FUSION RESEARCH CENTER

DOE/ER/54241--150

DOE/ER/542-41-150

FRCR #469

Experimental Investigation of Fast Electron Diffusion During ECRH

R. F. Steimle, G. Giruzzi*, D. R. Roberts

Fusion Research Center
The University of Texas at Austin
Austin, Texas 78712

*Association EURATOM CEA
sur la Fusion - Centre d'Etudes
Cardarache, France

June 7, 1995

THE UNIVERSITY OF TEXAS

Austin, Texas

RECEIVED
APR 22 1997
OSTI

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Experimental Investigation of Fast Electron Diffusion During ECRH

R.F. Steimle, G. Giruzzi*, D.R. Roberts

Fusion Research Center, University of Texas at Austin

* Association EURATOM CEA sur la Fusion, Centre d'Etudes de Cardarache, France

Abstract

The spatial diffusion of fast electrons created by electron cyclotron resonant heating (ECRH) is examined using electron cyclotron emissions viewed along a nearly vertical chord in the TEXT-U tokamak. Enhanced emission at frequencies downshifted from the cold cyclotron frequency is attributed to non-thermal electrons. The emission spectra during ECRH are consistent with the presence of low density suprathermal electrons. Comparison of the spectra measured during ECRH with a bounce averaged Fokker-Planck code which incorporates the effects of magnetic and/or electrostatic turbulence on the distribution function, shows that the level of magnetic fluctuations in the center of TEXT-U is between 3 and 5×10^{-5} . This level of magnetic fluctuation is a factor of 2 to 5 too small to explain the transport of thermal electrons ($E \sim 1$ keV) in TEXT. Thus, magnetic fluctuations are an unlikely major cause of the transport of thermal electrons in TEXT.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

1. Introduction

The transport of energy out of the core of magnetic fusion experiments is at least an order of magnitude higher than would be expected if neoclassical predictions were true. Anomalous transport is widely believed to be due to either electrostatic or magnetic fluctuations. There is evidence that transport in the edge of tokamaks is due to electrostatic turbulence, but the cause of transport in the core is unknown. A small level of magnetic fluctuations ($\frac{\delta}{B} \leq 10^{-4}$) could be responsible for the measured thermal electron energy transport properties in tokamak plasmas. Magnetic fluctuation levels of 2×10^{-5} have been measured at the plasma edge^{1,2}, however direct measurement of the level of magnetic fluctuations in the core is difficult since material probes would melt³. Transport due to magnetic fluctuations is expected to scale with $|v_{\parallel}|$, while transport due to electrostatic fluctuations is expected to scale with $\frac{1}{|v_{\parallel}|}$.⁴ Measurement of the transport of suprathermal electrons versus the transport of thermal electrons thus provides a measure of the relative importance of the role of magnetic fluctuations to that of electrostatic fluctuations.

Previous studies of fast electron confinement have usually shown that runaway electrons and fast electrons generated by auxiliary heating (most notably lower hybrid current drive) are frequently better confined than thermal electrons.^{3,5} This suggests that different mechanisms may be responsible for the transport of runaway and thermal electrons. With runaway transport being dominated by magnetic fluctuations and the transport of thermal electrons dominated by electrostatic fluctuations. Almost all suprathermal electron confinement studies have used techniques based on the interaction of fast electrons with radiation: they emit hard X-rays and, (because of the relativistic mass increase) they interact with electron cyclotron radiation at lower frequencies than thermal electrons.

Most commonly the thick target bremsstrahlung produced by runaway electrons as they strike the limiter is observed.^{6,7,8,9} Measurements of the photon energy spectra of

the hard x-ray flux during steady state discharges and changes in the flux during plasma position shift experiments have all been used to determine runaway electron confinement. Studies of the hard x-rays radiated by electrons in the plasma are rarer and usually associated with a lower hybrid current drive experiment^{10,11,12,13,14} because the low collision cross section of fast electrons can make gathering data a slow and noisy process.

Electron cyclotron emission (ECE)^{15,16,17,18} or absorption (ECA)^{19,20,21,22} measurements have some advantages over x-ray measurements, in that high energy electrons emit cyclotron radiation copiously so that gathering the data is not a difficult task. However, interpretation of suprathermal emissions viewed horizontally along the tokamak major radial axis is difficult for two reasons:

- 1) The optically thin emissions from suprathermal electrons are not spatially localized by the simple $\omega = n\omega_{ce}$ resonance condition, as they are for optically thick emission. Some indication of their location, besides frequency, must accompany the signal. (e.g. sawteeth).

- 2) Multiple reflections of the radiation can increase the level of observed optically thin emissions.

