
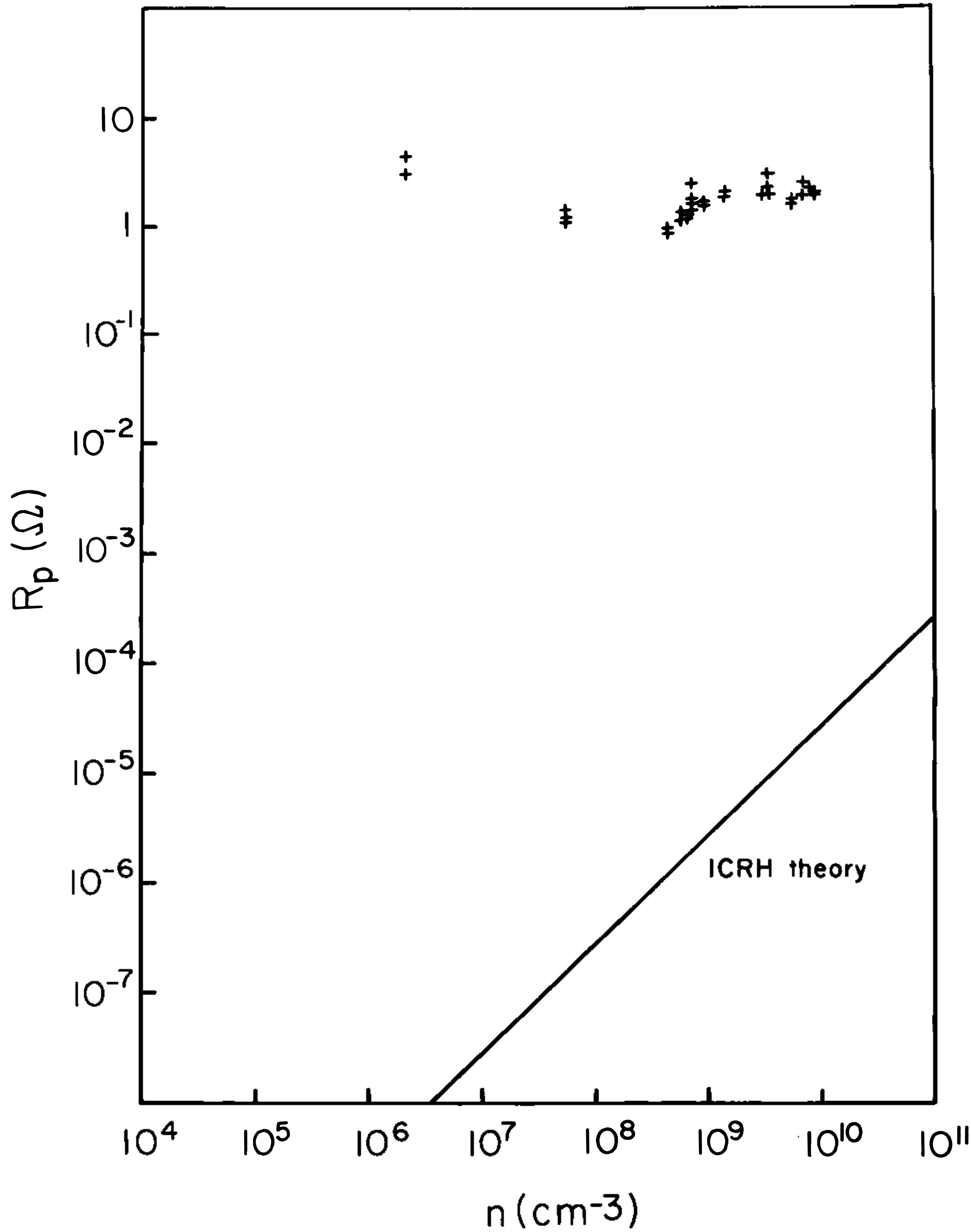


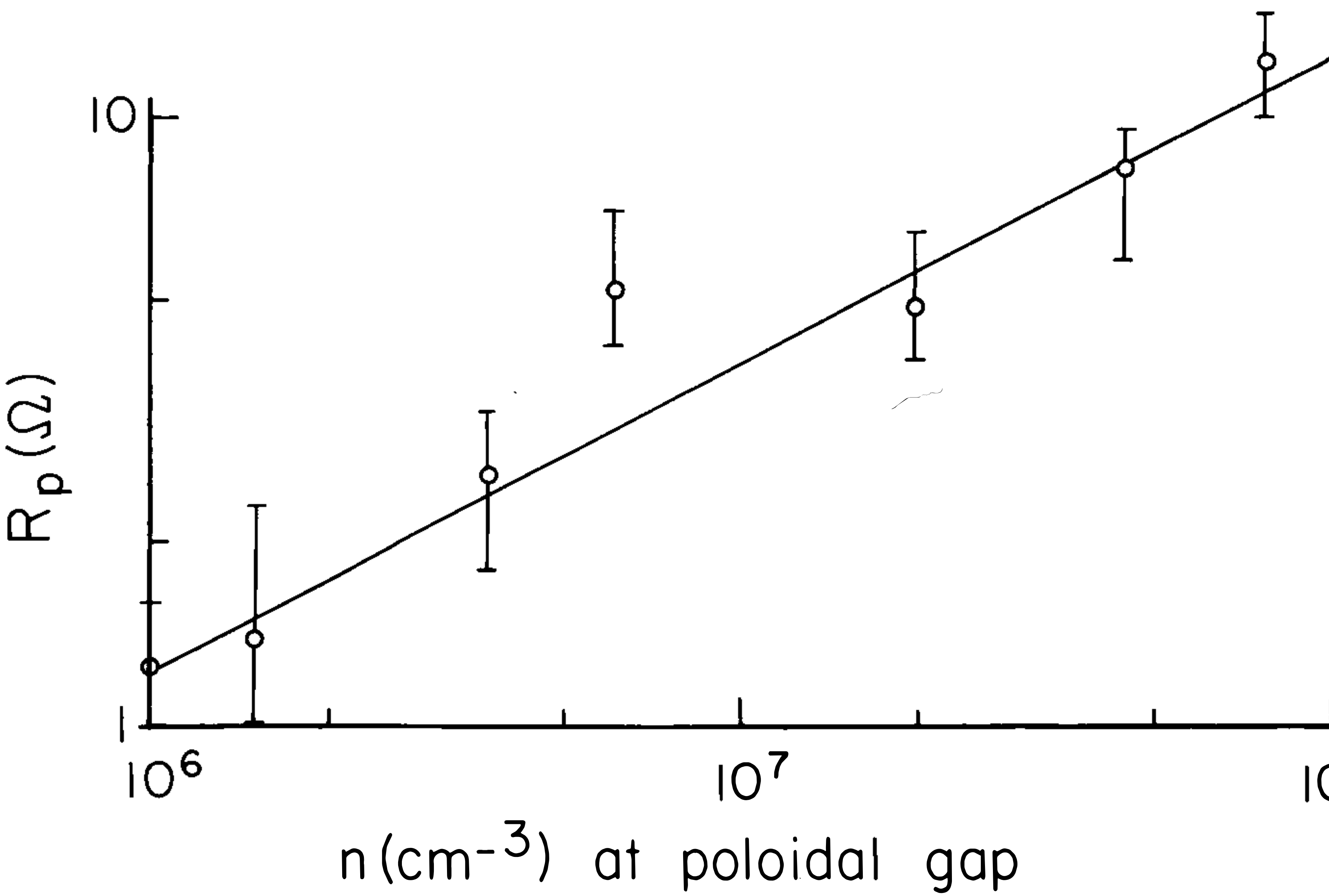
1
0.1
.01
.001
$|\dot{B}|$ (tesla / sec · v_{pp})
10^{11}
10^{10}
10^{9}
10^{8}
n(cm^{-3})
plasma density
without plasma
with plasma
5th Hoop
2
4
6
8
10
12
14
position (inches) above floor



