Abstract

Electron cyclotron emission (ECE) from hot, relativistic electrons has been measured simultaneously at several optically thin frequencies \( f/f_{ce} = 4.6, 7.0, \) and \( 9.6 \) on the Tandem Mirror Experiment-Upgrade. A method to determine the temporal evolution of the hot electron density, \( n_h \), and temperature \( T_h \) is discussed. Calculations of \( T_h \) agree with the analysis of the high energy x-ray spectra. Heating rates vary between 3 keV/ms and 13 keV/ms and temperatures over 300 keV have been reached by the end of the 50 ms discharge. The ECE analysis provides an order of magnitude improvement in time resolution over the x-ray analysis and shows that fast reductions in the diamagnetic loop signals are predominantly a loss of perpendicular energy stored by the mirror trapped hot electrons. These techniques for determining \( n_h(t) \) and \( T_h(t) \) will be used on the DIII-D tokamak in order to parameterize the nonthermal electron tail produced during ECH current drive experiments. A vertical view will be utilized and a fast (70 Hz) scanning Michelson interferometer will be used to measure the ECE spectrum between the 2nd and the 15th harmonic.
Introduction

Hot mirror-confined electrons, generated by second harmonic electron cyclotron resonance heating (ECRH) in the thermal barrier region of the Tandem Mirror Experiment-Upgrade, TMX-U [1], have been studied using optically thin electron cyclotron emission (ECE). Detection of perpendicular, X-mode emission at several frequencies ($f/f_{ce} = 4.6, 7.0,$ and $9.6$) was made simultaneously using multiple, fixed frequency radiometers. This paper discusses the method whereby these signals are used to determine the temporal evolution of the hot electron density, $n_h$, and temperature, $T_h$. Examples of typical hot electron behavior are shown and comparisons with $T_h$ derived from the analysis of the high energy x-ray spectrum are presented.

The final sections of this paper describe how these techniques will be applied on the DIII-D tokamak in an effort to parameterize the nonthermal electron tail produced during electron cyclotron current drive experiments (ECCD). The hardware to facilitate a vertical view and measure the ECE spectrum between the 2nd and the 15th harmonics is described. A computational prediction of the ECE spectrum is currently under development. As input, this code will be able to use either a general, model distribution function, or the resulting distorted distribution function as calculated by a Fokker-Planck code. Results of the Fokker-Planck code for a test case of ECCD is presented.

TMX-U Hardware

Shown in Fig. 1 is a schematic of the hardware used to measure ECE at 65, 98, and 130 GHz, arising from the thermal barrier region of the west end-cell in TMX-U. ECE from a narrow vertical column through the plasma is collected using an off-axis, ellipsoidal focusing mirror and horn antenna. The signals are routed to the receivers using overmoded waveguide, one 90° angle block, directional couplers, and appropriate waveguide transitions. X-mode is selected just after the horn antenna using W-band rectangular guide. From sidelab tests, the antenna pattern for all three frequencies had FWHM of $\sim$4 cm at the center of the plasma. No strong sidelobes and
no cross-polarization were detected. A Macor beam dump (reflectivity <5%) is used to reduce wall reflections from entering the collection optics and tests during plasma operation showed a reduction of ~40% in all ECE signal levels when the dump was in use.

Each receiver is a super-heterodyne system and uses a Gunn oscillator, waveguide mixer, 1 GHz bandwidth IF amplifier, and a 600 to 1000 MHz IF filter. The latter was found necessary to reduce 60 Hz noise in the system. Each receiver is calibrated using an in-band 1 eV noise tube. A calibrated attenuator is used to keep the plasma signal below the 1 eV noise tube level, resulting in a maximum signal to noise ratio of 50. The video output is amplified up to ~5 V, with 10 kHz bandwidth and transmitted on double shielded coax to the experimental rack.
Method of Analysis

A relativistic ECE code is used to calculate the X-mode, perpendicular emission coefficient as a function of frequency and temperature \( j_\perp(f, T_h) \), see Fig. 2(a). The code integrates the Schott-Trubnikov single particle emissivity [2] over a Maxwellian distribution function with a perpendicular temperature of \( T_h \). A loss-cone angle of 45° has been specified for the angular integration. For TMX-U, the radial vacuum magnetic field profile is flat to within 2% and \( f_{ce} = 14 \text{ GHz} \).