Viewing the emission vertically (VECE) opposite a "black" background (i.e. a microwave absorber), localizes the source to a particular location, improving comparison between theory and experiment²³. Such experiments in the past have most frequently been done in lower-hybrid heated plasmas, where the wave interacts with suprathermal electrons through Landau damping.

This paper describes measurements of fast electron diffusivity made using VECE on TEXT-U. Our discussion will be organized as follows: Section 2 describes the method of inferring suprathermal electron transport from electron cyclotron emissions. The experimental apparatus is discussed in section 3. VECE measurements of suprathermal emission during ohmic and ECRH discharges are presented in section 4. The experimental results are analyzed and the fast electron diffusivity is determined in section 5. A

comparison to previous TEXT measurements is made in section 6. Finally, the last section of this report are the conclusions from our study.

2. Principle of Measurement

The frequency ω at which an electron emits or absorbs radiation is given by the cyclotron resonance condition:

$$\omega = n \frac{eB}{m\gamma} + k_{\parallel}v_{\parallel}, \text{ where } n \text{ is the harmonic number.} \quad (1)$$

This resonance frequency is shifted from the cold cyclotron frequency, $n \frac{eB}{m}$ by the relativistic factor, γ , and the Doppler shift, $k_{\parallel}v_{\parallel}$. In general, for arbitrary propagation angles, this condition forms ellipses in momentum or velocity space. Radiation propagating perpendicular to a magnetic field line will be emitted by suprathermal electrons at frequencies lower than the cold cyclotron frequency, $\frac{eB}{m}$. Measurement of the ECE spectra along a chord of constant magnetic field strength (i.e. a vertical chord through a tokamak) is thus a measure of the energy distribution of suprathermal electrons in the sample volume. Spectra measured during low-density runaway or ECRH discharges will show enhanced emission over spectra in discharges where the electron distributions are close to Maxwellian.

The ECE spectra are thus a line integral of the suprathermal population and the spatial extent of this population is dependent upon $\tilde{b}$. Since the sightline of the diagnostic is much smaller than the plasma minor radius, a population of suprathermal electrons that is strongly dispersed by spatial diffusion will have a different ECE spectrum than a population that is contained entirely in the sightline of the diagnostic. In the latter case the emission level will be smaller because less suprathermal electrons occupy the viewing sample volume. Furthermore, since emission at a single frequency is contributed by

electrons within a certain energy range, the emission spectra measures the energy distribution as well as the total density of electrons along the sightline. Thus the shape of the ECE spectra is highly sensitive to $\tilde{b}$, which is expected to effect high velocity electrons more strongly than low velocity electrons.

A 3-D bounce-averaged Fokker-Planck calculation which takes into account collisions, the tokamak electric field, electron cyclotron heating, electrostatic and magnetic turbulence is used to calculate the spectrum during ECRH.²⁴ The confinement of suprathermal electrons in this simulation is modeled by adjustment of the electrostatic and magnetic turbulence parameters. ECE spectra are then calculated from the distribution function using a fully relativistic radiation transport code. Comparison of the measured spectra with the calculation determines the level of magnetic fluctuation.

3. Experimental Apparatus

Toroidal and poloidal cross sections of the experiment are shown in Figure 1. Fundamental harmonic, O-mode electron cyclotron heating is launched into the plasma by a focused toroidally steerable antenna.²⁵ This launcher can vary the launch angle of the beam continuously +/- 30 degrees from perpendicular injection, while maintaining the beam center within +/- 1 cm of the magnetic axis. Launching the beam in the direction of the electron drift velocity (opposite the plasma current) causes Doppler-broadened heating to interact with a population of suprathermal electrons which are created by the tokamak electric field in low density discharges. The following paragraph explains the interaction.

Figure 1 Experimental setup.

The electron cyclotron resonance condition (equation 1), which depends upon the wave frequency, cyclotron frequency and parallel wavenumber, has an elliptical shape in momentum space. Figure 2 shows the EC resonance curves of the heating beam (bold lines) superimposed on the level contours of a distribution function with a small parallel tail (fine lines). The resonance contours in this case correspond to a propagation angle of ± 75 degree with respect to the magnetic field, and a wave and cyclotron frequency of 60 GHz. (This is equivalent to a ± 10 degree angle of injection from perpendicular, once field line curvature is taken into account.) A sum of two Maxwellian distributions was chosen to illustrate the ECRH interaction with the naturally occurring runaway population in a low density tokamak discharge. The bulk temperature is 1.2 keV, while the suprathermal tail has a density of .01% of the bulk and a parallel temperature of 40 keV. Both sets of contours are plotted versus normalized momentum. Launching the beam in the direction of the electron drift velocity (opposite the plasma current) heats the population of suprathermal electrons, because the resonance contour overlaps the distribution. Waves launched opposing the electron drift direction, have no direct interaction with the tail, and have less effect on the suprathermal population.

