ABSTRACT. High energy X-ray emission ($E_x > 20$ keV) from superthermal plasma electrons during lower hybrid current drive on the Alcator C tokamak has been measured using sodium iodide (NaI) scintillation spectroscopy. The X-ray spectra are generally linear on a semi-log plot of count rate versus photon energy and extend out to several hundred kiloelectronvolts. For the range of densities ($n_e \approx (0.3-0.8) \times 10^{14}$ cm$^{-3}$) over which current drive was performed on Alcator, there was negligible emission before the injection of radio-frequency wave power. The radial profiles of the emission were also measured and indicate that the current carrying high energy electrons exist primarily within the inner half ($r/a < 1/2$) of the plasma column. Plasma parameter scans produced variations in the X-ray emission profiles that are consistent with changes in the launched Fourier power spectrum and the conditions imposed by lower hybrid wave accessibility. In addition, the velocity space distribution function of the energetic tail electrons has been determined using the angular variation in the X-ray emission.

1. INTRODUCTION

During lower hybrid current drive, an energetic, current carrying electron tail is created by the travelling radiofrequency (RF) waves [1]. This high energy tail emits a continuum of bremsstrahlung radiation due to collisions between the tail electrons and the bulk plasma ions. By measuring this emission, it is possible to diagnose these energetic electrons. To this end, two different arrays of NaI spectrometers have been used to measure the hard-X-ray ($E_x > 20$ keV) emission during lower hybrid current drive on Alcator C. The first array measured the X-rays emitted perpendicular to the magnetic axis and was used to determine the radial profile of the emission. This emission indicates that the energetic electron tail extends out to several hundred kiloelectronvolts and is contained primarily within the inner half ($r/a < 1/2$) of the plasma column. There is negligible radiation before the injection of RF power. Parameter scans were made by changing either the launched power spectrum, the magnetic field and the density or the toroidal plasma current. The observed variations in the X-ray emission were consistent with these parameter changes. In particular, variations in the plasma density and the magnetic field directly affect the accessibility characteristics of the injected lower hybrid waves. The second array measured the X-ray emission as a function of the angle between the toroidal magnetic field and the emission direction. The emission is greatly enhanced in the forward (Ohmic electron drift) direction, indicating a strong anisotropy of the electron distribution function. The data demonstrate the existence of a nearly flat parallel tail extending out to approximately 500 keV.

Similar measurements have been made on PLT and Versator [2, 3]. However, the high frequency ($f = 4.6$ GHz) and high RF powers (up to $\approx 1$ MW) used in Alcator C (major radius $R = 64$ cm, minor radius $a = 16.5$ cm) allowed us to make these measurements at comparatively high densities of up to $n_e \approx 0.8 \times 10^{14}$ cm$^{-3}$. The lower hybrid waves were launched by two $4 \times 4$ waveguide arrays located 180° relative to each other around the torus. As in past experiments [4], the primary winding of the Ohmic heating transformer was open-circuited just before application of the RF power. Without RF power, the plasma current decays inductively, with a typical time-scale of $t_L/R \approx 150$ ms. Upon injection of sufficiently high RF power, the current decay is arrested and a constant current with zero loop voltage is maintained by the waves. In such cases, the vertical equilibrium magnetic field and the internal inductance reach constant values within about 50 ms.
Hence, after this transient time interval, inductive effects are negligible and the toroidal current is driven by the RF power alone. X-ray spectra are then collected for the remainder of the RF-current-driven phase of the discharge, approximately 150 ms in duration.

The plan of this paper is as follows: Section 2 gives a brief discussion of the launched n, spectrum and the lower hybrid wave accessibility in relation to the measurements presented in Section 3. The perpendicular X-ray measurements are presented and discussed in Section 3. The angular X-ray data as well as the tail electron distribution function deduced from these data are presented in Section 4. Finally, a summary and conclusions are given in Section 5.