![Diagram](image)

**Fig. 2.** (a) \( j_\perp(f) \) vs \( f/f_{ce} \) for \( T_h = 100, 200, 300, 400, \) and 500 keV; (b) normalized ratio, \([1/C(98/65)] \cdot [P_r(98)/P_r(65)] \) vs \( T_h \).
The fact that the high frequency spectrum is continuous with a slope which can be related to the temperature provides the basis upon which the method of analysis is built. For optically thin emission that “fills” the antenna pattern, the power detected at a given frequency \( f \) is given by [3]:

\[
P_r(f) = 2\pi \Delta f \lambda^2 j_\perp(f, T_h) A(f) \int n_h(r) dr
\]  

(1)

where \( \Delta f \) is the receiver bandwidth, \( \lambda \) is the wavelength, and \( A(f) \) is the total attenuation of the transport system.

Since each signal arises from the same viewing chord, the ratio of any two ECE signals reduces to a nonlinear function of \( T_h \). For example,

\[
P_r(98)/P_r(65) = C(98/65) \cdot [j_\perp(98, T_h)/j_\perp(65, T_h)]
\]  

(2)

where \( C(98/65) \) is the ratio of wavelengths and attenuations. Figure 2(b) shows the normalized ratio, \([P_r(98)/P_r(65)] \cdot [1/C(98/65)], \) as a function of \( T_h \). Once \( C(98/65) \) is determined, the experimental ratio is then compared to this curve to determine \( T_h(t) \). Using \( T_h(t) \), the ECE code is then used to calculate \( j_\perp(98, T_h) \) and Eq. 1 is inverted to determine \( n_h \). The hot electron radial profile, a 15 cm gaussian, has been determined from x-ray pinhole camera results [4].

The ECE system is calibrated by using the afterglow plasma, in which only the hot electrons are present. By normalizing \( T_h \) to the Maxwellian temperature determined by the high energy x-ray spectra, the constant \( C(98/65) \) and thus the ratio of attenuations, \( A(98)/A(65) \) can be calculated. This calculation varies by less than 5% shot-to-shot. Then normalizing \( n_h \) to \( DML/T_h \), where \( DML \) is the hot electron diamagnetism measured by a calibrated diamagnetic loop, provides a measure of \( A(98) \). The ECE calculations of \( n_h \) are within 10% of those obtained from the interferometer system when the energetic electrons are corrected by \( 1/\gamma, (\gamma = 1 + E/mc^2) \) to account for their transparency [5]. This two-step process is equivalent to determining the absolute sensitivity of each receiver and the resulting calculations of \( A(f) \) are within 3 dB of initial estimates.
Experimental Results

The experimental results of the ECE calculations of $T_A$ are compared to those of the high energy x-ray measurements in Fig. 3(a). To improve the x-ray statistics and provide 5 ms time resolution, nine identical shots were added together. The ECE analysis of $T_A$ varied by less than 5% throughout the discharge for all nine shots, thus illustrating the improved temporal resolution of this technique.

![Graph](image1)

**Fig. 3.** (a) Comparison of $T_A$ calculated by ECE (single shot) and high energy x-ray spectra (sum of 9 shots), (b) the same comparison for shot of Fig. 4(c).

Three distinctively different types of temporal behavior have been observed for $T_A$ and $n_A$. In Fig. 4(a), $n_A$ is increasing while $T_A$ is constant during the first 10
FIG. 4. Characteristic behavior of the temporal evolution of $T_h$ and $n_h$. (a) Initially constant $T_h$ with increasing $n_h$, (b) rapidly increasing $T_h$, and constant $n_h$.

to 20 ms of the discharge, followed by increasing $T_h$ and decreasing or constant $n_h$ for the remainder of the discharge. This behavior resembles two-stage Fokker-Planck modeling on $n_h$ and $T_h$ based on a beta-shift of the resonance and the creation of an energetic electron tail by cavity fields [6].

In Fig. 4(b), instead of an initial plateau, $T_h$ escalates to over 250 keV at a rate of 13.3 keV/ms while $n_h$ is constant. This rate suggests direct beam heating and is probable due to refraction of the ECRH beam to larger magnetic fields, thereby preventing relativistic detuning.

In Fig. 5, the ECE analysis suggests that a rapid decrease in $T_h$ (at 47 ms), occurs with little change in $n_h$. Figure 3(b) shows that this temperature change is verified by the x-ray analysis (in this case, five identical shots are added together to improve the x-ray statistics). This rapid decrease was observed by three axially
separated DML signals and the resulting analysis of the hot electron axial profile, $L_h$ showed no change as a result of the drop. Thus the loss of perpendicular stored energy is not converted to parallel energy. The measured change in stored energy, from the diamagnetic signal can be accounted for by the calculated $\Delta T_h$ at constant $n_h$. This suggests that the stored energy is lost radiatively, possibly by a burst of radiation at or near 28 GHz ($2f_{ce}$) [1]. In addition, at $t = 120$ ms, $T_h = 220$ keV, thus $\gamma = 1.43$. Accounting for transparency, $n_h/\gamma = 2.2 \times 10^{11}/cm^3$, in excellent agreement with $n_{TOT}$, measured by interferometry.
Current Drive on DIII-D

Electron cyclotron current drive (ECCD) experiments are planned in 1988 on the DIII-D tokamak at GA Technologies. Both inside and outside launch will be investigated using up 2 MW of power at 60 GHz. Neutral beam injection will be available for additional heating and/or current drive.

