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Ion Heating in ATC Tokamak in the Ion-Cyclotron Range of Frequencies

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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.

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 experimental[1-5] and theoretical[6-11] investigation is irradiation of the plasma by electromagnetic fields in the ion-cyclotron range of frequencies (ICRF heating). Although earlier heating experiments[1,3,5] have produced encouraging results, it is not certain that the rf power can be deposited in the plasma in a meaningful manner by this method. In this Letter, results are reported from a recent series of experiments conducted in the adiabatic toroidal compressor[12] (ATC) near the second harmonic of the deuteron cyclotron frequency. These experiments extend the results of earlier efforts in the ST device[5] by thorough investigation of the nature of the observed ion heating.

All heating experiments reported here are conducted with the second-harmonic resonance layer positioned near the center of the plasma. Moving the resonance layer in and out of the plasma shows that the wave-damping processes take place on or near the layer. However, the damping strength inferred from measured cavity Q factor is much stronger than expected from the second-harmonic resonant-damping theory. Similar observations were made in other experiments.[3] The current theoretical model,[8-11] supported by some experiments,[1-4] is that the observed discrepancy is due to the influence of two-ion hybrid resonance between the majority deuterons and the minority protons. (The latter may be present in small quantities as impurities in a deuterium plasma.) However, the detailed mechanisms remain unclear, and this paper is primarily concerned with the investigation of power deposition.

The rf generator frequency (fixed at 25 MHz corresponding to the second-harmonic deuteron cyclotron frequency at 1.64 T) is matched well to the ATC device and the experiments can be conducted under favorable discharge conditions. Principally for this reason, the maximum rf energy input [limited by occurrence of magnetohydrodynamic (MHD) oscillations that often lead to plasma disruption] is one order of magnitude greater than for the ST experiments.[5] The rf power and plasma parameters are adjusted to avoid these MHD oscillations. The rf power level (maximum peak power approximately 200 kW) drops during the pulse and all values quoted below refer to the time average. The pulse length (10 ms) is comparable or longer than the ion-energy replacement time (5-11 ms). It is considerably longer than various ion relaxation times (equipartition, deflection time, etc.) and the heating at the pulse end can be reliably assessed. This Letter presents strong evidence, substantiated by several diagnostic techniques, that the majority species in the tokamak core can be heated by this method.

The principal ion temperature diagnostic is a three-channel charge-exchange (CX) neutral-particle analyzer aimed perpendicular (perpendicular temperature) to the plasma. A one-channel CX analyzer views the plasma tangentially (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] Interpretation of the CX spectra is complicated, because the high-energy part of the spectra, ordinarily used to determine the ion temperature in the plasma interior,[13] would now give temperatures too high as a measure of the thermal content of the ion species. 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. The CX analyzers used here are incapable of discriminating deuterons and protons. There are possibilities that these protons participate in ion heating and also influence the observed CX spectra.[2]

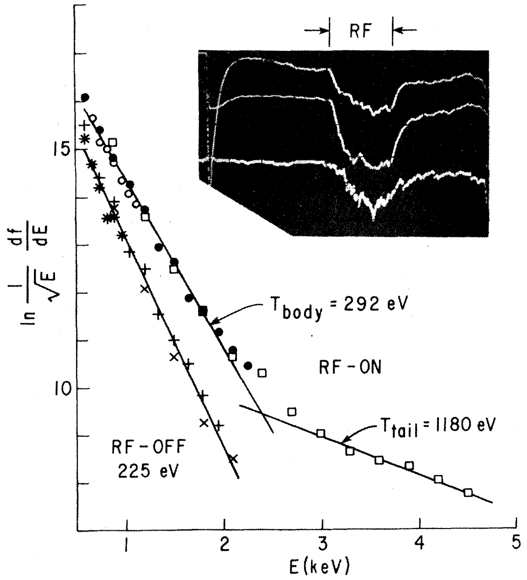

FIG. 1. Perpendicular charge-exchange neutral spectra with and without an rf pulse. The inset shows an oscillograph of three-channel charge-exchange-analyzer signals (inverted) (5 ms/div): The analyzer settings are from top to bottom, 1.125, 2.25, and 4.5 keV.

