EFFICIENT ION HEATING VIA FINITE-LARMOR-RADIUS ICRF

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ABSTRACT

Ion heating by externally launched ion Bernstein waves is investigated in the ACT-1 hydrogen plasma. Detailed measurements of wave absorption and of the ion temperature profiles have clearly identified various heating layers near the ion-cyclotron harmonics of deuterium-like and tritium-like ions. The observed heating of $10 \text{ eV/WATT}/10^{10} \text{ cm}^{-3}$ and the power-balance estimates suggest excellent overall efficiency for FLR-ICRF heating.

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Until now, radio frequency (rf) heating schemes have utilized cold plasma waves to carry the rf power into the plasma interior. Propagation of these modes is not critically influenced by the plasma temperature, and the cold modes have provided rich opportunities for successful wave physics investigations in research plasmas which are often cold and collisional. An entirely new heating possibility arises for hot collisionless reactor-grade plasmas, where a full finite-Larmor-radius (FLR) ICRF wave¹⁻³ can be utilized to carry rf power deep into the plasma interior. FLR-ICRF wave heating would have several important technological advantages for reactor-plasma heating.⁴ In physics terms, this method of plasma heating differs from the conventional schemes in that the wave power is mainly carried by acousticlike particle motion instead of by the Poynting flux. Reported here is the first experimental observation of FLR-ICRF heating. The apparatus used is the ACT-1 toroidal device with externally launched ion Bernstein waves (IBW). Hydrogen ions initially at $T_i \sim 1.5$ eV are heated to ~ 50 eV with an efficiency of $\Delta T_i / P_{rf} n_0 = 10 \text{ eV/WATT}/10^{10} \text{ cm}^{-3}$.

Applying the FLR-ICRF concept to the heating of a toroidal device such as a tokamak, ion Bernstein waves are launched from the low field side of the torus toward the ion cyclotron harmonic resonance layer, the latter being located in the higher field plasma interior as shown by Figs. 1(a) and (b). Due to the increasing B_0 (or decreasing ω/Ω_i), $k_{\perp} \rho_i$ increases,

and when B_0 increases sufficiently to satisfy the wave resonance condition $(\omega - m\Omega_j)/(k_{\parallel} v_j) \leq 3$, $v_j^2 \approx 2 T_j/m_j$, ion cyclotron harmonic absorption takes place with a damping rate $\text{Im } k_{\perp} = \text{Im } K_{xx}/(\partial K_{xx}/\partial k_{\perp})$ given by

$$\text{Im } k_{\perp} \approx k_{\perp} \frac{\sqrt{\pi} \omega_{pj}^2 m^2 Q_m(\lambda_j)}{|k_{\perp} \partial K_{xx}/\partial k_{\perp}| \omega k_{\parallel} v_j} \exp\left[-\left(\frac{\omega - m\Omega_j}{k_{\parallel} v_j}\right)^2\right] \quad (1)$$

where $Q_m(\lambda_j) \equiv I_m(\lambda_j) \exp(-\lambda_j)/\lambda_j$, $I_m(\lambda_j)$ is the modified Bessel function of argument $\lambda_j \equiv k_{\perp}^2 T_j/M_j \Omega_j^2$, m is the harmonic number and j denotes the resonant ion species. The term $Q_m(\lambda_j) \approx (\lambda_j/2)^{m-1}/m!$ increases rapidly with λ_j , so that ion Bernstein waves with $\lambda_j = \mathcal{O}(1)$ can interact with ion cyclotron harmonic resonances for $m \leq 7$ and, thus, can be used to heat ions even at relatively high harmonic cyclotron frequencies.