Figure 2 ECRH interaction with electron distribution function.

Second Harmonic X-Mode Electron Cyclotron Emissions (ECE) were viewed using a horn and lens antenna along a chord of nearly constant magnetic field strength through a polyethylene window on the P13 bottom port of TEXT-U.²⁶ The horn and lens antenna has a Gaussian pattern with a Rayleigh length of about 25 cm and a maximum beam diameter in vacuum of about six centimeters. The antenna can be moved to different positions in major radius to view emissions from different parts of the plasma. A silicon-carbide viewing dump was used to minimize reflected electron cyclotron emissions originating from other parts of the plasma from entering the sightline. The dump has a measured reflectivity of less than 1% and is offset toroidally from the VECE window since the vertical soft x-ray array occupies the opposing port. This offset causes the energy resolution of the diagnostic to be decreased because the beam is not perpendicular to the direction of the magnetic field, but at about an 80° angle to it.

Viewing perpendicular to a field line, in accord with equation 1, results in a one to one correspondence between the energy of an electron ($\gamma = n \frac{\omega_{ce}}{\omega}$) and the frequency of

the emission. Emission at an oblique angle to the magnetic field is Doppler shifted in addition to the relativistic shift. Figure 3 shows the energy of resonant electrons that lie on the momentum space ellipses versus the normalized parallel momentum for 12 different frequencies at a field strength of 2.14 T ($2\omega_{ce} = 120$ GHz). There is a large spread in energy for all frequencies, but lower frequencies are resonant with higher energy electrons. The lowest frequency, 98 GHz, is emitted by electrons which have energies between 60 and 200 keV. Emission in the X mode is weighted towards electrons with large perpendicular velocities, so not all electrons which are resonant at a particular frequency contribute equally to the emission. This makes it impossible to determine the distribution function uniquely from the emission.

Figure 3 Energy contours of VECE system.

Two heterodyne radiometers detect the received ECE radiation. The receivers covered the frequency spans from 98 to 112 GHz and 112 to 126 GHz respectively. The front ends of the receivers, consist of a high-pass filter followed by a mixer and a local

oscillator. This section down-converts the received radiation to the frequency span between 2 and 18 GHz. An intermediate frequency (IF) section following the front end, uses narrow-band filters to subdivide the received radiation into 8 separate frequency bands. Following detection by crystal detectors, the signals in each band are amplified and video filtered.

4. VECE During Ohmic and ECRH Discharges

Ohmic Spectra

Spectra measured along a vertical chord are markedly different than the spectra viewed using horizontal ECE. The magnetic field strength in a tokamak is proportional to $\frac{1}{R}$. In the limit that a particular mode and polarization (usually 2nd harmonic X-mode) is optically thick, and harmonic overlap is not important (a high aspect ratio device) the emission can be localized to a surface. Thus the radiation intensity emitted horizontally at the frequency, $\frac{neB(R)}{m}$, corresponds to the electron temperature at the position $R(B)$.

Radiation emitted along a vertical chord ($R = \text{constant}$) will be optically thick at some frequencies and optically thin at others.

Figure 4 shows a typical spectrum from an ohmic heated plasma viewed along a vertical chord. The vertical axis is labeled in radiation temperature, this is calculated from the classical limit of Planck's radiation formula:

$$I(\omega) = \frac{\omega^2 T_{\text{rad}}}{8\pi^3 c^2} \quad (2)$$

The three regions of the spectra will be labeled for convenience: 1) The optically thick region, 2) the Doppler up-shifted region, and 3) the relativistically downshifted region.

Figure 4 Vertically viewed ohmic spectra.

The absorption coefficient at the 2nd harmonic cyclotron frequency is very large and cyclotron emission from the hot core plasma is absorbed and re-emitted all the way out to the cooler edge. This causes the dip that is seen in the radiation temperature at $\omega = 2\omega_{ce}$. The optical depth varies with frequency, and is greater than one in the region between the peaks (roughly). Most of this radiation is optically gray and does not necessarily correspond to localized temperature in this region. The absorption is spread out along the entire chord and so the radiation temperature at some frequencies corresponds to more of an average temperature than the surface temperature of a black body.

Since we are viewing the radiation at a slight angle to the magnetic field, some of it is emitted at frequencies higher than the cold cyclotron resonance frequency. This is the result of Doppler shifted emission caused by electrons traveling along magnetic field lines towards the antenna. For these electrons there is a competition between the Doppler shift and the relativistic mass increase. As an electron travels faster and faster the Doppler shift

is towards higher frequencies, but the mass shift is toward lower frequencies. Once an electron exceeds a certain velocity the mass shift starts to dominate the Doppler shift and emission above a corresponding frequency is not possible along a given viewing chord. Because of this, the signal level at the very highest frequencies must be due to reflections from other regions of the plasma and not Doppler shifted emissions, as is indicated in the figure.

