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LOWER HYBRID HEATING EXPERIMENTS IN USA

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Lower Hybrid Heating Experiments in USA

In the last few years there has been an increasing interest in the heating of plasmas using microwaves with frequencies in the range of the lower hybrid resonance. For what concerns the U.S. fusion program this interest is reflected in the committment to perform two large scale experiments aimed at the full understanding of this heating technique. Table 1. shows the past, present, and future experiments in toroidal machines in the USA.

The ATC experiment broke the ground, showing efficient coupling of power to the plasma with relatively simple techniques. This experiment showed temperature increases, later confirmed by other experiments in France and Japan, but opened up questions on the heating mechanisms involved.

The current experiment on Doublet IIA is designed to investigate the possibility of modifying the temperature profile and of heating the electrons. In particular it should determine the importance of quasi-linear effects on the damping of the waves. Meanwhile the Alcator A experiment is mainly devoted to studying the power limitations on coupling and the penetration of the waves in high density plasmas. Several aspects of propagation and damping of the waves will be studied at moderate power levels in a small scale tokamak, the Versator II at M.I.T.

Finally, the experiment on PLT at Princeton should investigate all the physics aspects associated with this heating technique, while the Alcator C at M.I.T., with its large power, should demonstrate the possibility of heating high density plasmas.

The ATC Experiment

The lower hybrid heating experiment on the ATC tokamak was performed in 1975-76. The basic machine, plasma and RF parameters are summarized in Table 2.

Coupling

The coupling of the RF power to the plasma was achieved by means of phased arrays of waveguides excited in the TE_{ol} mode. The phase difference between adjacent waveguides was such as to satisfy the acessibility condition with the average value of $n_{||} = 3$. The coupling coefficient was found to be in excellent quantitative agreement with the theory developed by Brambilla . The transmission coefficient was of the order of 90% without the aid of any matching system, with no significant dependence on the power level.

Ion Temperature

Ion temperature was measured primarily from charge exchange neutrals and from Doppler broadening of impurity lines. Charge exchange measurements showed an increase of the body temperature of ions up to 150 eV and the development of an energetic ion tail with a slope corresponding to an effective temperature of 1.4keV (Fig. 1 and 2).

The decay time associated with these two distributions was ~ 1 msec for the body temperature and ~ 0.1 msec for the tail. The decay time for ΔT_i was somewhat less than the ion energy containment time in ATC; but the temperature increase was consistent with those obtained in very similar experiments, on the WEGA Tokamak in Grenoble and the recent JFT Tokamak in Japan. Furthermore these charge exchange measurement on ATC were confirmed by spectroscopic measurements of the Doppler broadening of impurity lines. The spectroscopic lines used were from C^{V} and O^{VII} ions, the latter being emitted from the central part of the plasma body. While these spectroscopic ion temperature increases were consistent with those from charge exchange this diagnostic showed without any doubt an energy decay time $\tau \sim 3$ msec. Fig. 3. The discrepancy between the decay times measured by these two diagnotics has not been satisfactorily resolved.

Electron Temperature

Although the launching structure would couple primarily to waves with phase velocity too fast to interact with the electrons in the plasma, a small portion of the total power (~10%) was carried by waves with a $k_{||}$ large enough to be damped in the tail of the electronic distribution by electron Landau damping: that is satisfying the condition $\omega/k_{||} \sim 3V_{the}$.

Thomson scattering, soft and hard x-ray techniques were employed to study the effect of the RF power on the electron energy distribution. All three systems showed that the interaction occurred near the center of the plasma, where the electron temperature is maximum. Fig. 4 shows the increase of the apparent "temperature" in the electron tail from soft x-ray measurement as a function of the minor radius.

Thomson scattering showed a small increase of T_e over a range of a few centimeters around the center of the plasma. In addition this increase was found to be proportional to T_e, consistent with the fact that larger fraction of the $k_{||}$ spectrum is damped by electron Landau damping as T_e is increased.