However, even in an extreme case in which the protons alone absorb the rf power, they are expected to share with the majority deuterons most of the energy acquired from the rf field, because the equipartition time (~0.1 ms at body temperatures and $\lesssim 2$ ms at tail temperatures) is short compared to the pulse length. However, because of these complications in interpreting the CX spectra, assessment of heating by this method needs to be corroborated by other measurements as described below.

Impurity ions of given state of ionization are concentrated within narrow annular regions in tokamak discharges determined primarily by the electron temperature. Moreover, these ions are strongly coupled thermally to the majority deuterons through frequent collisions. Thus a radial ion-temperature profile can be determined by measurement of impurity-ion temperatures. Temperatures of O VII, C V, and C IV (see Fig. 2) near the end of the rf heating pulse (P_{rf}~72 kW) are measured by a monochrometer equipped with a vibrating LiF plate, which rapidly scans the Doppler profile.[14] The radial locations of the annuli determined from the diffusion velocities and ionization times of these impurities[14] are indicated by the horizontal bars and the extent of shot-to-shot variation by the vertical bars. A factor of 2 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,[15] indicate that

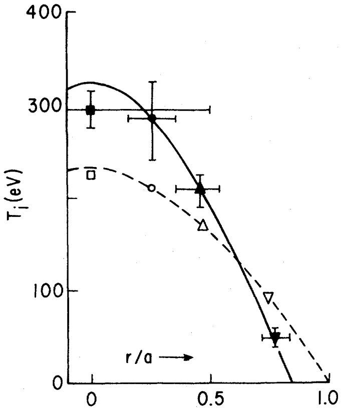

FIG. 2. Radial profiles of ion temperature determined from various temperature measurements: ■, charge-exchange; ●, O VII; ▲, C V; ▼, C IV. Open symbols without and solid symbols with rf heating.

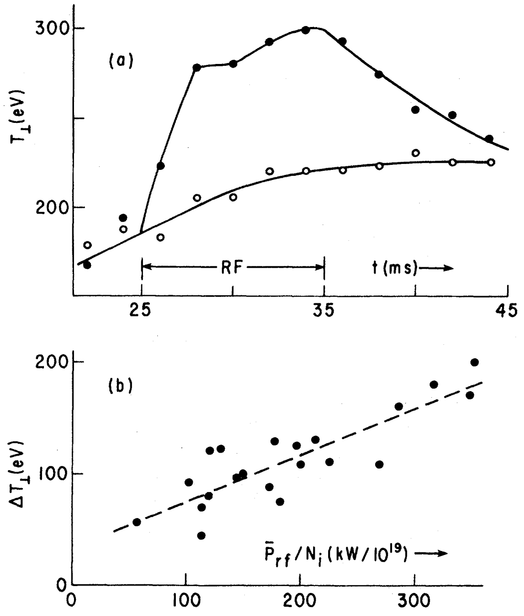

FIG. 3. (a) Evolution of perpendicular temperature: ● with rf, ○ without rf heating. (b) Incremental temperature rise attributable to rf heating. The abscissa is time-averaged rf power divided by total number of ions (in units of 10^{19}).

the measured CX temperature represents an average over the inner half of the plasma. A probable profile suggested by these measurements is shown in Fig. 2 by solid curve and a profile similarly determined for a discharge without heating by broken line. All temperatures in the figure, except that of C IV, increase in response to application of the heating pulse. The narrower profile with rf is believed to be a result of peripheral cooling due to impurity influx. The same influx is thought to be responsible for the observed electron density increase which is typically about 30% but which may vary greatly depending upon plasma conditions.

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. The neutron temperatures are determined assuming a deuteron deficiency of 0.5 and are found to be in reasonable agreement with the CX temperatures.

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 (~0.1 ms) 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 of fast ions assuming isotropic distribution. The time required for the CX signal to decay to half its initial value inferred from this solution is in the range of 1.5-1.8 ms for the cases studied (energies 3-4.5 keV) and is in good agreement with the experimentally observed value. This is further evidence that the ion heating occurs in the central core of the plasma.