Finally, the relativistically downshifted region will be dominated by emission from electrons with energies much greater than the thermal energy. Radiation at these frequencies is optically thin and suprathermal electrons anywhere within the viewing sightline can contribute to the signal. In practice, the suprathermal population is typically strongest where the thermal temperature is highest and the collisionality is lowest. In thermal discharges, suprathermal emission in this region of the spectrum is negligible and the measured intensity at very low frequencies is due to reflected radiation from elsewhere in the tokamak.

ECRH Spectra

The ECRH data was taken during low density discharges in the TEXT tokamak. Typical conditions for these discharges were: line averaged density, $1.2 \times 10^{13}/\text{cm}^3$, plasma current, 120 kA, loop voltage 2.0 V during the ohmic phase dropping to 1.7 V during ECRH. The electron temperature in the center of the plasma before ECRH was 800 eV, and increased to about 1200 eV during central heating. The RF power generated by the gyrotron was approximately 200 kW, however, because of transmission losses the power launched into the machine was about 170 kW. The angle of the toroidally steerable antenna was varied during this experiment to determine via the VECE spectra the effects on suprathermal generation; as discussed with regard to figure 2.

Figure 5 shows VECE spectra during ECRH with the toroidally steering antenna pointed in the co and counter electron drift directions as defined by the direction of the plasma current. (The angle of injection in both the co and counter injection directions was about 10° from perpendicular.) The ECRH injected in the co-electron drift direction interacts with electrons in the tail of the distribution that are created by the ohmic electric field of the tokamak as described in figure 2. This angle produced the maximum experimental suprathermal ECE when the ECRH antenna was pointed in the co-electron direction. Also shown for comparison is the ohmic spectra before ECRH. Emission at frequencies close to the cyclotron frequency is the same during co and counter injection, but emission at low frequencies is much greater during co-injected ECRH. The emission at $2\omega_{ce}$ increases very little compared to the ohmic level, since the radiation is coming from the edge plasma.

Figure 5 VECE Spectra during Co and Counter Injected ECRH.

Figure 6 shows the time response of the 98 GHz emission during ECRH. Electrons with energies between 40 and 200 keV emit radiation at this frequency. In this discharge, the critical energy above which an electron becomes a runaway²⁷, is approximately 60 keV. Emission increases by a factor of 20 over the ohmic level during CO-injection, but increase only slightly during counter-injection. Sawteeth are visible on the ECE signal indicating that the suprathermal electron population is peaked in the center of the plasma. The time response of the ECE signal at this frequency is slow (risetime $\approx$ 25 msec) compared to typical horizontally viewed ECE signals from thermal electrons, which have risetimes more on the order of 10 msec. Differences in the rise time is reflective of differences in the heating mechanism. The high energy electrons are created by the synergy of the tokamak ohmic electric field and ECRH. We next describe this process in further detail

ECRH increases an electrons perpendicular energy and causes velocity space diffusion through its interaction with the distribution function:

$$\frac{\partial f}{\partial t}_{\text{ECRH}} = \frac{1}{v_{\perp}} \frac{\partial}{\partial v_{\perp}} v_{\perp} D \frac{\partial f}{\partial v_{\perp}}, \text{ where } D = \frac{1}{2} \langle (\Delta v_{\perp})^2 \rangle / \Delta t. \quad (3)$$

Physically, $\Delta v_{\perp}$ is the bump in perpendicular energy an electron gets as it passes through the heating beam, while Δt is the time between transits of the beam. ECRH interacts strongly with electrons which are two or three times the thermal energy. The addition of perpendicular energy decreases these electrons collisionality and makes them more susceptible to acceleration by the ohmic electric field. The time that it takes to accelerate an electron to an energy of 40 keV accounts for the delay between when ECRH comes on at 300 msec and the signal beginning to rise at 302.5 msec. The slower time scale of the rest of the signal is due to the diffusive (in velocity space) nature of ECRH.

Figure 6 98 GHz ECE signal during co and counter-injected ECRH.

Figures 7 shows the time response of the 117.5 GHz emission in both the co and counter injection cases. Emission at this frequency is due to thermal or mildly suprathermal electrons ($E \approx 1-10$ keV). Both co and counter injection produce about the same level of increase in the level of the 117.5 GHz signal, suggesting that the temperature of the bulk plasma is approximately the same during heating in either direction. The time response of the signal to ECRH is prompt, since it is governed primarily by the response of the thermal electrons. The sawteeth amplitude is approximately the same in the co and counter heating direction, although the frequency is about 1.5 times higher in the co direction. This difference in the sawteeth is probably due to small differences in the current density profiles between the two cases, caused by the small suprathermal population which because of its high velocity carries a current in larger proportion to its number density.

