MASTER

MARCH 1977

PPPL-1332

ION HEATING IN ATC TOKAMAK IN
THE ION CYCLOTRON RANGE OF
FREQUENCIES

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Printed in the United States of America.

Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy \$ * ; Microfiche \$3.00

<u>*Pages</u>	<u>NTIS Selling Price</u>
1-50	\$ 4.00
51-150	5.45
151-325	7.60
326-500	10.60
501-1000	13.60

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ABSTRACT

Ion heating by irradiation of rf fields in the ion cyclotron range of frequencies is investigated using several diagnostic techniques. It is shown that substantial heating of the bulk of the ions can be achieved by this method.

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It is generally believed that some form of supplementary heating will be required to heat Tokamak plasmas to thermonuclear temperatures. One such method currently under intensive experimental¹⁻⁵ and theoretical⁶⁻¹¹ investigation is irradiation of the plasma by electromagnetic fields in the ion cyclotron range of frequencies ("ICRF" heating). This paper documents ion heating observed in a recent series of experiments conducted in the Adiabatic Toroidal Compressor (ATC)¹² near the second harmonic of the deuteron cyclotron frequency. Technical details of the experiment will be described in a separate publication.

The principal ion temperature diagnostic is a three-channel charge-exchange (CX) neutral particle analyzer aimed perpendicularly ("perpendicular temperature") at the plasma. There is also a one-channel CX analyzer viewing the plasma in the direction tangent to the torus ("parallel temperature"). An oscillograph of the perpendicular analyzer output and examples of energy spectra are shown in Fig. 1. At high energies the spectrum is distorted by the presence of a "tail" created by the rf fields.^{1,2,5} (There is evidence² that such tails may consist of protons present in small quantities in deuterium plasmas.) Because the high energy part of the spectra that would ordinarily be used to determine the ion temperature in the plasma interior¹⁴ is now unavailable, interpretation of the CX spectra is complicated. The CX spectrum for the rf-on case in Fig. 1 is fitted with two straight lines by the least-squares method. The fit in the low energy part (900-1950 eV) is used to determine "body temperature" and the one in the high energy part (3000-4500 eV) "tail temperature". The body temperatures are used to evaluate the amount of heating.

Impurity ions of given states of ionization are concentrated within narrow annular regions in Tokamak discharges determined primarily by the electron temperature. Thus a radial ion temperature profile can be determined by measurement of impurity ion temperatures. Temperatures of O^{VII} , C^V and C^{IV} near the end of the rf heating pulse are measured by a monochrometer equipped with a vibrating LiF plate, which rapidly scans the Doppler profile,¹⁵ and are plotted in Fig. 2(a). The radial locations of the annuli determined from the diffusion velocities and ionization times of these impurities are indicated by the horizontal bars and the extent of shot-to-shot variation by the vertical bars. A factor of two uncertainty in the values of the ionization rate constant or diffusion velocity would affect the radial positions by less than 1 cm. These impurity temperatures are compared with the CX body temperature. Detailed studies of the CX signal source function, using the neutral density profile calculated by Stott,¹⁶ indicate that the measured CX temperature represents an average over the inner half of the plasma. This temperature is plotted in the same figure with an appropriate horizontal range bar. A probable profile suggested by these measurements is shown by solid curve and the profile similarly determined for a discharge without heating is shown for comparison. All temperatures in the figure, except that of C^{IV} , are seen to increase in response to application of the heating pulse.

The third method used to determine ion temperature makes use of neutron counting ("neutron temperature"). Upon termination of the rf pulse, the plasma is compressed to higher temperatures and densities and the neutron temperatures are determined assuming a deuteron deficiency of 0.5. In Fig. 2(b) these temperatures are compared to the CX body temperatures. The temperatures reached after compression are in agreement with predictions of the adiabatic toroidal compression theory¹² indicated in the figure by the lines marked A. T. C.

Additional information on the location of the observed heating can be obtained from examination of the CX signals. For example, if the heating were confined within the plasma periphery, the dominant ion loss would be through uncontained drift orbits with a time constant comparable to the bounce time around the banana orbits. The CX signals, especially at high energies (say, 3-4,5 keV), would then decay rapidly after termination of the heating pulse. On the other hand, if the observed signals originate from the central core (say, $r/a < 0.3$), the governing fast-ion depopulating process is the slowing-down due to the ion and electron drag. Thus comparison of the observed signal decay time with theoretical predictions provides a clue to the origin of the heated ions that undergo charge-exchange and are intercepted by the analyzer. A Fokker-Planck equation with the ion and electron drag terms only is solved to investigate slowing-down fast of ions assuming isotropic distribution.¹⁷ In Fig. 3(a), the CX signal decay process inferred from this solution is compared to the experiment at one energy and in Fig. 3(b) the theoretical and experimental half-widths (decay time at half-height) are shown for a range of

energies. The good agreement between theory and experiment is further evidence that the ion heating occurs in the central core of the plasma.

An example of the temporal variation of the perpendicular body temperature is shown in Fig. 4(a) for discharges with and without an rf pulse. After termination of the heating pulse the temperature relaxes to the value without rf in time consistent with the calculated ion energy replacement time. This shows that no significant deterioration of the energy confinement is caused by the rf heating and that the heating is attributable to the rf power input and not to a change in Ohmic heating caused by impurity influx.⁵ The parallel body temperature exhibits a somewhat higher value, but its temporal evolution is essentially the same. Fig. 4(b) shows the temperature increase attributable to a 10 ms rf heating pulse. The temperature rise is seen to increase with increasing rf power per ion.

In summary, evidence from several diagnostic techniques, of ICRF heating near the second harmonic of ion cyclotron frequency in ATC device demonstrates an increase in the thermal content of the majority ion species. Heating is not limited to the tail of the distribution nor to the minority ion species. Comparable heating in both the perpendicular and parallel degrees of freedom is also observed. Furthermore, the heating occurs in the central core of the plasma. Maximum heating results in a 200 eV increase in the ion temperature at an rf power level of 145 kW.

ACKNOWLEDGMENT

The authors are grateful to the ATC operating team led by Mr. R. Shoemaker.

This work is supported by U.S.E.R.D.A. Contract E(11-1)-3073.

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¹⁷The calculation assumes that the tail of ion distribution consists of protons². Deuterons would give theoretical half-widths 10% shorter than the values presented here.

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Fig. 1. Perpendicular charge-exchange neutral spectra with and without an rf pulse. The inset shows an oscillograph of three-channel charge-exchange analyzer signals (inverted) (5 ms/div): the analyzer settings are from top to bottom, 1.125, 2.25 and 4.5 keV.

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 Fig. 2. (a) Radial profiles of ion temperature determined from various temperature measurements: ■ charge-exchange, ● O^{VIII} , ▲ C^{IV} , ▼ C^{IV} : Open symbols without and solid symbols with rf heating. (b) Charge-exchange temperature (solid lines) and neutron temperature (● with and ○ without rf heating) in discharges compressed at 30 ms.

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 Fig. 3. Charge-exchange signal relaxation process after termination of the rf pulse. S is the CX signal amplitude normalized by its value at the pulse end. Theory is shown by solid curves and experiments by $\circ$: (a) Time evolution at $E = 2.7$ keV; (b) Decay time to half-value against energy.

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Fig. 4. (a) Evolution of perpendicular temperature: $\bullet$ with rf, $\circ$ without rf heating; (b) Incremental temperature rise attributable to rf heating. The abscissa is time-averaged rf power divided by total number of ions (in units of $10^{19}/\text{m}^3$).