Heliumlike Titanium Spectra Produced by Electron-Cyclotron-Heated Tokamak Plasmas

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We have measured the heliumlike titanium emission lines produced during electron-cyclotron heating (ECH) of Doublet III tokamak plasmas. The spectra observed during ECH at a level of 1 MW show considerable departure from those of Ohmically heated plasmas. Theoretical analysis of line intensities shows that the ECH plasma is in disequilibrium with a net state of ionization and relatively little recombination. A departure from the Maxwellian electron distribution is inferred. Electron temperatures deduced from ratios of dielectronic recombination lines to the resonance line are in significant disagreement with temperatures measured by the Thomson scattering system.

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Ohmic heating of tokamak plasmas is not expected to reach thermonuclear conditions, because of the decrease in plasma resistivity with increasing temperatures and plasma disruption under high toroidal current. Two auxiliary heating methods under active investigation are neutral-beam injection of energetic hydrogen or deuterium atoms and radio-frequency wave heating.[1] Of the wave-heating techniques, the injection of waves at electron-cyclotron or upper-hybrid resonance frequencies in the range of tens of gigahertz has recently, with the advent of high-power gyrotrons, become viable as a method of plasma heating in large tokamaks. One key issue in electron-cyclotron heating (ECH) is the degree to which superthermal electrons are generated in the plasma.

On large tokamaks, high-resolution spectroscopy of impurity radiation in the soft x-ray region has proved a powerful technique for the measurement of ion and electron temperatures, plasma rotation, charge-state distribution, and equilibrium conditions.[2-5] But the bulk of the reported results concern Ohmically heated plasmas during the quiescent phase of the discharge, when the electron distribution is expected to be nearly Maxwellian, especially at high-density operation. Data on high-resolution measurements of x-ray emission in ECH plasmas has been scarce. Bryzgunov *et al.*[6] have presented heliumlike chromium spectra for T-10 tokamak discharges heated with 500 kW of ECH for 50 ms. The instrumental resolution $\lambda/\Delta\lambda$ was 3300 and the spectra were recorded on photographic film, integrated over nine plasma discharges during the ECH phase.

We report here the results of time-resolved (20 ms resolution) heliumlike titanium spectra measured during high-power ($P_{ECH} \sim 1$ MW), long-pulse-length ($\tau_{ECH} > 150$ ms) ECH experiments on the Doublet III tokamak. We have correlated the electron densities and temperatures inferred from the measured titanium line ratios to Thomson-scattering measurements of electron temperatures and densities.

The ECH system, discussed elsewhere,[7] includes six 60-GHz Varian VGE-8006 gyrotrons generating 1.2 MW (~ 1 MW absorbed in the plasma) for pulse lengths > 150 ms. The plasma cutoff density for wave propagation is $8.8\times 10^{19}/\mathrm{m}^3$ and the resonant magnetic field is 2.14 T. The wave propagates in a cone angle of 12° FWHM and is launched from inside (the high-field side) of the tokamak. The rf power is fully absorbed in an area about 10 cm in height and 5 cm in the radial direction at the major radius of the magnetic field resonance. A Thomson-scattering system measures the central electron temperature and density at one point, ~ 0.4 m from the magnetic axis, taking the data at the peak of the power absorption.

The spectrometer used in this experiment is a Johann-geometry Bragg crystal spectrograph constrained to a 3-m Rowland circle. A curved quartz crystal cut along the $(20\overline{2}\overline{3})$ plane with a $2d$ spacing of 2.75 Å diffracts and focuses x rays onto a position-sensitive delay-line gas proportional counter with a spatial resolution of 200 μm. The resolving power of this instrument, $\lambda/\Delta\lambda$, is $\sim 19\,000$. The data are acquired in fifteen time segments of (nominally) 20 ms per segment. A detailed description of this instrument is found elsewhere.[8] The center of the spectrometer acceptance cone is tangential to the tokamak magnetic axis. The combination of this long view chord through the center of the plasma with the high temperature observed in the center of the plasma ensures that the contribution from the cooler outer edges of the discharge is insignificant.