Figure 7 117.5 GHz ECE signal during co and counter-injected ECRH.

The TEXT soft x-ray arrays complement the 117.5 GHz ECE channel because they are also sensitive to electrons in the energy range of 1 to 10 keV. The time response of the central soft x-ray chord to co and counter injected ECRH is shown in Figures 8. The response of the the soft x-ray signal to the oppositely injected ECRH is identical, except again for the sawtooth period. Furthermore, the shape of the soft x-ray profiles for the two discharges is nearly identical. If differences in the VECE spectra were due to changes in the level of reflected thermal emissions (caused by differences in the temperature profiles) from elsewhere in the plasma, the soft x-ray profiles should indicate a difference in the co-injection and counter-injection cases. Since it does not, the changes in the low frequency ECE channels are not due to temperature profile effects.

Figure 8 Soft x-ray signal through a central chord during ECRH.

5. Analysis

Inversion of the experimentally measured ECE spectra alone to determine the electron distribution function is impossible. Optically thin ECE at a particular frequency in a specific mode of propagation is a moment of the distribution function. If a particular form of the distribution function is assumed, such as a bi-Maxwellian, the experimental spectra can be inverted to give a "best fit" suprathermal density and temperature. However, such a description is over-simplified and, moreover, not unique. Several different distribution functions could be used to model the same spectra, each differing only in their dependence on parallel velocity. (In many ways this is akin to measuring the plasma density profile using only one chord averaged density measurement.) Direct comparison of the spectra with a detailed computational model is more insightful, since the actual

distribution functions are the result of several physical processes. This is the approach that we have chosen.

The computational model that we use is a Fokker-Planck simulation that has been developed for the investigation of the radial diffusion of fast electrons. The code is 3-dimensional (2-D velocity, 1-D configuration) and solves a bounce-averaged kinetic equation which includes the effects of coulomb collisions, the DC electric field, ECRH and the radial diffusion of the electrons produced by magnetic and electrostatic turbulence:

$$\left\langle \frac{\partial f}{\partial t} \right\rangle = \langle \hat{C} f \rangle + \left\langle \frac{eE_{\parallel}}{m_e} \frac{\partial f}{\partial v_{\parallel}} \right\rangle + \langle \hat{D}_{ECH} f \rangle + \langle \hat{D}_T f \rangle \quad (3)$$

$$\text{where,} \quad \hat{D}_T f = \frac{1}{r} \frac{\partial}{\partial r} r D_T \frac{\partial}{\partial r} f, \quad D_T = 2\pi q R \tilde{b}^2 |v_{\parallel}|.$$

The code has been extensively benchmarked against experiments on several different machines^{10,21,28,29}. Evaluation of the distribution function requires that accurate and detailed information on the ECRH launching geometry, RF power, plasma temperature, density, loop voltage and current be input to the code. The distribution function computed using the program is then used to evaluate the 2nd harmonic X-mode ECE spectra. Iterative comparison of the calculated spectrum with the experimental spectrum determines the value of D_T . From this the value of $\tilde{b}$, assuming a connection length of $2\pi q R$, is calculated.

Analysis of the experimental spectra made during central heating by one 56 GHz gyrotron and using the toroidally steering antenna has been performed. Plasma conditions during this experiment were: plasma current = 120 kA, line averaged density = $1.2 \times 10^{13}/\text{cm}^3$, loop voltage = 1.7 V, central electron temperature = 1200 eV, $Z_{eff} = 2$ and ECRH power = 170 kW. Shown in Figure 9 are the experimental results and spectra simulated using three different values of $\tilde{b}$. (The vertical error bars on the experimental data are due to uncertainties in the calibration of the system. These uncertainties are caused

by variations in the transmission coefficient over frequency of the polyethylene window. The horizontal error bars are due to the filter bandwidths in the IF section and uncertainty in the exact position of the receiving antenna.) The effect of increasing $\tilde{b}$ is most noticeable at the low frequency end of the spectra, this is because low frequency ECE is due to high velocity particles which diffuse most rapidly in turbulent magnetic fields. The experimental data seems best fit by a value of $\tilde{b}$ between 3 and 5×10^{-5} .

Figure 9 Experimental $\tilde{b}$ determination.