From a diagnostic standpoint, the challenge will be to provide detailed knowledge of the nonthermal electron tail distribution function. With this knowledge, estimates of the electron tail density, energy content, dissipated power (through collisions, cyclotron emission, and bremsstrahlung) and energy confinement time can be calculated. In addition, an assessment of the efficiency of ECCD can be made.

DIII-D Hardware

Figure 6 shows the schematic of the vertical viewing ECE system planned for operation on DIII-D. The viewing optics consist of an ellipsoidal focusing mirror and a spherical retroreflector, the latter intended to act as a viewing dump by folding the beam back on itself. The ECE is routed out of the machine through a wedged quartz window and is transported approximately 12 m using TPX lens and flat mirrors to a Michelson interferometer located outside of the radiation shield wall. The Michelson interferometer produces 70 interferograms/sec, each occurring in a 2 ms window. Details of the focusing opticals will limit operation to a spectral range of approximately 120 to 900 GHz (4 to 30 cm⁻¹) and sidelab tests show a spectral resolution of between 9 and 14 GHz. After alignment of the entire optical chain, an in-situ calibration using an LN cooled blackbody source will be performed.

DIII-D Analysis

Building upon current drive diagnostic techniques developed on PLT [7] and Alcator-C [8], a combination of x-ray and electron cyclotron spectral measurements will be employed on DIII-D. The previous ECE work focused on the analysis of the lower harmonic spectrum where, in the absence of harmonic overlap, there exists
Fig. 6. Cross-sectional view of DIII-D showing vertical viewing ECE hardware in relationship to plasma.

a one-to-one correspondence between energy and frequency. In addition, ratios of harmonics or polarizations were used to determine the anisotropy. In the case of DIII-D, the vertical view will be off the magnetic axis and ray tracing results [9] indicate that refraction by the plasma will be troublesome for the lower harmonics (n < 4). However, in a manner analogous to the ECE work on TMX-U, the high harmonic spectrum (n > 5) will be used to parameterize the energetic electron tail.

The relativistic electron distribution function $f_e(p_{\parallel}, p_\perp, r)$ which results from the injection of the ECH has been calculated at various radii $r$ in DIII-D using a comprehensive three-dimensional Fokker-Planck code [10]. The distortion of $f_e(\vec{p}, r)$ is included in the calculations of the local emissivity and absorptivity. Figure 7(a)
shows $f_e(\bar{p}, r)$ at a location near the magnetic axis for a test case of ECCD. The code assumed 1 MW of O-mode, outside launched ECH into a DIII-D plasma with the resonance located at the magnetic axis, $n_e = 5 \times 10^{12}/\text{cm}^3$ and $T_{\infty} = 2.5$ keV. In Fig. 7(b), perpendicular and forward-parallel cuts through the Fokker-Planck distribution function are shown. Energetic electrons with energies up to 100 keV are expected.

The ECE spectra, resulting from a prescribed $f_e(\bar{p}, r)$ will be calculated using a new radiation transport code presently under development, HORACE [11]. This code will calculate the local emissivity and absorptivity at each point along a selected
path or ray by performing a numerical integration over a given distribution function. This distribution function can be either the Fokker-Planck output or a more general, model distribution function. This computational work will be essential in assessing the experimental data and providing feedback for optimization of the intended experiments.

Estimates of the energetic electron tail density will be made using the integrated ECE spectral power. This will require an absolute calibration of the ECE system and detailed computational work using model distribution functions. Input for the latter will be derived from a planned x-ray PHA system, capable of measuring the bremsstrahlung spectrum up to 300 keV. This system will contain radial and tangential viewing chords and will be used primarily to determine the shape or form of both the perpendicular and parallel electron tail distribution function. A pin-hole camera is planned to assess the radial profile of the bremsstrahlung.

Finally, it should be noted that Michelson interferometer will provide information on a fast time scale in regard to the evolution of the perpendicular distribution function.

Conclusions

A method for using optically thin electron cyclotron emission to determine, on a fast time scale, parameters of an energetic electron distribution function has successfully been applied on TMX-U. These techniques, combined with x-ray spectral measurements, will be used on DIII-D during electron cyclotron current drive experiments.

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References


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