A comparison of the titanium spectra measured dur-

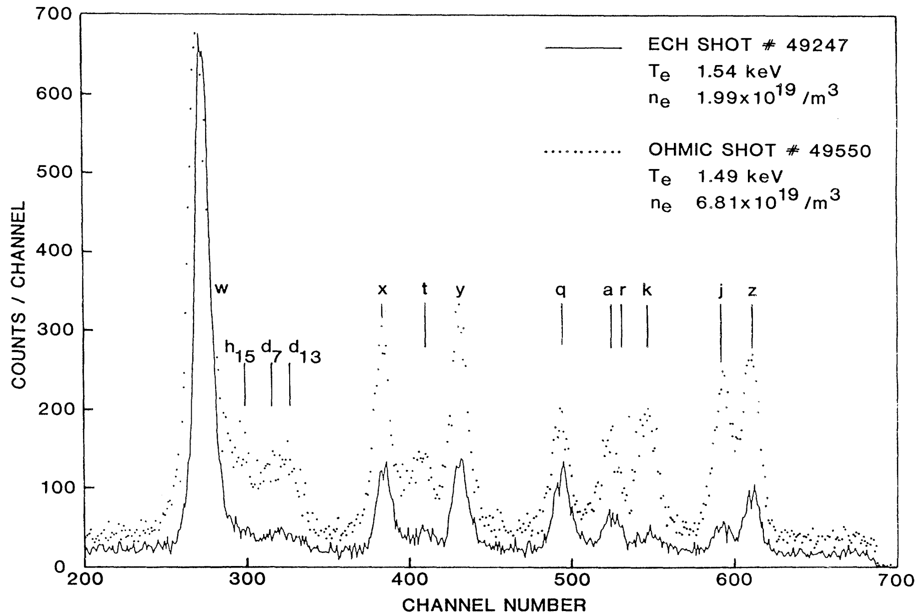

FIG. 1. Comparison of Ohmically heated and electron-cyclotron-heated tokamak discharges. Each spectrum was acquired over a 200-ms period and normalized to the same peak value of the resonance line w, for comparison purposes. The prominent lines have been identified according to the usual notation (Ref. 9). The measured electron temperatures from Thomson scattering for the two cases are nearly identical; however, the spectra are dramatically different. The ECH spectrum has notably lower intensities for the nondipole lines, e.g., x, y, and z.

ing Ohmic and ECH tokamak discharges is shown in Fig. 1. Each spectrum is presented with an integration time of 200 ms and is scaled to make the resonance line w the same height in both spectra.[9] The prominent heliumlike lines are the resonance line w, the intercombination lines x and y, and the forbidden line z; they derive from the transitions 1^1S_0-2^1P_1, 1^1S_0-$2^3P_{2,1}$, and 1^1S_0-2^3S_1, respectively. The stronger $n=2$ satellite lines are t, q, unresolved (a,r), k, and j. Also identified are the $n=3$ dielectronic recombination satellite lines h_{15}, d_7, and d_{13}.[10] With the w lines in both ECH and Ohmic shots of equal intensity in Fig. 1, the other lines may be seen to be of considerably lower intensity in the ECH plasma, by about a factor of 4 for the z and of 1.5 for the q lines. The measured electron temperatures for the cases shown here are similar for these shots, 1.54 keV for ECH and 1.49 keV for Ohmic. The spectra are dramatically different; the ECH spectrum appears to emanate from a hotter plasma (e.g., smaller line ratios $I_{d_{13}}/I_w$, I_k/I_w, and I_j/I_w).

Time-dependent titanium spectra have shown that the emission line intensities are roughly constant over the duration of the ECH period. This observation is consistent with the localized nature of ECH resonance, $\sim 10^{-3}$ m^3 for ECH heating volume as compared to 8.5 m^3 for the bulk plasma volume, whereby the processes of plasma transport and classical collisional redistribution of superthermal electrons generated by ECH with the bulk plasma thermal electrons are expected to reach a steady state.

In earlier reports[2-4,11] good agreement was found between the observed line intensities in Ohmically heated plasmas and theoretical values calculated in coronal equilibrium and with Maxwellian-averaged rates for excitation, ionization, and recombination processes. The rates are calculated at a given temperature characterizing the Maxwellian distribution. The line ratios of particular interest are $G=(I_x+I_y+I_z)/I_w$, which is sensitive to electron temperature and ionization balance of the impurity element under observation, and $R=I_z/(I_x+I_y)$, which is sensitive to the electron density. It is readily inferred that in a non-Maxwellian distribution, with an enhanced nonthermal tail, we may expect the ionization ratio n_{z+1}/n_z for an element in successive ionization stages to be greater than that for a Maxwellian distribution. We may also expect the intensity of allowed dipole transitions (e.g., the resonance line w) to be higher than the intensities of nondipole transitions, e.g., x, y, and z. (At high energies, the excitation cross section for dipole transitions behaves like $\ln E/E$; for nondipole transitions, it falls off much faster, i.e., like $1/E$.)