A typical example of the temporal variation of the perpendicular body temperature is shown in Fig. 3(a) for discharges with and without an rf pulse ($P_{rf} \sim 72$ kW). After termination of the heating pulse the temperature relaxes to the value without rf in a time consistent with the calculated ion-energy replacement time. Thus, the rf heating causes no noticeable change in the energy confinement, and 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. Figure 3(b) shows the temperature increase attributable to a 10-ms rf heating pulse. The rf power plotted along the abscissa is normalized by the ion density. The temperature rise increases with increasing rf power per ion. Ion heating efficiency based upon the ion energy increase and average rf power ranged from 10 to 40%[16] when we take account of the finite ion-energy confinement time.

In summary analysis of data from several diagnostics demonstrates an increase in the thermal content of the majority ion species due to ICRF heating near the second harmonic of ion cyclotron frequency. 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 [see Fig. 3(b)].

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Anomalous Decrease in the Kapitza Resistance between Liquid ^{3}He and $Cu(NH_3)_4SO_4 \cdot H_2O$ at the Magnetic Phase Transition

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An anomalous steep decrease in the Kapitza resistance between liquid ^{3}He and a single crystal of $Cu(NH_3)_4SO_4 \cdot H_2O$ has been observed for the first time just below its magnetic-phase-transition temperature, $T_N = 0.43$ K. The decrease can be enhanced by the application of a magnetic field. These phenomena occur because of the strong coupling between ^{3}He spins and electron spins of the magnetic salt, as detected in the previous NMR measurement.

My previous NMR investigation[1] of liquid ^{3}He in contact with copper tetrammine sulfate monohydrate $Cu(NH_3)_4SO_4 \cdot H_2O$ (denoted hereafter as CuTA) has revealed an anomalous decrease in the longitudinal relaxation time of ^{3}He spins near the ordering temperature of CuTA, $T_N = 0.43$ K. The anomaly has been interpreted in terms of a strong magnetic coupling between moving ^{3}He spins and some spin-wave modes of electron spins in CuTA at its magnetic phase transition. In this Letter I present experimental evidence that such a strong magnetic coupling between liquid ^{3}He and the magnetic substance can contribute to the phenomenal decrease in the Kapitza resistance between them.

Guyer[2] has derived a fundamental relationship between the energy relaxation time, $[T_1]_{12}$ and the thermal-boundary resistance, R_B, in the two interacting systems 1 and 2, so that

$$\frac{1}{[T_1]_{12}} = \frac{A}{C_1}\frac{1}{R_B},$$

where thermal energy flows from system 1 to system 2, A is the area of the interface between systems 1 and 2, and C_1 the specific heat of system 1. If energy relaxation is mainly due to the magnetic coupling between nuclear spins and electron spins, $[T_1]_{12}$ is related to the effective correlation time of both spins, τ, which depends on

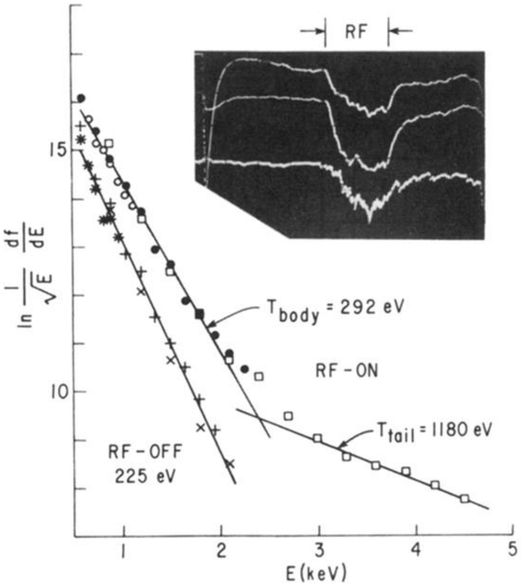

FIG. 1. Perpendicular charge-exchange neutral spectra with and without an rf pulse. The inset shows an oscillograph of three-channel charge-exchange-analyzer signals (inverted) (5 ms/div): The analyzer settings are from top to bottom, 1.125, 2.25, and 4.5 keV.