Experiments were carried out in the 5 kG field of the ACT-1 toroidal device.⁵ A schematic plan of the experimental setup is shown in Fig. 1(b). A hydrogen plasma is created by a hot tungsten filament source operating with a neutral pressure of 1.7×10^{-5} Torr and producing a low collision, warm ion plasma [$\omega \approx 2\Omega_i \approx 10^8 \gg v_{ij}$, $v_{i0} \leq 10^4$] with $T_e = 2.5$ eV, $T_i \approx 1.5$ eV, and $n_0 \leq 10^{11} \text{ cm}^{-3}$. To preserve the Maxwellian nature of the plasma and to minimize electron Landau damping, the high energy ionizing electrons ($\varepsilon \leq 150$ eV) are carefully kept out of the experimental region. Waves are detected by rf probes (configured as shown in Fig. 1(b) to minimize the probe shadow effect⁶) and by a CO₂-laser scattering apparatus.⁶ At the same

time, the hydrogen ion temperature is monitored by the newly developed IBW T_i diagnostic technique which utilizes the measured wave dispersion characteristics of a lower power IBW test wave.^{6,7} A high-frequency lock-in amplifier (PAR 5202) has been used to detect selectively the test wave in the presence of higher power heating waves. With alternately phased electrostatic antennas, ~70% of the applied rf power is coupled to the plasma in the form of inward propagating ion Bernstein waves.

The linear wave physics, mode-transformation process, propagation, dispersion relation, etc., have already been described⁶⁻⁸ in detail for this case of ion Bernstein wave launching. Wave absorption layers are provided by the ion cyclotron harmonic resonances of the naturally occurring hydrogen molecular ions H_2^+ and H_3^+ (concentrations 20-25%, denoted here as D and T) which, from a wave physics point of view, behave identically to deuterium and tritium ions, respectively.^{7,8} The measured wave dispersion relation near the fifth harmonic resonance of H_3^+ has been plotted in the solid triangles in Fig. 1(a). Strong IBW absorption, observed near the resonance layer, can be seen in the measured radial wave packet amplitude profiles shown, in Fig. 1(c), at several wave frequencies. The dashed curve indicates the position of the center of the resonance layer. Due to the simple toroidal magnetic field geometry of ACT-1,⁵ the heating layer (constant B_0 surface) coincides with the ion

drift surface, a circumstance which greatly simplifies the heating layer identification. Figure 2(a) shows measured ion temperature profiles for various rf power levels. The ion temperature undergoes a nearly thirty-fold increase from its 1.5 eV unheated value (applied rf power of 10 W at $n_0 \approx 2.5 \times 10^{10} \text{ cm}^{-3}$). The position of the ion temperature peak coincides well with the observed region of strong wave absorption. In Fig. 2(b), the observed peak ion temperature is plotted as a function of applied rf power. The heating efficiency is $\Delta T_i / P_{\text{rf}} / n_0 \approx 10 \text{ eV/WATT} / 10^{10} \text{ cm}^{-3}$. The present FLR-ICRF heating has an interesting power scaling in that with increasing rf power, the higher T_i , longer λ_i , faster v_{ph} and v_g , and lower collision frequency γ_i will all contribute to improved wave penetration.

The measured ion energy increase, $\Delta(n T_i)$, is plotted in Fig. 3 as a function of radius for the 10 W case. Also in this figure, the shaded area portrays the power deposition predicted by a detailed ray tracing calculation. The calculation indicates that Doppler shift will cause the wave absorption to take place in front of the resonance layer ($\omega \approx 5.1 \Omega_T$) and this prediction is in excellent agreement with the experimental observation.

An estimate of power balance can be made from a comparison of the observed ion energy confinement time, obtained from the

measured ion energy increase per unit rf power, with the expected losses due to neutral cooling and ion drift. In an insert within Fig. 3, the neutral cooling loss, the ion drift loss, and the combined total loss are plotted as functions of ion temperature. Also shown in the insert is the observed loss rate based on the measured ion energy increase. These comparisons support the conclusion that the overall FLR-ICRF heating efficiency is excellent even in the relatively low temperature ACT-1 plasma.