An electrostatic turbulence term,

$$D_e = 2\pi q R \frac{1}{|v_{\perp}|} \left(\frac{E_{\perp}}{B} \right)^2, \quad (4)$$

was added to equation 3 to also simulate the effects of electrostatic turbulence on the distribution function. The level of this term ($E_{\perp}/B = 1 \text{ km/s}$) was taken to be consistent with the transport of thermal electrons in the interior of TEXT.³⁰ Simulations which included both magnetic and electrostatic fluctuations did not significantly differ from

simulations which only included magnetic fluctuations. This is because the electrostatic term scales with $1/v_{||}$, and so mostly affects low velocity electrons, which are not responsible for the bulk of the emissions. Finally, simulation of the spectra using the electrostatic term alone (figure 10) results in a spectrum that slopes up at lower frequency, which is in contrast to the experimentally determined spectra and the spectra with $\tilde{b} = (3-5) \times 10^{-5}$. The higher velocity electrons would be much better confined than the thermal electrons if electrostatic turbulence was responsible for the transport of both thermal and suprathermal electrons. Thus, the loss of high energy electrons seems due to a mechanism with a velocity scaling more like magnetic turbulence than like electrostatic turbulence.

Figure 10 Effect of electrostatic turbulence on VECE spectra.

There is some uncertainty in the other plasma parameters used in the code. In addition to the magnetic fluctuation level, the spectra are sensitive to the tokamak ohmic electric field, RF power, and plasma Z_{eff} . Unfortunately, none of these parameters is

known precisely. For example, the loop voltage measured outside the plasma places an upper limit on the ohmic electric field inside, but because of inductive effects is not a good measurement of the interior electric field. The effect on the spectra of varying these parameters has been determined. The net result is that the above simulation probably overestimates the amplitude of magnetic fluctuations and should be taken as a worst case estimate.

During the ECRH pulse, the electron temperature in the center of the plasma rises in about 10 msec. The central plasma conductivity σ , which is proportional to $T_e^{3/2}$, rises at the same time, but the plasma current profile, $J(r)$, changes on a much longer time scale because of the inductance of the plasma. As a result the electric field ($E=J/\sigma$) in the center drops more rapidly than at the edge. The loop voltage change measured outside the plasma thus lags the electric field change in the center. In the Fokker-Planck simulation we used the measured loop voltage as an estimate of the electric field inside the plasma - and this voltage/field is thus an overestimate. Simulations using the one-dimensional transport code, CHAPO³¹, indicate the loop voltage in the plasma center could be as low as 1.4 volts during ECRH. Fokker-Planck simulations using this lower value of toroidal electric field will produce agreement for a somewhat smaller level of $\bar{b}$.

The initial simulation used 170 kW as an estimate of the ECRH power launched into the plasma. This is a best case estimate based on the 56 GHz gyrotron generating 200 kW power and an 85% transmission efficiency from the tube to the tokamak. Probably the actual power is less due to mode conversion in the transmission line, and because the launched power is a mixture of O and X modes. The simulation again shows that a smaller value of $\bar{b}$ would be necessary to achieve agreement with the measured data.

Finally, the estimate of Z_{eff} is based on a Thomson scattering measurement of temperature. As such, the value is an averaged Z_{eff} over the entire plasma. Most likely the distribution of impurities is not uniform and may be peaked in the center. The effect the value of Z_{eff} has on the spectra is somewhat complicated. Increasing Z_{eff} raises the

threshold energy at which electrons runaway from the main distribution; but it also increases the pitch angle scattering of the high energy electrons, making the distribution more isotropic. Since we are measuring X-mode ECE, electrons with higher perpendicular energies contribute more strongly to the emission. However, the net effect of increasing Z_{eff} in the simulation is that it decreases the emission level at low frequencies. Simulation using Z_{eff} of 4 and 6 again demonstrate that the simulation shown above is a worst case estimate of the magnetic fluctuation level.

6. Discussion

Our measurement of suprathermal diffusivity and/or $\tilde{b}$ can be compared to previous measurements on TEXT. The contribution of $\tilde{b}$ to the thermal diffusivity can be calculated, and compared to other measurements of the transport of thermal electrons, showing that magnetic turbulence does not dominate thermal transport. Good agreement is found between our measurement and a direct measurement of magnetic fluctuation levels using external coils outside of the limiter. The fluctuation level measured by our experiment is 3-5 time higher than that inferred from the measured diffusion of runaway electrons in the edge plasma during position shift and ergodic limiter experiments. However, this disparity may not be as large as it seems.

The calculated contribution to the thermal diffusivity from magnetic fluctuations based on this "experimentally" determined $\tilde{b}$ is between 0.1 and 0.3 m²/sec:

$$\chi_e = 2\pi q R \tilde{b}^2 |v_e|, \text{ where } v_e \text{ is the electron thermal velocity.}$$

The value of χ_e in the center of the plasma during ECRH based on power balance for typical TEXT-U³² discharges is about 2 m²/sec. Thus, the contribution to thermal

transport from magnetic fluctuations is about an order of magnitude smaller than the actual thermal diffusivity.