Although it was difficult to measure accurately such a small temperature increase, the magnitude and parametric dependence of the increase was found to be consistent with electron Landau damping in every case. No other explanation was satisfactory.

Beam-RF Interaction

An interesting experiment was carried out which could give insight into the nature of the wave damping mechanism. A nearly monocromatic energetic ion beam at 26 keV and low power was injected tangentially in the plasma. While this beam was circulating in the plasma, confined in a small region in the center of the discharge, RF power was turned on, and its effect on the beam monitored with several C-X neutral analyzers aimed at different angles with respect to the beam. It was found that the particles in the beam were gaining energy (several keV) and were scattered at increasing angles perpendicular to their original direction of motion. In reference[1] a possible theoretical explanation of the decaying of the wave is presented in terms of a stochastic damping mechanism. When the RF was turned on with a deuterium beam in a deuterium plasma, we observed a 50% increase in neutron yield over that obtained with the beam alone.

Doublet II A

The experiment at General Atomics is performed on the Doublet II A tokamak, an/8kG, 100kA machine in which the electron temperature ranges between 200 and 300eV. Because of this low temperature, waves can be damped in the plasmas only if they carry high values of $n_{||}$, that is of the order of 10-20. In order to achieve this condition waves are coupled by means of a slow wave antenna consisting of a strip-line with a large number of phased elements. Preliminary results, obtained with Thomson scattering, seem to show heating for parameters consistent with quasi-linear theory (i.e. plateau formation in the electron energy distribution). Thermalization of this plateau appears to heat the electron body only if the density if sufficiently high. The experiment is scheduled to run through the summer of 1979.

PLT and Alcator C

Both experiments on PLT at Princeton and on Alcator C at MIT will use phased arrays of waveguides as couplers. Six adjacent waveguides will be used on PLT to perform a variety of experiments, ranging from ion heating to electron heating by means of linear and quasi-linear damping: the ion temperature should increase by a factor of ~ 3.

A similar increase is expected in the MIT experiment which will use 16 arrays of 4 waveguides each with a total of 4MW of power. This experiment is intended to demonstrate the possibility of heating high density plasmas and to increase the plasma parameters in the Alcator C machine.

Table 1

US LOWER HYBRID EXPERIMENTS

	Machine	Frequency	Power	Coupling System	Year
Past Exps.	ATC	800MHz	150kW	phased array of waveguides	6/75-6/76
Present Exps.	Doublet II A	800MHz 915MHz	350kW 200kW	slow wave antenna $n_{\|\|}=11-28$	1978-
	Alcator A	2.5GHz	100kW	waveguides	1978-
	Octomak	415MHz	low power	antenna $n_{\|\|}=76$	1977-78
Future Exps.	Versator II	800MHz	200kW	waveguides	10/1978-1979
	PLT	800MHz	1MW	waveguides	early 1980
	Alcator C	4GHz	4MW	waveguides	late 1980

Table 2 ATC

	ATC		RF
Toroidal field	19kG	Frequency	800MHz
Major radius	80-90cm	Total power	150kW
Minor radius	15-17cm	Max. pulse length	20msec
Plasma current	70kA	Coupler	phased array of waveguides
Peak density	2-3x10^{13}		
Peak electron temperature	1000-1500 eV		
Peak ion temperature	150-200eV		
Gas	H_2 or D_2		

Reference

1. E. Lazzaro, "Stochastic Heating of an Ion Beam by Lower Hybrid Waves" Proc. Third Topical Conf. or Radio Frequency Plasma Heating, paper G.1 — Pasadena (1978).

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Figure Captions

Fig. 1 Energy distributions from charge-exchange neutrals analysis (o no RF, ● with RF).

Fig. 2 Perpendicular ion temperature versus time from charge exchange neutrals analysis.

Fig. 3 Perpendicular ion temperature versus time from Doppler broadening of O^{vii} line.

Fig. 4 Apparent electron temperature vs. radius from soft xrays and Thomson scattering.