2. LOWER HYBRID WAVE COUPLING AND ACCESSIBILITY

The theoretical n, 'Brambilla' power spectrum [5] for the Alcator C waveguide array is shown in Fig. 1 [6]. The n, spectrum for 180° phasing (0−π−0−π) peaks at |n,| = 3, with most of the power between 2 and 4. Since this phasing is symmetric, the n, spectrum is symmetric in the positive and negative toroidal directions. The positive direction here is defined arbitrarily as the Ohmic electron drift direction. Also shown is the power spectrum resulting from +90° phasing (0−π/2−π−3π/2). This is the phasing typically used in current drive experiments. In this case, most of the power is launched in the positive direction in the range +1 < n, < +2.5. Note, however, that about one third of the power is unavoidably launched in the negative direction and is centred near n, = −6. The negative part of the spectrum is expected to be absorbed near the plasma surface [7].

The slow wave launching structure initially fixes the value of n, for a given wave packet. As the wave packet propagates inward towards the plasma centre, its n, value can undergo changes which are due to toroidal effects [7], density fluctuations [8], the anomalous Doppler effect [9], or parametric decay [10]. However, for the plasma conditions under which current drive experiments were performed on Alcator, regardless of the wave packet's local n, value, the maximum extent of its penetration is determined by cold plasma lower hybrid theory [11]:

\[ n_\parallel = \frac{\omega_{ce}}{\omega_{pe}} + \sqrt{1 + \left(\frac{\omega_{pe}}{\omega_{ce}}\right)^2 - \left(\frac{\omega_{pi}}{\omega}\right)^2} \]

This condition defines a contour of accessibility which a wave packet with a given value of n, cannot penetrate. In general, plasma accessibility for a wave improves with lower plasma density and larger magnetic field. Thus, the contours of accessibility are concentric circles (due to the plasma density) that are slightly distorted (owing to the toroidal...
magnetic field. Figure 2 gives an example of these contours (after Ref. [12]). It is clear from the figure that waves with fast parallel phase velocities (low \( n_{\parallel} \) values) are restricted so that they are further from the plasma centre than slower waves. Therefore, the most energetic resonant electrons may be generated not at the plasma centre but at some distance radially outward. Furthermore, the collisional slowing-down time of a fast electron increases with energy. Hence, fast electrons have sufficient time to diffuse out of the plasma interior, whereas slower electrons are stopped there.

3. PERPENDICULAR X-RAY MEASUREMENTS

3.1. Experimental set-up

All the measurements described here were made by viewing the X-ray emission along chords through the plasma volume. The spectrometers were placed under the tokamak, viewing vertically upward, perpendicular to the horizontal midplane. A given set of measurements were always made with spectrometers at the same toroidal location viewing along parallel beamlines that formed a poloidal plane of intersection. These beamlines were narrowly collimated with a diameter of about one centimetre.

Figure 3 shows a schematic diagram of the X-ray detector array used to collect the data discussed in this section. The array consisted of seven 2.54 cm \( \times \) 7.62 cm NaI scintillation spectrometers.

The instrument was designed to measure only direct plasma bremsstrahlung. The reason for this was twofold. First, X-ray emission from any source other than the plasma does not directly indicate the real space or velocity space distribution of plasma electrons. Secondly, the major sources of non-plasma emission were the vacuum vessel wall and the plasma limiter, and this type of emission, called 'thick target bremsstrahlung', is difficult to model theoretically. To prevent non-plasma X-radiation from entering the crystals and distorting the measured plasma signal, the entire array was placed inside a lead shield approximately 24 cm thick. Also, the viewing lines were tightly collimated so that only the plasma column was observed. The vacuum window was made of 0.025 cm thick aluminium and was mounted on the outside of an Alcator port. This window permitted the unattenuated detection of photons with energies greater than 10 keV, while preventing non-plasma
radiation from scattering into a collimator. The window was mounted approximately 45 cm from the plasma surface at the end of a viewing slot. This further prevented limiter and wall radiation from striking the vacuum window. Similarly, the viewing lines were focused on a port on the top of Alcator which functioned as a 'black' beam dump. The array was also placed inside a magnetic shield approximately 3 cm thick. This shield prevented the penetration of the poloidal field into the photomultiplier tubes on the X-ray detectors, since this would have distorted the measured signal.