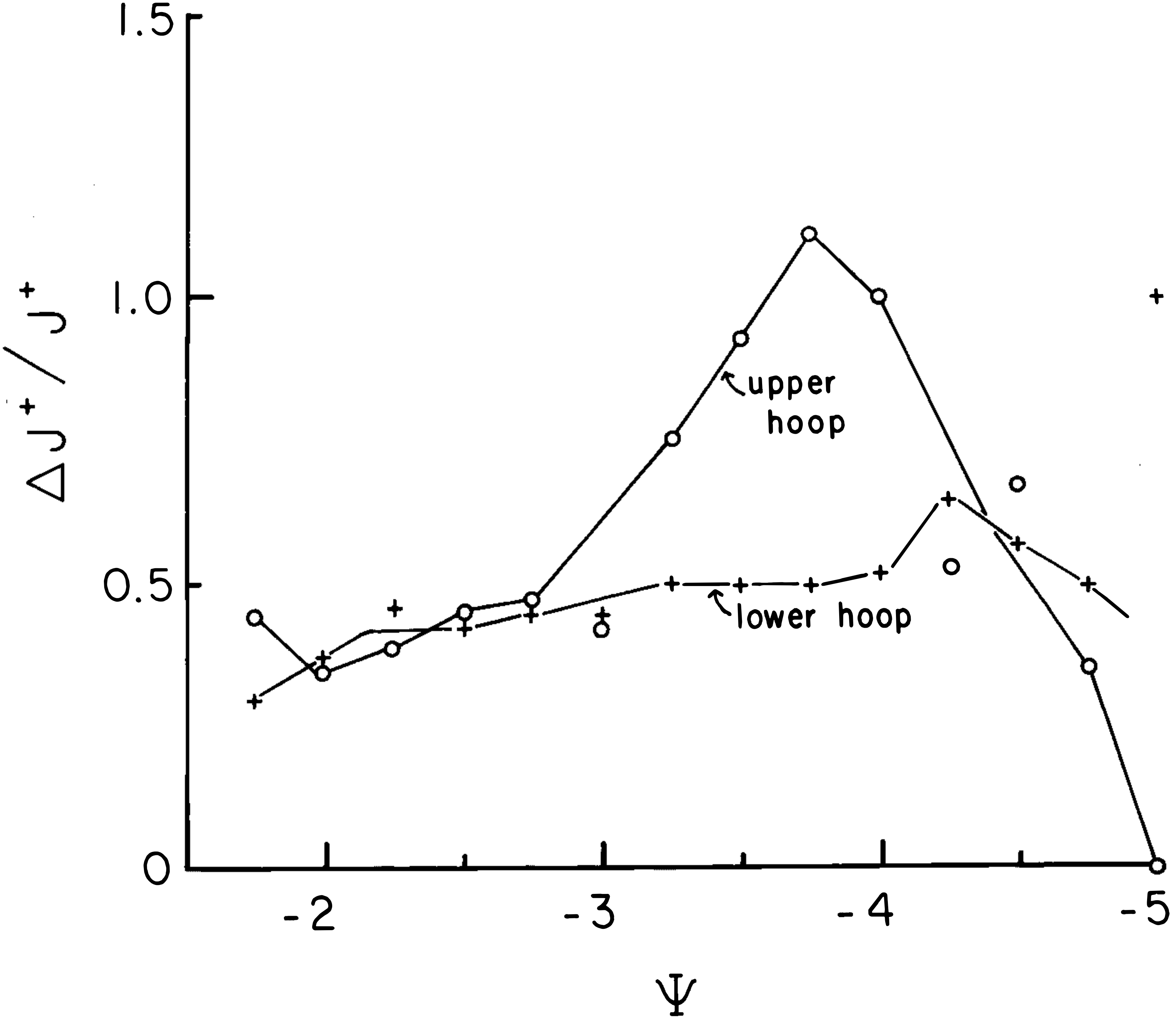
RF pulse: 1 MHz; 2 kVop; 144 μsec
with RF ⟨E⟩ = 33 eV
100 μsec after
RF termination
without RF
⟨E⟩ ≲ 3 eV
f(1̄V) (arbitrary units)
E (eV)
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0
20
40
60
80
100
120
140



10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
R_p (Ω)
ICRH theory
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
n (cm-3)



$R_p (\Omega)$
10
1
10^6
10^7
10^8
$n(cm^{-3})$ at poloidal gap



1.5
1.0
0.5
0
$\Delta J^+ / J^+$
upper hoop
lower hoop
-2
-3
-4
-5
Ψ