The level of $\tilde{b}$ that we infer from the code can be compared to somewhat more direct measurements made on the outside of TEXT using magnetic probes¹. The probes measured a root-mean-square level of magnetic fluctuation at about 2×10^{-6} . Extrapolation of these signals,^{1,2} measured outside of the limiter to the plasma edge yielded an estimate of $\tilde{b}$ at the plasma edge of $\tilde{b} = (2-3) \times 10^{-5}$. The agreement in the level of fluctuations that are measured is quite good, although one might expect larger differences depending on the mechanism by which the fluctuations are driven.

Measurements, based on the flux of runaway electrons to the limiter during position shift experiments and limits on the level of magnetic fluctuations based on the runaway energy spectra, put the magnetic fluctuation level at closer to 1×10^{-5} . Our measurement is 3 to 5 times higher than the measurement based on the runaway electron flux. There are three differences between the two measurements: 1) The VECE measurement is during ECRH. It is well established that auxiliary heating adversely affects the confinement of runaway electrons, as well as thermal electrons.⁶ A higher level of level of runaway diffusivity would be measured during electron cyclotron heating than during an ohmic discharge - hence the level of $\tilde{b}$ should be greater during ECRH. 2) The hard x-ray measurement is in the edge plasma while our measurement is in the core. 3) The energy range of the electrons measured by the ECE is between 40 and 200 keV, while the energy of the runaway electrons measured by hard x-rays is about 1 MeV. It's possible that drift orbit averaging of the magnetic fluctuations reduces the transport of the runaway electrons. If the deviation of the drift orbit from a flux surface is larger than the perpendicular correlation length of the turbulence (the island size), the perturbation in the magnetic field is averaged out over the drift orbit. The deviation from a flux surface for the runaway electrons may be as much as 0.4 cm and the deviation for the electrons observed using VECE is probably about 0.1 cm (smaller q and v_H), thus the energies observed using VECE

may be a more sensitive test for magnetic fluctuations than runaway electrons are. In any case, since ours is a worst case estimate, the discrepancy may not be as large as it appears.

7. Conclusions

The electron cyclotron emission spectra from suprathermal electrons has been measured through a nearly vertical chord in the TEXT-U tokamak. The spectrum measured using ECRH injected in the co-electron direction shows much greater emission at low frequencies than a comparable spectrum measured using counter-injected ECRH. Since all other plasma parameters are the same for these discharges, the change in the level of emission must be due to suprathermal electrons.

By comparing the experimentally measured ECE spectrum with the results of a comprehensive Fokker-Planck calculation, the diffusion of fast electrons has been measured in the plasma core of TEXT-U during electron cyclotron heating. The simulation includes the effects of both magnetic and electrostatic fluctuations on the transport of fast electrons. The experimental spectra are best fit by spectra that include magnetic fluctuations with $\tilde{b} = (3-5) \times 10^{-5}$. Addition of an electrostatic fluctuation term does not significantly change the results and the electrostatic term by itself cannot explain the experimentally measured data. Uncertainties in the level of RF power, internal toroidal electric field and Z_{eff} profile limit the accuracy of this measurement. However, this measurement indicates that an upper limit can be placed on $\tilde{b}$ in the core of between 3×10^{-5} and 5×10^{-5} . This result is in fair agreement with measurements made outside of the TEXT limiter using magnetic probes and with measurements of runaway electron diffusivity in the outer edge of the plasma. Since a magnetic fluctuation level of 10^{-4} would be necessary in order to explain transport in the core plasma, the magnetic fluctuation levels inferred here are unlikely to be the dominant cause of the transport of thermal electrons in TEXT-U.

Acknowledgments

The authors would like to thank G. Cima, D. Ross, D. Sing, C. Watts and A. Wootton for their help and useful discussions. TEXT-U is supported by the US Department of Energy under grant DE-FG03-94ER-54241.