Each detector of the array collected an X-ray energy spectrum. The spectra are generally linear on a semi-log plot of count rate versus X-ray energy and extend out to several hundred kiloelectronvolts. The effective 'temperature' (defined here as the mean photon energy of the spectral distribution) of the spectra is in the range of several tens of keV. Each detector views emission from a particular chordal (radial) position in the plasma ranging from 12.4 cm to 9.4 cm. In general, each spectrum required several plasma shots (4 to 15) to achieve adequate statistical resolution at the high energy end. The crystals used in the detectors were large enough so that over the entire range of measured X-radiation (20–500 keV) no secondary scattered photons escaped. Thus, any incident photon deposited its full energy in the detector crystal. (The photofraction was greater than 0.95.) In this way, no corrections had to be made to the raw data; corrections would have resulted in greater uncertainties.

Figure 4 shows the photon energy spectrum collected from the plasma centre. Also shown is the high-energy plasma X-ray emission during the discharge before the RF power was turned on. The emission before the RF power is seen to be negligible compared to the emission during the RF driven phase of the discharge. This is a common feature of the RF driven discharges in Alcator and shows that over the range of plasma densities for which current drive experiments were performed here, there is usually no preformed high energy runaway electron tail. For the plasma conditions given, the X-ray spectrum tail extends out to at least 500 keV. However, the smallest value of $n_e$ permitted in the plasma centre by lower hybrid theory is $n_e = 1.2$. This corresponds to a resonant electron energy of 400 keV. The discrepancy is probably due to the fact that since the measurement is chord averaged, the entire plasma density profile is sampled. Because of lower densities further out radially, faster waves are permitted there, leading to values of resonant electron energy of up to at least 800 keV. However, this does not imply that the spectrum terminates owing to the effects of accessibility. Indeed, the spectrum shows no indication that a cutoff has been reached and in fact is actually turning slightly upward. This could be due to energetic electrons beyond the resonant quasi-linear plateau, the effects of a small residual electric field, or simply noise (which is comparable to the signal level at the highest measured photon energies). Many of the spectra shown in this section do not extend out to the accessibility limit prescribed by lower hybrid theory for their respective plasma conditions. The reason for this is that since the spectra fall off exponentially, experimental run time was often not available to collect complete spectra. This was particularly true when radial profiles were being measured.

Figure 5(a) shows line-averaged (brightness) spectra from three different radial positions. As mentioned above, the high energy tail portion of each spectrum (20–200 keV) is very linear, with a correlation coefficient greater than 0.90 and a fractional standard deviation of less than 20% in all cases. Therefore, each spectral tail can be characterized by an 'X-ray temperature'. Caution must be exercised in interpreting this X-ray temperature in that, unlike in the case of low-energy X-ray emission (soft-X-ray spectroscopy), the X-ray temperature here does not equal the mean energy of the emitting electrons. As a general rule, the
true mean energy of the emitting electrons will be greater than the resulting X-ray spectrum temperature. The reason for this is that as the electrons approach relativistic energies, the bremsstrahlung emission cross-section exhibits a complicated velocity space structure, tending to fall off with emitted photon energy even for monoenergetic electrons.

In spite of this limitation, the X-ray spectrum temperature provides a very good relative measure of the mean energy of the emitting electrons. Thus, if two spectra are compared and one spectrum has a higher temperature than the other, then the electrons that produced the former spectrum are more energetic than the electrons that produced the latter spectrum. Figure 5(a) shows a linear least-squares fit to the semi-log data for the three radial positions given. As mentioned above, the fits are very good. It can be seen that the tail electrons, while fewer in number, become more energetic at larger plasma radii. This is a general feature of the data resulting directly from the accessibility effects illustrated in Fig. 2.

Since spectra are obtained for several radial positions, it is possible to extract X-ray emission profiles at each measured photon energy. The small vertical arrows in Fig. 5(a) indicate five photon energies at which emission profiles have been obtained. These profiles are shown in Fig. 5(b). The emission profile for a given photon energy does not directly show the profile of the electrons of the same energy. This is due to the fact that all electrons with energies greater than the given photon energy contribute to the emission and that the emission is also proportional to the bulk electron density. However, the emission profiles do provide a good relative measure of the fast electron density profiles. Figure 5(b) shows that the emission profiles become broader with increasing photon energy. This indicates that the relative abundance of high energy electrons compared to low energy electrons is greater in the outer region of the plasma than in the inner region. This is a general feature of the data obtained during current drive experiments.