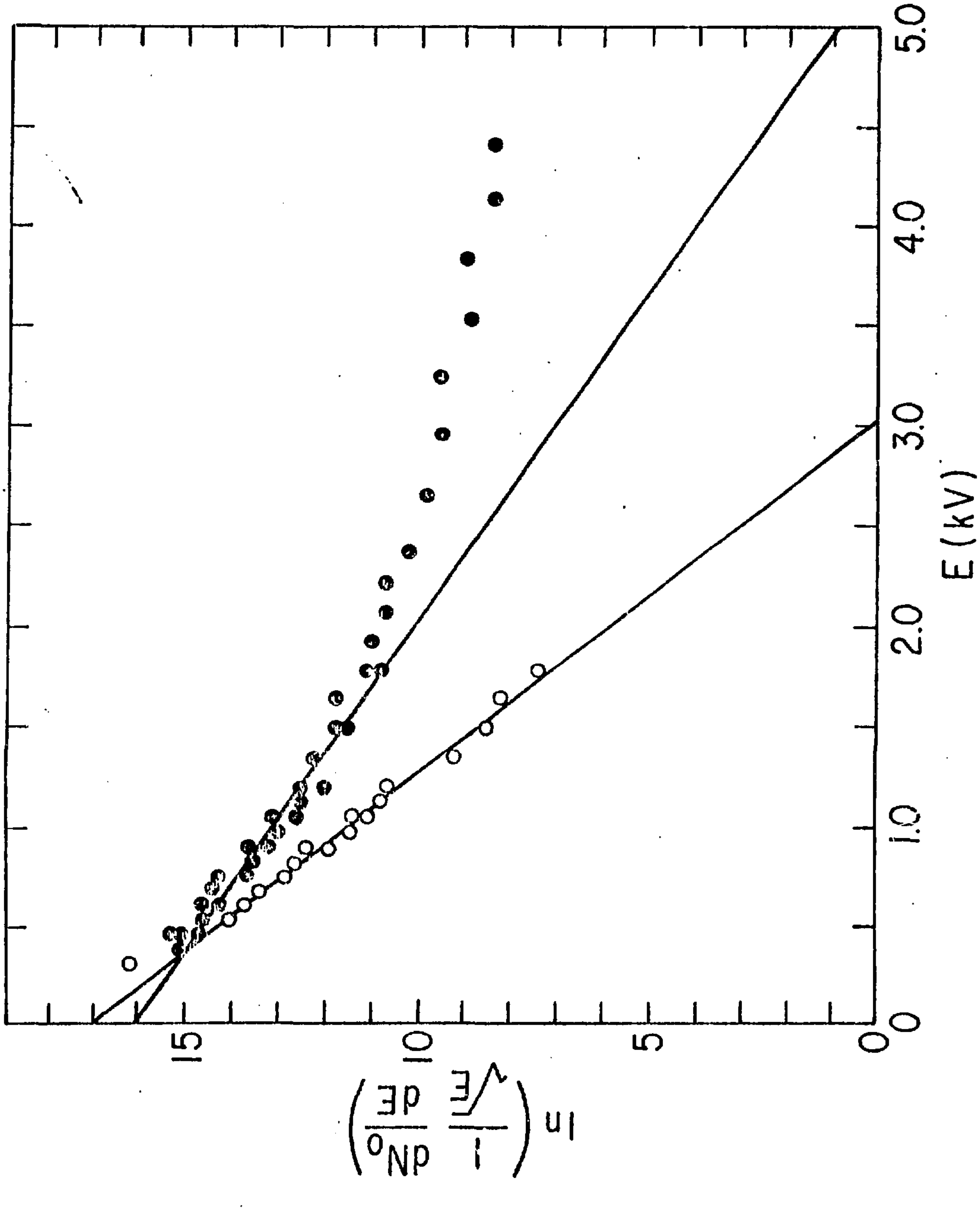
E (kV)
0
1.0
2.0
3.0
4.0
5.0
0
5
10
15
$\ln\left(\frac{1}{\sqrt{E}}\frac{dN_0}{dE}\right)$

