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Measurements of Strong Electron Core Heating During Alfvén-Wave Heating on the TCA Tokamak

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Recent results from the Alfvén-wave heating experiments on the TCA tokamak have confirmed very strong sawtooth activity on the peak electron temperature, with the delivered rf power roughly equal to the Ohmic power. This could be interpreted as being due to a very peaked rf-power deposition profile, in which case it would not correspond to the dissipation of all the Alfvén-wave energy locally at the resonance layers. It is possible that the mechanisms responsible might be the conversion to, and subsequent dissipation of, the kinetic Alfvén wave.

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It has been widely predicted that Alfvén-wave heating (AWH) would lead to an energy deposition profile local to the resonance layers and consequently no heating at the center of the plasma. In this Letter we present new experimental results which suggest that strong electron core heating may be taking place.

The resonance condition for shear Alfvén waves can be written, in cylindrical geometry, as

$$\omega(r)=B_\phi[n+m/q(r)][\mu_0\rho(r)R^2]^{1/2},$$

where (n,m) are the toroidal and poloidal mode numbers, $q(r)$ and $\rho(r)$ are the local values of the safety factor and mass density, and R and B_ϕ are the major radius and toroidal field. This relationship defines a set of resonance surfaces which move out to greater minor radii as the plasma density increases, thereby defining sets of resonance continua. AWH experiments on the TCA tokamak have already shown increases in stored plasma energy, electron and ion temperatures, and plasma density.[1,2] The questions of global efficiency have already been briefly addressed.[2] In this Letter we present new results showing a very strong electron temperature excursion during the sawtooth period, confirming earlier tentative results from the enhanced sawtooth modulation amplitude of the soft x-ray emission signals.

These AWH experiments are being carried out on the TCA tokamak ($R,a=0.61, 0.18$ m, respectively, $B_\phi=1.5$ T, $I_p=130$ kA) at a frequency of 2.5 MHz. The phasings of the currents in the eight antenna groups were set to excite the toroidal mode number $n=\pm2$. As a result of the toroidal coupling[3] several poloidal modes were excited, $m=\pm1$ being nonetheless dominant. The present maximum available antenna current employed was of the order of ~ 1000 A per antenna group, for all eight groups, yielding a total rf power of ~ 150–255 kW delivered to the plasma depending on conditions. This power level exceeded the 150 kW of Ohmic heating power in the target plasma.

For the first results, the rf power was applied to a low-density hydrogen plasma, with $\bar{n}_e \sim 2\times10^{13}$ cm^{-3}. This condition corresponds to the part of the Alfvén-wave spectrum just below the threshold of the toroidally coupled $(n,m)=(2,0)$ continuum. Because of the rise in density which accompanies the rf pulse, this threshold was then crossed, shown in time as a dotted line in Fig. 1. At this moment the new resonance surface appears at the center of the plasma, subsequently moving out. In this figure we illustrate the soft x-ray emission signals (A) for nine quasihorizontally viewing chords, noting their radii of closest approach to the axis. Because of the peakedness of the radial profile of the emitted soft x-ray flux, the inversion of the projected profile does not change the character of the traces particularly. The heights of the traces have been separately normalized to their maximum values for clarity. On the right-hand side of the figure the relative sawtooth modulation amplitude $\Delta A/A$ is shown, ΔA being the sawtooth excursion. After the $(n,m)=(2,0)$ threshold is crossed and the dominant surface is central, there is a strong increase in both the amplitude of the sawtooth and their relative amplitudes, both in the center and, inverted, for diodes viewing outside the inversion radius (5 cm). The radius of the sawtooth inversion did not change markedly during the rf pulse at the power level used. The same sudden increase in the outer sawtooth amplitudes has been observed when other Alvén-wave thresholds are crossed.

The new electron temperature data were obtained from a Thomson-scattering system providing a measurement at one point, the profile peak, and at one time during the discharge. The electron-cyclotron second-harmonic emission diagnostic is not useful over the range of densities covered, at the low toroidal field of TCA. The electron temperature was systematically measured at a time 7 msec after the start of the rf pulse, corresponding to a delay of $\sim 2\tau_{Ee}$. At this time the radiated power loss within the $q=1$ surface, measured by a sixteen-channel radiation bolometer, has not had time to have changed following any