Although the X-ray emission profiles are generally symmetric about the plasma axis, there appears to be a consistent enhancement of the emission from the inboard side of the tokamak. This effect becomes more pronounced at higher photon energies. There are several possible explanations for this behaviour. One possibility relates to the magnetic topology of the tokamak. The current direction is such that the helical twist of the field lines forces the current carrying high energy electrons to travel slightly downward on the inboard side. The relativistic forward scattering of bremsstrahlung radiation could then lead to enhanced emission from the inside of the tokamak. (The bremsstrahlung radiation emission pattern from a relativistic electron is approximately a narrow cone oriented in the same direction as the electron motion with an angular spread which varies as $1/\gamma^3$ [13].) Another possible mechanism relates to the constancy of the magnetic moment $\mu$. Since the local magnetic field is larger on the inboard side of the tokamak than on the outboard side, the inboard electrons will have a slightly larger fraction of their total energy in the perpendicular direction than the outboard electrons. Again, because of the forward scattering of bremsstrahlung radiation, this could lead to enhanced emission from the inboard side.

As was done for X-ray spectra temperature, the emission profile widths can be quantitatively characterized by fitting an analytic function to the profile data. Figure 6 shows emission profiles for two photon energies fitted with shifted Gaussian curves. The fits for all cases are good, with a fractional
standard deviation of less than 30%. The results of Fig. 6 indicate quantitatively that the emission profiles broaden with increasing photon energies.

3.3. Parametric dependence of X-ray measurements

The data in the previous section have been quantitatively characterized in two different ways. First, the X-ray temperature, which gives a relative measure of the mean emitting electron energy, has been extracted from the X-ray spectra for each radial position. Second, the emission profile width, which gives a relative measure of the profile width of the emitting electrons, has been extracted from the emission data for each photon energy.

Using these characterizations, the following two subsections illustrate the emission data dependence on relative waveguide phasing, toroidal magnetic field, bulk plasma density and toroidal plasma current.

FIG. 6. Brightness profiles shown in Fig. 5(b) fitted with Gaussian curves. The energies and profile widths are (a) 40 keV with a 1/e width of 7.4 cm, and (b) 120 keV with a 1/e width of 8.6 cm.

FIG. 7. Perpendicular X-ray spectra slope (effective X-ray 'temperature') as a function of the collecting detector position parametrically in (a) waveguide phasing, (b) toroidal magnetic field, (c) line-averaged plasma density, and (d) toroidal plasma current.
3.3.1. X-ray spectra

Figures 7(a)–7(d) show plots of the effective temperature of the perpendicular X-ray emission as a function of chord position (or, equivalently, radius). The photon energy range of the spectra to which the temperatures were fitted is 20–200 keV. As can be seen in all plots, the X-ray temperature clearly has a smaller value at the plasma centre than at either the inside or outside radial positions. Within experimental error (statistical), the shape of each plot is symmetric about the plasma axis. This behaviour is a common feature of all data which cover a broad range of RF wave and plasma parameters. The temperature at the plasma edge is typically 50–70% larger than the temperature at the plasma centre. This percentage difference is approximately the same as that existing between the maximum resonant electron energies permitted in the plasma centre (~350 keV) and at the periphery (~600 keV) by lower hybrid accessibility theory.

Figure 7(a) shows the X-ray temperatures for two different values of relative phasing of waveguides in the launching antenna. At each radial location the emitting electrons are more energetic with 67.5° phasing than with 135.0° phasing. Emission data taken only from the centre for 67.5°, 90.0°, 112.5° and 135.0° show the same behaviour. Thus, it is clear that the mean energy of all RF produced tail electrons increases as the relative phasing of the launching antenna decreases. This is a direct reflection of the fact that with 67.5° phasing there is significantly more power in low \( n_B \) waves of the launched power spectrum than with 135° phasing, as can be seen from Fig. 1. This means that a greater fraction of the power is being damped on more energetic electrons. Thus, the measured X-ray spectra, which are reflective of the relative mean energy of the emitting electrons, 'track' the launched RF power spectra.