Figure 1

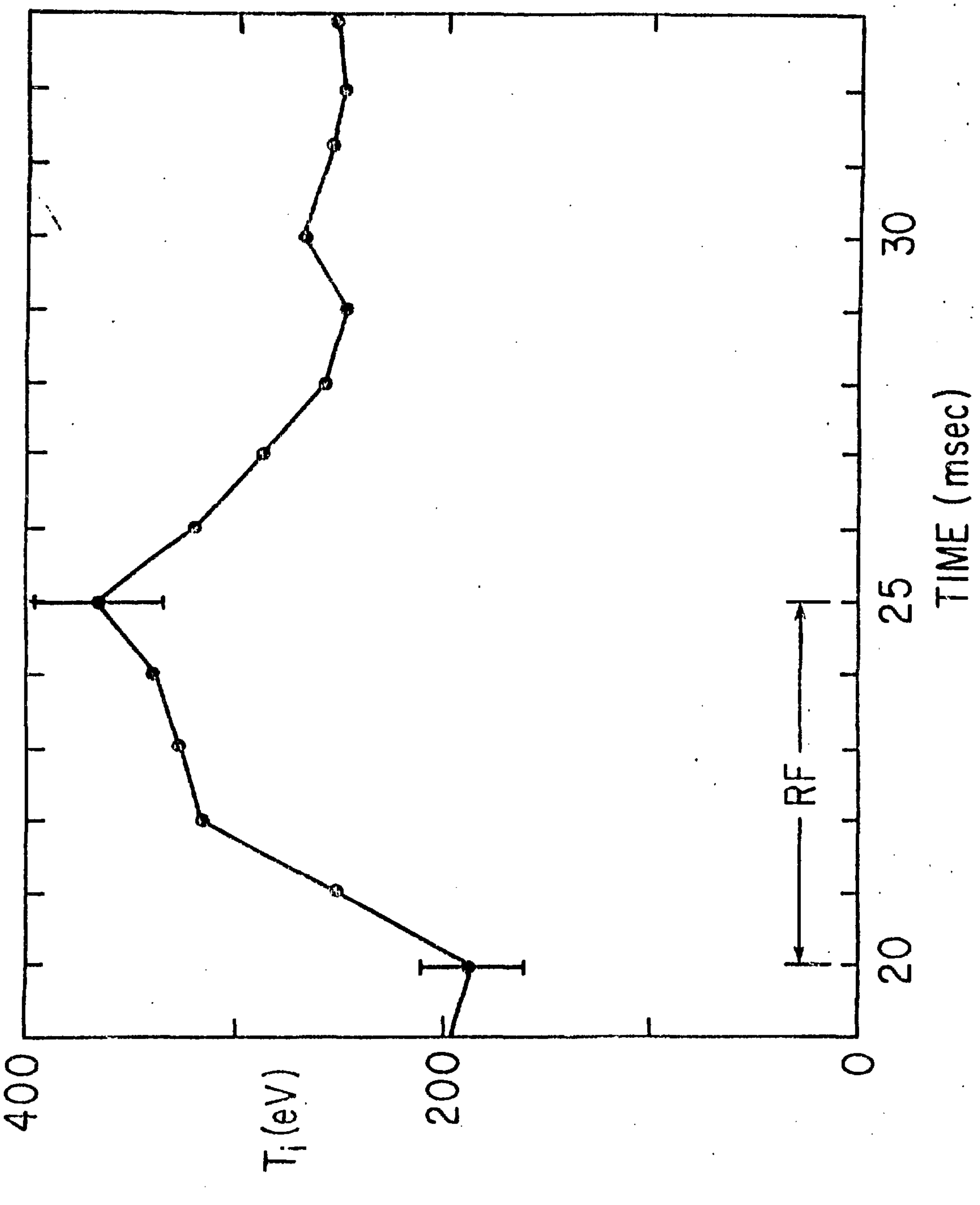

Figure 2

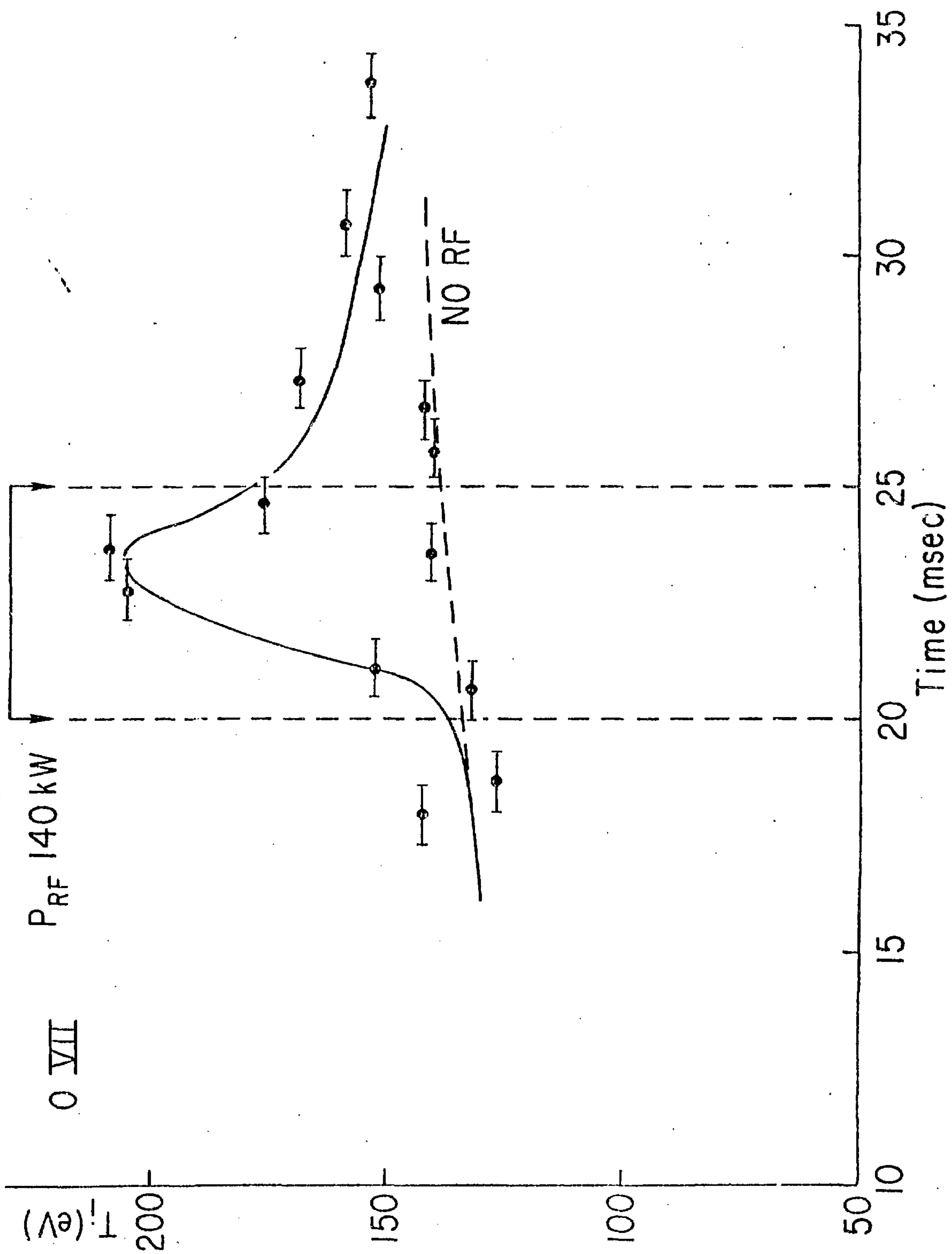
O VII
P_RF 140 kW
NO RF
T_i (eV)
200
150
100
50
10
15
20
25
30
35
Time (msec)