Figure 2 shows the dependence of the line ratio G on measured electron temperature in both Ohmic and ECH discharges. The titanium spectra were measured within 20 ms of the Thomson-scattering measurements mentioned above. Note that nearly all G ratios

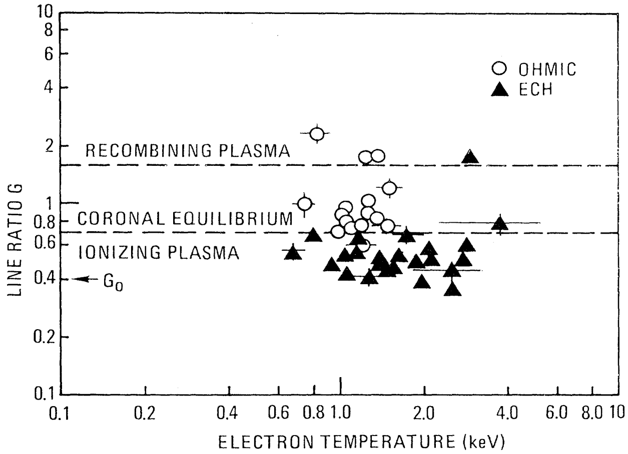

FIG. 2. Plot of the line ratio $G=(I_x+I_y+I_z)/I_w$ as a function of Thomson-scattering electron temperature for Ohmically heated and ECH plasmas. Most of the Ohmic shots are in the coronal equilibrium region, e.g, $0.7 < G < 1.8$, while most of the ECH shots indicate ionizing plasma. Also shown is the value G_0, the lower limit determined by the electron-impact excitation rates, below which no data points should be found.

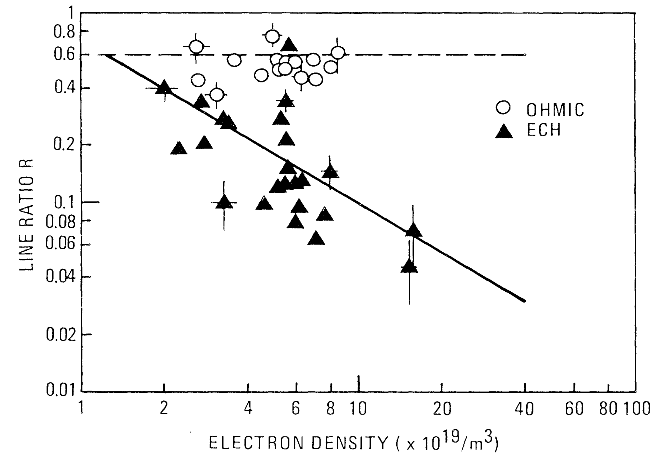

FIG. 3. Line ratio $R=I_z/(I_x+I_y)$ dependence on electron density for Ohmically heated and ECH plasmas. The dashed and solid lines show trends in the data. Theoretically, a dependence of R on electron density is expected for $n > 10^{21}/\mathrm{m}^3$. The Ohmic data agree with the theory, but the ECH data show density dependence at an electron density 2 orders of magnitude lower than predicted.

for ECH are less than 0.7, which, on theoretical grounds, indicates an ionizing plasma.[12] A plot of the ratio R as a function of measured central electron density is given in Fig. 3 for ECH and Ohmic plasmas. At high electron densities (i.e., $n > 10^{21}/\mathrm{m}^3$ for Ti), the collisional excitation from 2^3S to 2^3P is expected to deplete the z line relative to the x and y lines and hence to lead to a decrease in R. For ECH, the decrease in R is observed to occur at densities 2 orders of magnitude smaller than predicted; hence the decrease in R may be ruled out as a density effect (the Ohmic R ratio, although measured for a smaller range of densities, is observed to be consistent with theory).

The effect of nonthermal electron distribution on the emission lines has been predicted by Gabriel and Phillips[13] from iron satellite lines d_{13} and j, and observed by Apicella *et al.*[14] for the d_{13} line of chromium. Electron-temperature–sensitive line ratios, such as $I_{d_{13}}/I_w$, I_k/I_w, and I_j/I_w, are also anomalously smaller for ECH shots than the corresponding Ohmic values. For example, the temperature dependence of the ratio I_j/I_w is shown in Fig. 4. The solid line is the theoretical prediction,[15] and the experimental data are shown as open circles and solid triangles for Ohmic and ECH discharges, respectively. Typical error bars for the electron temperatures and line ratios are also given. The Ohmic data are distributed about the theoretical value with the scatter in the data larger than the errors in the measurements. Scattering in the data larger than what can reasonably be expected as statistical fluctuations have also been observed in other tokamak plasmas.[16] The ECH line ratios, however, are significantly lower than predicted and considerably lower than the corresponding Ohmic line ratio (at the same electron temperature).