Figures 7(b) and 7(c) show the X-ray temperature as a function of plasma radius for several different values of toroidal magnetic field and plasma line-averaged electron density, respectively. Figure 7(b) indicates that the emitting tail electrons become increasingly energetic at all radii within the plasma as the magnetic field is raised. This is due to the fact that, as the magnetic field is increased at a local point within the plasma, with all other parameters held constant, the minimum value of \( n_B \) accessible to that point decreases. Hence, the maximum extent of the high energy tail, at a given point in the plasma, increases with increasing toroidal magnetic field. Similarly, as shown in Fig. 7(c), the emitting tail electrons become more energetic as the electron density is lowered at all plasma radii. This is again a consequence of the fact that, for lower density, waves with smaller values of \( n_B \) are accessible to that position.

Finally, Fig. 7(d) shows a plot of the X-ray temperature versus the plasma position for three different toroidal plasma currents. These plots indicate that the mean energy of the tail electrons increases with increasing plasma current. There is no simple explanation for this behaviour, since plasma current does not directly affect lower hybrid wave accessibility. However, one possible explanation involves the relationship between plasma current and RF power. The amount of RF power required for current drive increases linearly with increasing plasma current [4]. Thus, as the plasma current is increased, the quasi-linear plateau of the electron distribution function may become flatter in velocity space owing to the increase in the injected RF power. This effect, which has been observed in the numerical studies of current drive by Bonoli et al. [14], could lead to more energetic X-ray emission.

3.3.2. Radial profiles

Figures 8(a)–8(d) show plots of the X-ray profile width of the perpendicular X-ray emission as a function of photon energy. The profile widths were obtained by fitting Gaussian curves to the emission data at photon energies of 40, 80, 120, 160 and 200 keV. As can be seen in all plots, the X-ray profile width clearly increases with increasing photon energy. This behaviour is again consistent with the fact that lower hybrid wave accessibility restricts the fastest waves, and consequently the most energetic resonant electrons, to the plasma periphery.

Figure 8(a) shows the X-ray profile widths for two different values of relative waveguide phasing in the launching antenna. At all photon energies, the X-ray emission profiles are more peaked in the case of 67.5° phasing than in the case of 135.0° phasing. Also, the relative difference in profile widths increases at higher photon energies. Thus, it is clear that the radial distribution of RF produced tail electrons becomes narrower as the relative phasing of the launching antenna is decreased. This result is consistent with the fact that the 135° power spectrum has a greater fraction of power in high \( n_B \) waves than the 90° power spectrum. These higher \( n_B \) waves tend to damp further out from the plasma.
FIG. 8. Perpendicular X-ray profile widths as a function of the collecting detector position parametrically in (a) waveguide phasing, (b) toroidal magnetic field, (c) line-averaged plasma density, and (d) toroidal plasma current.

centre where the electron temperature is lower. Thus, the tail electron profiles tend to be broader in the case of 135° phasing.

Figures 8(b) and 8(c) show the X-ray emission profile width as a function of photon energy for several different values of toroidal magnetic field and line-averaged electron density, respectively. Figure 8(b) indicates that the emitting tail electrons have a narrower radial distribution at all energies as the magnetic field is raised. Similarly, Fig. 8(c) shows that the profile of the high energy tail electrons becomes more peaked at all energies as the electron density is lowered. The difference in profile widths is greater for higher photon energies in both cases. As the field is lowered, or the density is raised, the minimum value of $n_e$ accessible to the plasma interior increases and the mean energy of the electrons present in the plasma interior decreases. This profile broadening is particularly pronounced at higher photon energies. This is probably due to the fact that the higher energy electrons, which determine the emission of the most energetic photons, are most significantly affected by accessibility. At the lowest values of emitted photon energy, the profile width changes, as a function of magnetic field or density, are significantly smaller.

Figure 8(d) shows a plot of the X-ray emission profile width versus photon energy for three different toroidal plasma currents. These plots indicate that the radial distribution of the tail electrons broadens with increasing plasma current. Again, there is no simple explanation for this behaviour. Waveguide phasing effects, magnetic field effects and density effects, as discussed above, are all directly related to properties of the launched wave spectrum or lower hybrid wave accessibility. This is not the case for effects associated with varying the plasma current because the plasma current has no direct bearing of the RF wave accessibility. However, the plasma current can affect the RF ray propagation through the $q(r)$ profile (where $q(r) = B_T/B_θ(r)R$). Numerical ray tracing studies by Bonoli et al. [14] indicate that the RF wave power deposition profile broadens with decreasing $q(a)$ (toroidal effects). This broadening is due to greater variation in the poloidal mode number $m$, experienced by a propagating wave packet for lower values of $q(a)$. The variation in $m$ can cause large increases in $n_e$ which lead to wave damping at larger plasma radii. This mechanism can be used to explain the broader X-ray emission profiles experimentally observed at larger plasma currents. It is also consistent with the observation that the measured X-ray emission profile width increases with decreasing magnetic field.
4. ANGULAR X-RAY MEASUREMENTS