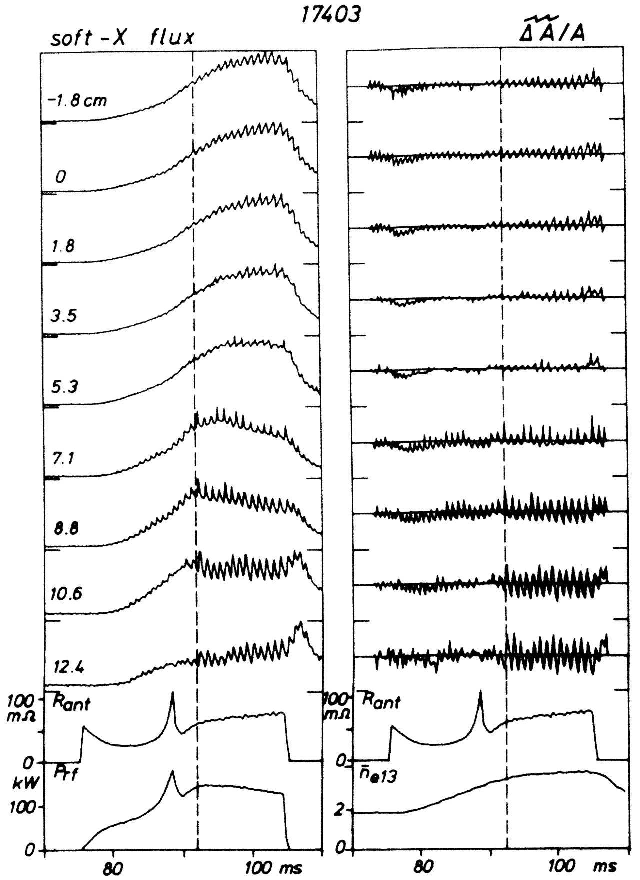

FIG. 1. Discontinuous behavior of the sawtooth amplitude of the soft x-ray flux observed at crossings of the $(n,m)=(2,0)$ Alfvén-wave threshold (dotted line). The left-hand side shows the normalized traces for different chords and the right-hand side shows the relative sawtooth amplitude (50% per division). [1.5 T; H_2; $q\approx 3.5$; $(N,M)=(2,1)$].

impurity influx. The radiated power loss on axis was less than 0.05 W/cm^3. The phase of the sawtooth was recorded for each discharge at the instant the electron temperature was measured, by reference to the soft x-ray flux measured on a minor diameter.

Figure 2 shows typical results obtained in deuterium plasmas. The top curve is the amplitude modulation of the soft x-ray signal. The next curve corresponds to the temperature excursion when the rf pulse was applied at a plasma density of $n_e(0)=(4.5\text{–}5.0)\times 10^{13}$ cm^{-3}. In these conditions the innermost and predominantly excited resonance layer was the toroidally coupled $(n,m)=(2,0)$ surface. The positions in the spectrum of all the measurements taken are shown in Fig. 3 against the antenna loading curve as a function of density. The period of the sawtooth (Δt) increased only slightly when the rf was applied. A straight line fitted through the measured points of Fig. 2 yields a temperature excursion during the sawtooth period of $\Delta T_e \sim 360$ eV or $\Delta T_e/T_{e,\max}\sim 0.34$ with only 150 kW

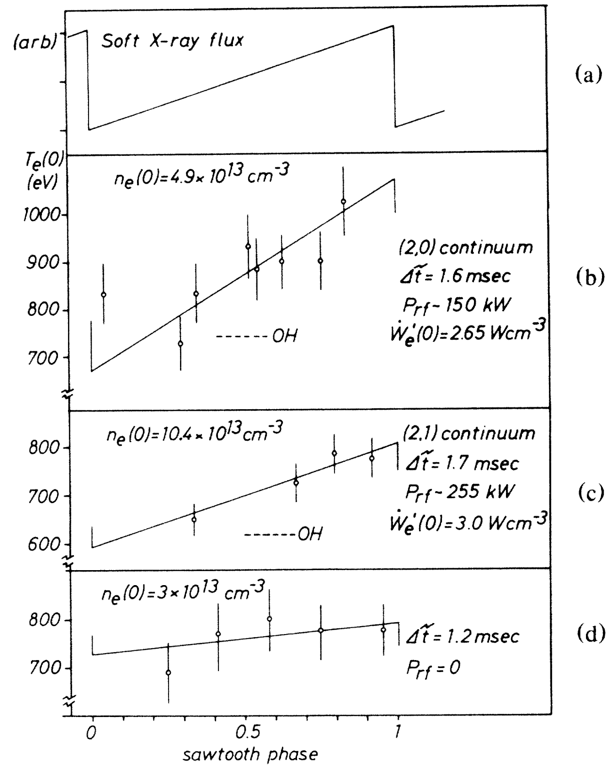

FIG. 2. Electron temperature excursion during the sawtooth period for several conditions: (a) modulated part of the soft x-ray signal, (b) rf applied in the $(n,m)=(2,0)$ continuum, (c) rf applied in the $(n,m)=(2,1)$ continuum, and (d) the OH target plasma [1.5 T; D_2; $q\sim 3.2$; $(N,M)=(2,1)$].