Various heating layers can be readily identified by scanning the heating wave frequency while monitoring the ion temperature at a given radial position, keeping other wave and plasma parameters constant. Two strong heating layers with comparable heating efficiencies of $10 \text{ eV/WATT}/10^{10} \text{ cm}^{-3}$ are observed near $5 \Omega_T$ [Fig. 4(a)] and $5 \Omega_D$ [Fig. 4(b)]. A partial absorption layer resonance can also be seen in Fig. 4 (b) at $8 \Omega_T$. A heating layer at $7 \Omega_T$ with a somewhat smaller heating efficiency of $\Delta T_i/P_{rf}/n_0 \approx 7 \text{ eV/WATT}/10^{10} \text{ cm}^{-3}$ has also been seen. These heating efficiencies are maintained up to the maximum plasma density, $n_0 \approx 10^{11} \text{ cm}^{-3}$, obtainable in our low pressure filament discharge. This experiment has seen no significant deleterious effects associated with high power rf except when the ions are heated above 50 eV; here the particle losses in ACT-1 become significant and prevent meaningful heating studies.

In conclusion, efficient ion heating by FLR-ICRF has been observed for the first time in the ACT-1 toroidal device. Detailed measurements on wave absorption and ion temperature profile have clearly identified strong heating layers near the fifth harmonics of deuteriumlike and tritiumlike ions. The observed heating is consistent with a calculation based on the ion cyclotron harmonic damping. From power balance estimates, nearly all of the applied rf power can be accounted for by the observed ion energy increase, indicating excellent overall efficiency of the present heating process.

Although FLR-ICRF heating should work most favorably in high temperature, high field, reactor-grade plasmas, the present ACT-1 heating result and further theoretical investigations^{4,9,10} suggest that a timely experiment could be performed on existing medium-size tokamaks ($R \geq 100$ cm) with relatively high magnetic fields ($B_0 \geq 15$ kG). It is also worth noting that the present experimental observation may be relevant for ongoing tandem mirror¹¹ and EBT¹² ICRF heating experiments where anomalous ion heating has been reported at relatively high ion cyclotron harmonic frequencies ($m \geq 3$), a result which is difficult to explain solely in terms of fast-wave damping.

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FIGURE CAPTIONS

- FIG. 1. (a) IBW dispersion relation near $5 \Omega_T$ resonance layer. Solid curve is theory and the solid triangles are experimental values $H_1^+ : H_2^+ : H_3^+ = 0.45 : 0.25 : 0.28$. (b) Experimental setup. The antenna is located at $r = 7.8$ cm. (c) Radial wave packet amplitude profiles at several frequencies. Dashed curve defines the $\omega = 5 \Omega_T$ layer.
- FIG. 2. (a) Ion temperature profiles for various rf power levels (as labeled). (b) Peak ion temperature vs rf power. $f = 11.6$ MHz, $B_O = 4.75$ kG, $n_O \approx 2.5 \times 10^{10} \text{ cm}^{-3}$. Lower efficiency for $P_{rf} \leq 2$ W is due to the collisional absorption which causes partial absorption of IBW before it reaches the resonance layer.
- FIG. 3. Radial profile of net ion energy increase and theoretical power deposition profile (shaded). Insert - the measured ion energy loss rate (circle) and the classical loss rate; cx-neutral cooling, v_D -ion drift, and total-cx + v_D loss. $P_{rf} = 10$ W, $f = 11.6$ MHz, and $B_O = 4.75$ kG.
- FIG. 4. Ion temperature vs rf frequency (a) $\omega/\Omega_H = 1.6-1.9$. (b) $\omega/\Omega_H = 2.4-2.75$. $P_{rf} = 10$ W, $r = 3$ cm, $B_O = 4.75$ kG, and $n_O = 2.5 \times 10^{10} \text{ cm}^{-3}$.

Fig. 1

Fig. 2

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Fig. 3

Fig. 4

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