All of the above measurements have been made for the real space distribution of the RF generated high energy electrons. Of equal importance to the understanding of the physics issues associated with current drive is the velocity space distribution of these electrons. To determine the high energy electron distribution function, \( f(p) \), generated during lower hybrid current drive experiments on Alcator C, a series of spectroscopic X-ray measurements have been made. This technique, which has been successfully used on the PLT tokamak [2, 15], has been described in detail in Refs [13, 16], so only a brief discussion is given here.

In general, the bremsstrahlung X-ray emission due to a distribution of energetic plasma electrons is a convolution integral of the distribution function with the bremsstrahlung cross-section. As mentioned in Section 3, the bremsstrahlung cross-section becomes increasingly peaked in the direction of the velocity of the emitting electron as the energy of the electron increases [13]. Thus, high energy bremsstrahlung emission in a given direction, relative to a fixed direction (the magnetic axis), tends to be due primarily to electrons whose velocity is also in the given emission direction. By measuring the X-ray emission at various angles relative to the magnetic axis, the anisotropy of the tail electron distribution function can be inferred. These 'angular' measurements were made with the detector array shown in Fig. 9. (Only a single detector is shown; five such detectors, each with a different viewing angle, are stacked atop one another.)

Because of the Alcator port construction, the detectors were only 5 mm \( \times \) 5 mm in size and could only be surrounded by about 3 cm of tungsten collimation. This limited the maximum photon energy for which the X-ray spectra could be reliably measured to about 200 keV. Wall radiation, which could contaminate the measurements, was probably not a problem since the spectra from the 90° angular detector and the central channel detector of the vertical array were virtually identical for the same plasma conditions. Since the measured X-ray spectrum for each angle was chord averaged in order to compare the level of emission from angle to angle, each spectrum had to be normalized to the effective chord length. The electron tail density profile needed to perform the normalization was assumed to have the same shape as the X-ray emission profile discussed in the previous section (for the same plasma conditions) [15].

As mentioned above, the success of this technique relies on the fact that the bremsstrahlung cross-section forces a correlation between the direction in electron velocity space and the X-ray emission direction in real space. However, the measured X-ray energy distribution is not the electron energy distribution. The reason for this is that photons of a given direction and energy, \( k \), can still result from electrons moving in an arbitrary direction and with any kinetic energy greater than \( k \). Because of these difficulties it is not possible to uniquely determine the electron distribution from the bremsstrahlung data. Instead, a relatively simple model electron distribution function must be assumed. The parameters of the model giving a calculated bremsstrahlung which best matches the measured data can then be determined by iteration. The resultant distribution function is obviously not unique, but it should be a close approximation to the true electron distribution and therefore include many of its essential features.
features. The model distribution function used here is a 'three-temperature Maxwellian'. The tail has a Gaussian velocity space shape and is characterized by three fitted parameters — a forward parallel temperature \( T_{\parallel f} \), a perpendicular temperature \( T_{\perp} \), and a backward temperature \( T_{\parallel b} \). The terms forward and backward refer to the direction of propagation of the lower hybrid waves with low \( n_{\parallel} \). A fourth fitted parameter — a cutoff of the Maxwellian in the forward direction, \( T_{\max} \) — is used to simulate the results of detailed computer code calculations [14]. These calculations indicate that the high energy distribution function formed during lower hybrid current drive is a very flat parallel plateau extending out to a sharp cutoff determined by lower hybrid wave accessibility. The shape of the model distribution function is assumed to be independent of plasma radius. Clearly, the results of the previous section indicate that this assumption is not strictly correct. However, the PLT results suggest that the error incurred in this assumption affects only the electrons with energy greater than the limit prescribed by accessibility at the plasma centre. For the plasma conditions under which the measurements presented in this section were made, this energy is about 400 keV. A position dependent function of the distribution model would remove these most energetic electrons from the inner half \( (r/a < 1/2) \) of the plasma and confine them to the outer half. The tail properties of either model (stored energy, dissipated power, cyclotron emission) are virtually identical.