References

- ¹ Y.J. Kim, Ph.D. thesis, University of Texas at Austin, 1989; Y.J. Kim, K.W. Gentle, Ch. P. Ritz, T. L. Rhodes, and R. D. Bengston, *Phys Fluids B* **3**, 674 (1991)
- ² G. G. Castle and A. J. Wootton, *IEEE Transactions on Plasma Science*, **625**, (1994)
- ³ Wootton, A.J., "The effects of magnetic perturbations on plasma transport, or is magnetic turbulence important in tokamaks?," in *Transport, Chaos and Plasma Physics*, (Benkadda, S., Doveil, F., and Elskens, Y., Ed.), World Scientific, Singapore, (1993) 130-140.
- ⁴ J. R. Myra and P. J. Catto, *Phys. Fluids B* **4**, 176 (1992).
- ⁵ Y. Peysson, *Plasma Phys. Control. Fusion* **35**, B253 (1993)
- ⁶ S. J. Zweben, D. W. Swain, and H. H. Fleischmann, *Nucl. Fusion* **18**, 1679 (1978).
- ⁷ C. W. Barnes and J. D. Strachan, *Phys. Fluids* **26**, 2668 (1983).
- ⁸ O.J. Kwon, P.H. Diamond, F. Wagner, G. Fussmann, and the ASDEX and NI Temas, *Nucl. Fusion* **28**, 1931 (1988).
- ⁹ P.J. Catto, J.R. Myra, P.W. Wang, A.J. Wootton, and R.D. Bengston, *Phys. Fluids B* **3**, 2038 (1991); P.W. Wang, Ph.D. thesis, Massachusetts Institute for Technology, 1991.

- 10 S. Jones, J. Kessner, S. Luckhardt, F. Paoletti, G. Giruzzi, S. von Goeler, S. Bernabei, R. Kaita and the PBX-M Team, *Phys. Plasmas* **2**, 1548 (1995)
- 11 J.P. Bizzaro, et al. *Phys. Fluids* **B5**, 3276 (1993)
- 12 S. Knowlton, M. Porkolab, Y Takase, *Phys Plasmas* **1**, 891 (1994)
- 13 E. Barbato and others, *Proc. 18th European Conf. on controlled Fusion and Plasma Physics, Berlin III* 417, (1991) (JET??)
- 14 R. Bartiromo, Barbato E et al 1992 ENEA report RT/NUCL/92/35 (Centro Ricerche Energia Frascati, Rome, Italy and to be Published in *Nucl. Fusion*. (ASDEX?))
- 15 K. Kato and I. H. Hutchinson, *Phys. Fluids* **30**, 3809, (1987).
- 16 T. C. Luce, P. C. Efthimion, and N. J. Fisch, *Rev. Sci. Instrum.* **59**, 1593 (1988).
- 17 S. Ide, K Ogura, H. Tanaka, M Iida, K. Hanada, T. Itoh, M. Iwamasa, H. Sakakibara, T. Minami, M. Yoshida, T. Maekawa, Y. Terumichi, S. Tanaka, *Nucl. Fusion* **29**, 1325 (1989).
- 18 R.W. Harvey, M.R. O'Brien, V.V. Rozhdestvensky, T.C. Luce, M.G. McCoy and G.D. Kerbel, *Phys. Fluids* **B5**, 446 (1993).
- 19 E. Mazzucato, P. Efthimion, and I. Fidone, *Nucl. Fusion* **25**, 1681 (1985).
- 20 R. K. Kirkwood, I.H. Hutchinson, S.C. Luckhardt, and J.P. Squire, *Nucl. Fusion* **30**, 431 (1990).
- 21 J.L. Sequi and G. Giruzzi, *Plasma Phys. Contr. Fusion* **36**, 897 (1994).
- 22 F.J. Skiff, D.A. Boyd, J.A. Colborn, *Phys. Fluids* **B35**, 2445 (1993)
- 23 I. Fidone, G. Giruzzi, G. Granata, R.L. Meyer, *Phys. Fluids* **26**, 3284 (1983)

- 24 G. Giruzzi, I. Fidone, X. Garbet, Nucl. Fusion 32, 1011 (1992).
- 25 D.R. Roberts, D. C. Sing, R. F. Steimle, Nucl. Fusion 33, 1707 (1993).
- 26 D.R. Roberts, R.F. Steimle, G. Giruzzi, G. Cima and C. Watts, Rev. Sci. Instrum. 66, 427 (1995).
- 27 H. Knoepfel and D.A. Spong, Nucl. Fusion 19, 785 (1979)
- 28 R.A. James, G. Giruzzi, B. de Gentile, L. Rodriguez, R. Harvey, J. Lohr, T. C. Luce, K. Matsuda, C. P. Moeller, R. Prater, R. Snider, A. Fyakhertinov, Yu. Gorelov, V. Trukhin, and S. Janz, Phys. Rev. A 45, 8783 (1992)
- 29 G. Giruzzi, E. Martines, Phys. Plasmas 1, 2653 (1994)
- 30 J.R. Myra, P.J. Catto, A.J. Wootton, R.D. Bengston, P.W. Wang, Phys. Fluids B4, 2092 (1992)
- 31 J.C. Wiley, FRC Report #328
- 32 K.W. Gentle, G. Cima, D. Roberts, D. Sing. C. Watts, to be published in proceedings of the ninth joint workshop on ECE and ECRH