In a non-Maxwellian distribution, the temperature T_e is no longer well defined. One may still, however, attempt to predict the spectra either by employing

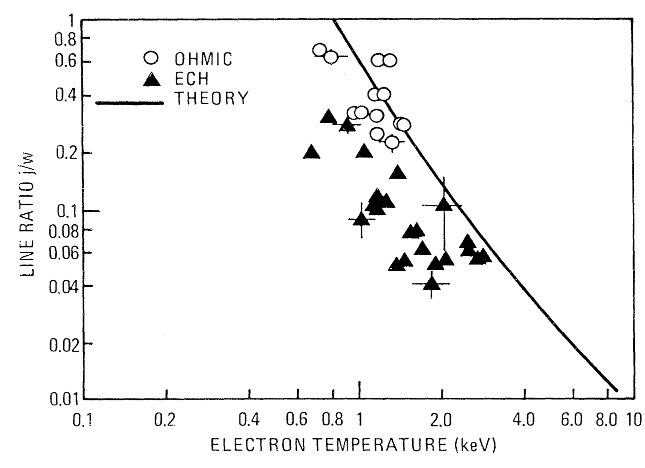

FIG. 4. The temperature-sensitive line ratio I_j/I_w is shown for Ohmic and ECH discharges. The solid line is the theoretically predicted curve based on the rate coefficients given by Bely-Dubau *et al.* (Ref. 15). The Ohmic data are clustered about the solid line with scattering greater than the errors in the measurements. The ECH data, by contrast, are systematically below the theoretical values.

TABLE I. Theoretical line ratios for Ti XXI with Maxwellian excitation rates. Columns I, without the contribution from radiative cascades; columns II, with cascades.

T (keV)	I_z/I_w I	I_z/I_w II	$I_z/(I_x+I_y)$ I	$I_z/(I_x+I_y)$ II	$(I_x+I_y+I_z)/I_w$ I	$(I_x+I_y+I_z)/I_w$ II
0.94	0.14	0.23	0.24	0.38	0.74	0.84
1.50	0.11	0.21	0.23	0.43	0.59	0.70
1.80	0.10	0.20	0.23	0.47	0.51	0.62
2.60	0.07	0.16	0.21	0.49	0.38	0.48

rates calculated as a combination of two temperatures or by assuming a non-Maxwellian distribution with an enhanced high-energy region and an associated T_e related to the mean energy of the electrons $\langle kT \rangle$. Preliminary calculations using both these approaches indicate that the resulting increase in the excitation rate for the w line and to a small extent the y line, relative to the z line, could explain the observed ECH line ratios. Modeling on the basis of such calculations should then yield the degree of departure of the electron distribution from a Maxwellian form in an ECH plasma. In Table I, we give the theoretical line ratios in the noncoronal limit of no recombination contribution to level populations and we find that with the Maxwellian-averaged excitation rates, the line ratios should be as given under column II, since the electron densities are insufficient to negate the effect of radiative cascades. However, the observed ratios are much lower than the column II values indicating, we believe, that the dipole transition w is enhanced because of the non-Maxwellian nature of the electron distribution. It also follows that the dielectronic satellites k, j, etc., relative to the w, are observed to be less intense than theoretical values and other observations.[2] It is clearly necessary to carry out far more detailed calculations than in Table I involving a variety of approximations to represent the non-Maxwellian effect and a recalculation of all relevant atomic rates.

In conclusion, our measurements of the heliumlike titanium line emission from Doublet III plasmas under high-power injection (<1 MW) of rf waves yield characteristic ECH spectra that deviate significantly from Ohmic spectra. The lines originating from nondipole transitions, e.g., x, y, and z, are weaker in ECH than in Ohmic plasma, for equal intensities of the w lines. Furthermore, the ratio $(I_x+I_y+I_z)/I_w$ indicates that the plasma is ionizing while the ratio $I_z/(I_x+I_y)$ shows a dependence other than the density effect. Temperature-sensitive dielectronic satellite ratios, I_k/I_w and I_j/I_w, during ECH are observed to be anomalously smaller than theoretical predictions.

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