of rf power. In spite of the large sawtooth temperature excursion, the base line of the sawtooth was not much different from the mean value of the electron temperature during an Ohmically heated discharge at the corresponding density, shown in the figure as a horizontal dashed line. The next case, in Fig. 2, corresponds to a higher density in the $(n,m)=(2,1)$ con-

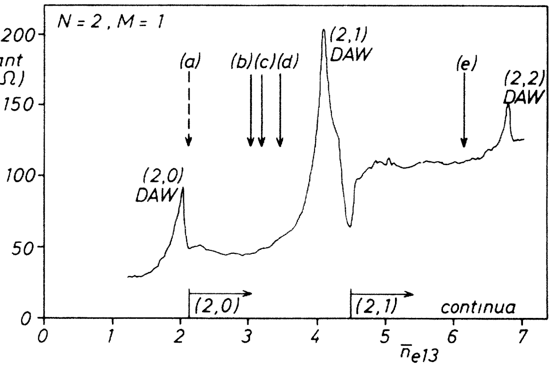

FIG. 3. The positions of the various measurements, relative to the Alfvén-wave antenna-loading spectrum for the excitation of toroidal model number $n=2$.

tinuum above the $(n,m)=(2,1)$ discrete Alfvén-wave resonance (see Fig. 3), and the temperature excursion was correspondingly lower. These experiments were carried out for four different target plasma densities, as well as without the additional heating pulse, and the results are summarized in Table I, in which we have also calculated

$$\dot{W}_e'(0)=1.5en_e(0)\Delta T_e(0)/\Delta t,$$

the rate of increase of axial electron energy due solely to the temperature rise. We have not taken into account the term due to the considerable rate of increase of electron density since in Ohmic plasmas we generally observe that the extra energy is obtained without significantly depressing $T_e(0)$. The inclusion of the rate of increase in density would increase our estimated power input.

We notice first that the value of $\dot{W}_e'(0)$ exceeds the axial Ohmic heating by a factor of 2 if we assume that $P_{\text{OH}}(0)=j(0)U_s/2\pi R$, U_s being the surface voltage and the current density on axis $j(0)$ being calculated from the assumption that $q(0)=1.0$. It is probable that $U(0)<U_s$ during strong sawtooth activity, so that we are, in any case, overestimating $P_{\text{OH}}(0)$. It is then clear that even if we were, in an extreme case, to switch off all loss channels and also the electron-ion equilibration power transfer, the sawtooth slope $\dot{W}_e'(0)$, being greater than $P_{\text{OH}}(0)$, still requires intense additional central power. The relative amplitude of the central soft x-ray sawteeth $(\Delta A/A)$ is smaller than the measured temperature excursion would predict. It is probable that a large fraction of the increase in the average soft x-ray flux is due to effects other than the temperature and density increases, thereby rendering the absolute modulation difficult to interpret. The most likely candidate is line radiation from the Si $K\alpha$ line measured at 1.8 keV, the limiters being coated with silicon carbide.

The value of $\dot{W}_e'(0)$ has been conventionally[4–6] related to the locally deposited heating power, provided the radiative losses are not important. On this basis we have also tabulated the value $W_e(0)/\langle P_{\text{rf}}\rangle$ for these conditions, which is a measure of the deposition profile peakedness, $\langle P_{\text{rf}}\rangle$ being the volume-averaged delivered rf power. The greatest peaking is for the lowest density (case b), and is higher than the assumed Ohmic power peaking given roughly by $q(a)/q(0)\sim 3.2$. We must stress that this accepted manner of estimating the core heating assumes, first, that the mechanism behind the sawtooth activity is unchanged by the additional rf power, and second, that the rf dissipation inside the radius of $q=1$ remains a locally determinable quantity. This question is open to considerable debate as it is now accepted that the heat diffusion is not always locally determinable.[7] The assumption made is invalid, of course, if a mechanism exists to transport energy to the plasma center, up the pressure gradient, when it has been dissipated at the plasma edge. No such mechanism has been proposed in the literature, to our knowledge, as an explanation of an enhanced sawtooth amplitude. Our working hypothesis is strongly supported by results from electron-cyclotron resonance heating experiments on T-10[8] and CLEO[9] both demonstrating that the sawtooth amplitude during the rf pulse is extremely large when the power deposition is within the $q=1$ radius, but that it can be suppressed totally when the resonance layer is further out. Even more recently, results from JET[10] using ion-cyclotron resonance-frequency (ICRF) heating show the same qualitative behavior; the power deposition profile is considered to be radially localized because of the large size of the device. This ICRF experiment therefore also supports the relationship between the sawtooth amplitude during additional heating and the power deposition profile. We have not observed any significant change in the qualitative behavior of the central sawtooth activity, nor have we taken the considerable increase in ion temperature into account in this simplified analysis thereby ignoring any change in the electron-ion equilibration rate $(P_{e\text{-}i})$ during a sawtooth period, which would tend to increase the estimate of the core deposition.