Figure 10(a) shows the calculated X-ray emission which best matches the measured data for a waveguide phasing of 90°. A contour plot of the model electron distribution function which results in the calculated bremsstrahlung is shown in Fig. 10(b). The parameters for this distribution are:

\[ T_{\parallel f} = 800 \text{ keV}, \ T_{\perp} = 100 \text{ keV}, \text{ and} \ T_{\max} = 600 \text{ keV}. \]

Note that the model distribution function has an enhanced temperature in the forward (wave phase velocity) direction. The calculated bremsstrahlung duplicates the two main features of the data: (1) the general peaking of the emission in the forward \( (\theta_y > 90^\circ) \) direction, and (2) the slope of the X-ray spectrum at each viewing angle (i.e. the spacing between the lines of constant-photon-energy emission).

The cutoff energy \( T_{\max} \) was introduced to simulate the high energy limit on the distribution function that could result from a restriction imposed on the maximum wave phase velocity prescribed by the lower hybrid accessibility condition. However, it is not
possible with the present data to clearly distinguish between models with a cutoff energy and models without a cutoff energy. This is particularly true in this case, where the experimental conditions limited the maximum measured photon energy to about 200 keV. A best fit with $T_{\text{max}} \rightarrow \infty$ is obtained for $T_{\text{lf}} = 500$ keV. In this case, the parallel forward temperature is somewhat lower than that in the previous model in order to compensate for the larger number of high energy tail electrons. The parallel backward and perpendicular temperatures are not affected by the choice of $T_{\text{max}}$ since they are so much lower. In either case, there is clearly a large high energy electron tail which extends preferentially in one toroidal direction. To distinguish between the two models, data from studies with temperatures above 500 keV would be required.

For the plasma conditions under which the emission data of Fig. 10 were collected ($n_e = 3 \times 10^{13}$ cm$^{-3}$, $B = 8$ T, hydrogen gas, $I_p = 140$ kA), the lower hybrid wave accessibility restricts the resonant electron energies to below 400 keV at the plasma centre. This value increases at larger radii because of the decreased density and increased magnetic field. The cutoff value of $T_{\text{max}} = 600$ keV was chosen because it best fits the data. Also, it is not possible to fit the data with a smaller value. Thus, it must be concluded that the measured distribution function is actually the true distribution averaged over the plasma poloidal cross-section. This is in keeping with the fact that the measurements are all chord averaged.

Figure 11(a) shows actual and fitted emission data for plasma conditions similar to those of Fig. 10(a), but with a waveguide phasing of 135°. The model distribution used to fit the data is shown in Fig. 11(b). The general features of the distribution function here are similar to those of the 90° case, except that the temperatures of the distribution are significantly reduced, i.e. $T_{\text{lf}} = 200$ keV and $T_{\text{lb}} = T_{\text{l}} = 70$ keV. The cutoff energy was kept at $T_{\text{max}} = 600$ keV since the plasma conditions, which determine accessibility, are unchanged. The depreciation of the temperatures is particularly severe for the forward parallel temperature. As shown in the previous section, this is due to the difference in the shape of the launched Fourier power spectrum. Figure 1 shows that there is much more power at low values of $n_\parallel$ (corresponding to waves with high phase velocity) in the 90° case than in the 135° case. This is reflected in the slope of the distribution function. In particular, for 90° phasing the power in the launched Fourier spectrum increases monotonically as $n_\parallel$ decreases from 3 to 1. This corresponds to kinetic energies of resonant electrons ranging from 30 keV to the value prescribed by accessibility. For the 135° case, the power spectrum peaks at about $n_\parallel = 2$ ($\approx 100$ keV) and extends from $n_\parallel = 4$ down to the accessibility limit. For $T_{\text{max}} \rightarrow \infty$, $T_{\text{lf}}, T_{\text{lb}}$ and $T_{\text{l}}$ are unchanged. The reason for this is that $T_{\text{max}} \gg T_{\text{lf}}$, in the 135° case, so that the shape of $f(p)$ is determined only by the launched RF power spectrum and not by accessibility. Thus, the exact value of $T_{\text{max}}$ has little effect on the calculated emission.