Figure 3

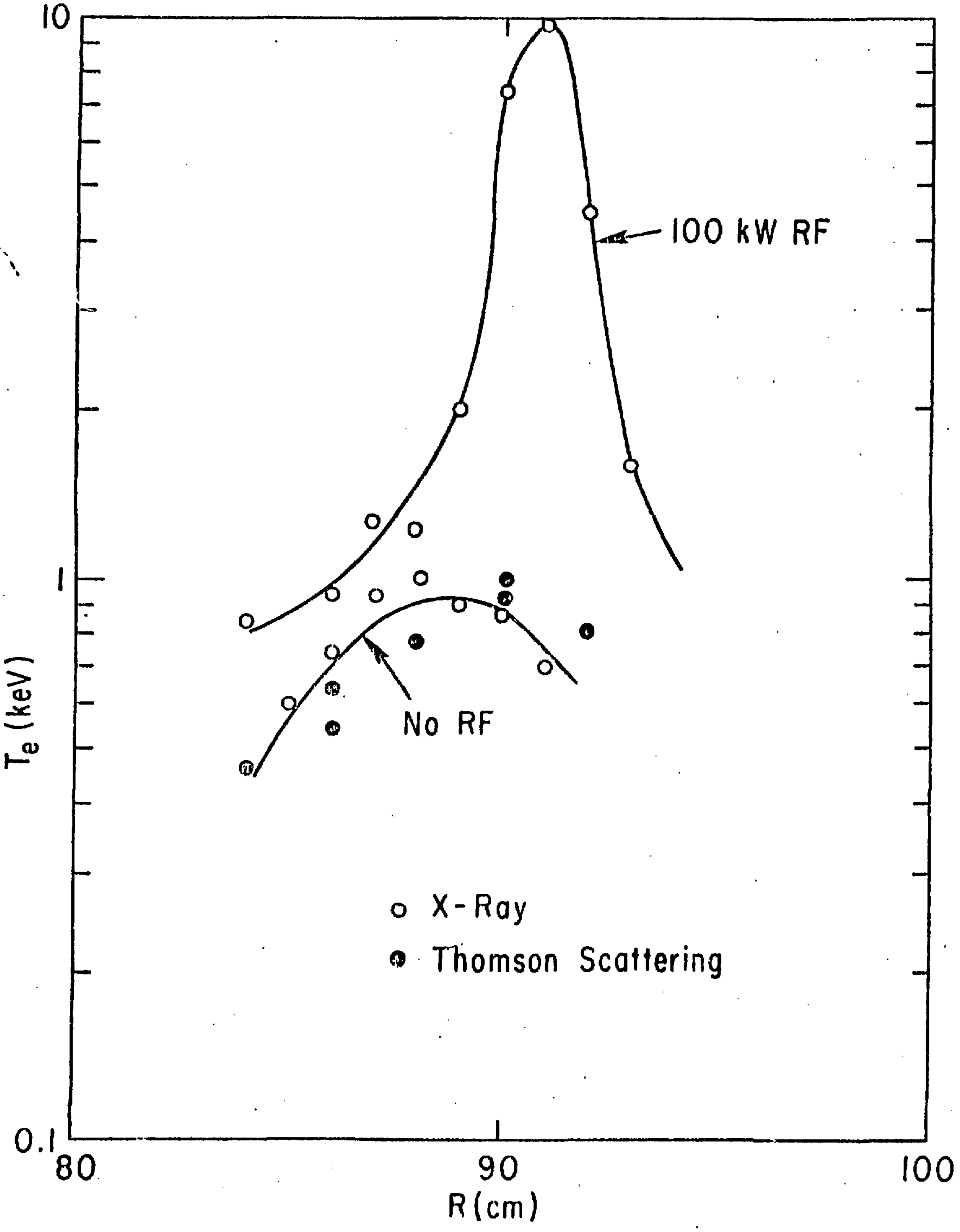
10
1
0.1
80
90
100
R(cm)
T_e (keV)
100 kW RF
No RF
○ X-Ray
● Thomson Scattering

Figure 4