The power deposition peaking factor has also been evaluated for other heating methods using the same arguments. The PDX tokamak obtained an extremely peaked power deposition using electron-cyclotron resonance heating[4] with a peaking factor of 37, claiming a power deposition profile totally contained within the $q=1$ surface. ICRF heating experiments have shown a lower peaking factor, obtaining 1.9 on PLT[6] with 2 MW, attributed to substantial minority heating via ^{3}He

TABLE I. Summary of the electron temperature sawtooth excursion data.

Case (main mode)	$n_e(0)$ (10^{13} cm^{-3})	Δt (msec)	$\Delta T_e(0)$ (eV)	$\dot{W}_e'(0)$ (W cm^{-3})	P_{rf} (kW)	$\dot{W}_e'(0)/\langle P_{\text{rf}}\rangle$
a, OH	3.0	1.2	60	0.4	· · ·	· · ·
b, (2,0)	4.7	1.4	420	3.4	165	8.1
c, (2,0)	4.9	1.6	360	2.65	150	6.9
d, (2,0)	5.2	1.5	300	2.5	160	6.1
e, (2,1)	10.4	1.7	202	3.0	155	4.6

ions, and 1.5 on TEXTOR.[5] Strong sawtooth activity was observed during neutral-beam injection on Doublet-III and a peaking factor of 2.2 was obtained.[11] The ratio of additional power to Ohmic power was greater in the last three cases, but no data are available on the degradation of the deposition peaking during the degradation of global confinement of the higher powers.

Let us now turn to what has been predicted. In the first, low-density cases, the $(n,m)=(2,0)$ resonance layer is estimated to lie at $r_s/a \sim 0.65$. In the second case, the $(n,m)=(2,0)$ layer has moved out to $r_s/a \sim 0.85$ and the new $(n,m)=(2,1)$ layer is at $r_s/a \sim 0.6$. In neither case could local deposition lead to the strong core heating observed. It was realized previously, however, that the mean "heating radius" is not necessarily the conversion radius. It is generally expected that the energy can be transported away from the resonance layer by the kinetic Alfvén wave[12] propagating inwards when, as in our conditions, $\beta(r_s) > m_e/m_i$. The most recent and most elaborate 1D calculations[13] have fully solved the kinetic equation, but with no equilibrium current. These calculations have even shown, in particular cases, that there can be very strong core heating of the electrons. In order to judge the order of magnitude of the damping length we can estimate the perpendicular wave number of the kinetic Alfvén wave from the expression[12]

$$k^{-2} = \rho_i^2 \frac{\frac{3}{4} + (T_e/T_i)[1 - i(\pi/2)^{1/2}\delta_e]}{\delta_A^2 - 1},$$

where ρ_i is the ion Larmor radius and δ_e, δ_A are the ratios of the parallel phase velocity to the local values of the electron thermal velocity and the Alfvén velocity, respectively. We calculate a perpendicular wavelength in the range ~ 2–2.3 cm for the lower density case and ~ 2.5–2.8 cm for the higher density. Similarly, we estimate the damping lengths from the imaginary part of the expression to be of the order of 1.7–2.0 and 3.3–4.0 cm, respectively. These wavelengths and damping lengths represent a considerable fraction of the minor radius of the resonance layers, allowing, as shown in the 1D calculation cited, the possibility of core heating via the kinetic Alfvén wave. Unfortunately no complete model in 2D, including the Hall term, resistivity, and kinetic terms, exists at present. We must conclude that transport via the kinetic Alfvén wave is a plausible interpretation, but by no means proven.

We have therefore demonstrated experimentally, according to preestablished criteria, a strong central heating of the electrons, shown up by a large sawtooth amplitude during Alfvén-wave heating. Conventional analysis shows that the deposition must be peaked, less so than the case of electron-cyclotron resonance heating, but comparing favorably with data from other experiments. Calculations performed elsewhere suggest that the kinetic Alfvén wave might, in some conditions, be able to carry this power towards the plasma core, and it remains a challenge on TCA to demonstrate whether this mechanism might be the one responsible.

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