5. SUMMARY AND CONCLUSIONS

Perpendicularly emitted hard-X-ray spectra of the plasma ($E_\gamma > 20$ keV) have been collected from Alcator C during discharges driven by purely lower hybrid currents at seven different chordal (radial) locations. The spectra were linear on a semi-log scale, extended out to several hundred kiloelectronvolts and had effective 'temperatures' (defined here as the mean photon energies of a spectral distribution of photons) of several tens of keV. There is negligible emission before the RF power is turned on; the emission profiles are generally radially peaked and exist primarily within the inner half ($r/a < 1/2$) of the plasma column. The data were characterized by displaying (a) the temperature of the spectra for each radial position and (b) the width of the emission profile for each photon energy. For all data presented, the temperature of the spectra increases with plasma radius. Equivalently, the emission profiles are broader at higher photon energy. The reason for this is believed to be the fact that the plasma density is lower at larger radii so that waves with correspondingly lower minimum values of $n_\parallel$ are accessible there. Thus, the mean tail electron energy increases with plasma radius and this is reflected in the X-ray emission.

Scans of waveguide phasing, magnetic field, density and current have been made. The temperatures of the spectra at all positions were found to increase with decreasing waveguide phasing, increasing magnetic field, decreasing density and increasing current. The 'hardening' of the spectra with decreasing phasing is due to the greater fraction of power concentrated in the low $n_\parallel$ waves of the launched Fourier spectrum. This means that the X-ray spectra 'track' the launched power spectrum (at least at high energies, i.e. low values of $n_\parallel \lesssim 3$). The hardening of the X-ray spectra
with increasing magnetic field and decreasing density is directly related to wave accessibility. For a given plasma position, as the field is raised or the density lowered, the minimum value of $n_t$ at which waves can penetrate decreases. Thus, the mean energy of electrons, and hence the emitted X-ray spectrum temperature, increases at each position. The temperatures of the X-ray spectra increase with plasma current at all plasma radii. This is not a consequence of accessibility, but may simply result from the fact that more RF power is required to produce steady-state current drive as the amount of current being driven is raised. As the power is raised, the quasi-linear electron tail becomes flatter. This can result in a more energetic X-ray spectrum.

The X-ray emission profile widths were also presented as a function of waveguide phasing, magnetic field, density and current. The emission profiles broaden with increasing waveguide phasing. This is consistent with the fact that high $n_t$ waves, which are more prevalent at larger values of waveguide phasing, tend to damp further out from the plasma centre where the electron temperature is lower. The emission profiles broaden as the magnetic field is lowered or the density raised. The effect is particularly pronounced for the highest photon energies. As the field is lowered or the density raised, accessibility of the plasma interior is increasingly restricted for low $n_t$ waves. The resulting average tail electron energy there is lowered, and this can give rise to broader emission profiles. The emission profiles broaden as the plasma current is raised. The decreased q(a) tends to give larger upshifts in $n_t$ which can lead to a broadening of the wave power deposition profile. A similar effect occurs as the magnetic field is lowered, but accessibility, which determines the location of the centre of power deposition, probably dominates.

The X-ray emission measured as a function of the angle between the magnetic axis and the emission direction has been used to reconstruct the distribution function of the high energy tail electrons. The tail distribution function was found to be highly anisotropic, with a forward temperature about eight times larger than the perpendicular temperature or the backward temperature. The distribution function was found to 'track' the launched RF power spectrum in the same manner as the perpendicular X-ray emission.

Finally, we note that the present experiments give little information on the low and intermediate energy electrons (electrons with energies in the range $E \gamma \leq 30$ keV which resonate with waves having $n_t > 3$). This is the regime where little or no RF power is launched yet large numbers of electrons must exist to feed the high energy tail population. In particular, this is the regime of the 'spectral gap', where some mechanism must exist to upshift a significant part of the launched wave spectrum to diffuse electrons from the bulk. Unfortunately, the soft-X-ray emission is dominated by the high energy electrons, and therefore quantitative information on low energy electrons is difficult to obtain.

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