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Using a Tunable Correlation Electron Cyclotron Emission
System on Alcator C-Mod

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Measurement of Electron Temperature Fluctuations Using a Tunable Correlation Electron Cyclotron Emission System on Alcator C-Mod

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A tunable correlation electron cyclotron (CECE) system was recently installed on the Alcator C-Mod tokamak to provide local, quantitative measurement of electron temperature fluctuations in the tokamak core. This system represents a significant upgrade from the original CECE system, expanding the measurement capabilities from 4 to 8 total channels, including 2 remotely tunable YIG filters (6-18 GHz; 200 MHz bandwidth). Additional upgrades were made to the optical system to provide enhanced poloidal resolution and allow for measurement of turbulent fluctuations below $k_0 \rho_s < 0.3$. These expanded capabilities allow for single shot measurement of partial temperature fluctuation profiles in the region $\rho = 0.7 - 0.9$ (square root of normalized toroidal flux in a wide variety of plasma conditions. These measurements are currently being used to provide stringent tests of the gyrokinetic model in ongoing model validation efforts. Details of the hardware upgrades, turbulent fluctuation measurements, and ongoing comparisons with simulations are presented.

I. INTRODUCTION

In the core of fusion plasmas, experimental levels of heat, particle, and momentum transport are commonly found to exceed the predictions of neoclassical theory. It is now generally accepted that these observed "anomalous" levels of transport are the result of microinstabilities and plasma turbulence driven unstable by gradients in the plasma’s kinetic profiles. Advances in cutting-edge gyrokinetic codes have begun to shed light on the origins of plasma turbulence, but remain largely untested against detailed experimental measurements. The turbulence responsible for anomalous transport is thought to manifest itself as small-amplitude, high frequency fluctuations in the plasma density, temperature, potential, and magnetic fields. Measurements of multi-fielded fluctuations are invaluable for understanding the origins of anomalous heat transport and provides data for direct comparison with nonlinear gyrokinetic turbulence models for validation studies.

Measurement of Electron Cyclotron Emission (ECE) is a standard technique for measurement of electron temperature in magnetically confined fusion plasmas, capable of achieving excellent spatial and temporal resolution. However, due to the thermal noise inherent in these systems, they are unable to measure the small-amplitude electron temperature fluctuations associated with plasma turbulence. The effects of thermal noise can be mitigated when ECE radiation from separate measurements is correlated, eliminating the thermal noise and allowing for increased sensitivity for measurement of small-amplitude fluctuations. This technique, known as Correlation ECE (CECE) has been employed on fusion devices worldwide with varying levels of success. In this paper we present the design of a new, tunable, Correlation Electron Cyclotron Emission (CECE) radiometer recently installed on the Alcator C-Mod tokamak at MIT and a description of recent upgrades to the system. This diagnostic has demonstrated the ability to provide quantitative measurement of long wavelength turbulent fluctuations of the electron temperature ($\tilde{T}_e$) associated with anomalous electron heat transport levels in a variety of plasma conditions.

II. DESCRIPTION OF THE TUNABLE CORRELATION ECE RADIOMETER AND ADDITIONAL SYSTEM UPGRADES

An in-depth description of the original CECE system on Alcator C-Mod was previously published. This system features in-vessel optics, a radio frequency (RF) section and intermediate frequency (IF) section with a total of four fixed frequency measurements. Here we focus on the recent upgrades to the original diagnostic setup and the hardware associated with the newly installed IF section, which have allowed for detailed measurements of turbulent fluctuations in a variety of plasma conditions. For details of the original system setup, we refer the reader to reference 22.

The Alcator C-Mod CECE system is an ECE radiometer which measures second harmonic, X-mode ECE emission in the frequency range of 230-248 GHz, at a location approximately 7 cm above the low field side, midplane. To allow for measurement of small amplitude (<1%) temperature fluctuations, this system employs the spectral decorrelation technique, relying on the fact that thermal noise from radiometers separated in frequency space are uncorrelated. Signals from slightly separated channels can be cross correlated to extract RMS amplitudes and power spectra of electron temperature fluctuations. A diagram of the in-vessel optical system and RF section

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b) Contributed paper published as part of the Proceedings of the 20th Topical Conference on High-Temperature Plasma Diagnostics, Atlanta, Georgia, June, 2014
FIG. 1. A cross section of the Alcator C-Mod tokamak is shown with a typical plasma equilibrium. The CECE beam width (blue), in-vessel optics (green), and RF section (red) are shown.

installed on Alcator C-Mod can be found in Figure 1. The previous system, described by Sung et al. featured an in-vessel mirror setup designed to provide measurements in the core plasma at standard Alcator C-Mod magnetic field, $B_T = 5.4$ T. However, studies of high performance ELM-suppressed regimes, such as I-mode\textsuperscript{23,24}, and the persistent shortfall in gyrokinetic predictions of transport at DIII-D\textsuperscript{25}, motivated investigation of temperature fluctuations in the outer-core region of the plasma ($\rho \sim 0.7 - 0.9$). As a result, both the in-vessel optics as well as the RF section were modified to provide reduced measurement spot size (and therefore increased poloidal resolution) in this region of interest. A redesign of the in-vessel mirror system was carried out changing the effective focal length of these components from $f = 23.4$ cm to 14.5 cm, and modification of the system’s collimating lens from $f = 10$ cm to 5 cm. These system upgrades reduce the effective emission spot size to less than 1 cm over the radial range $\rho \sim 0.7 - 0.9$ with a minimum value occurring at approximately $\rho = 0.8$.

The choice of effective spot size was based on previous work\textsuperscript{26}, which used gyrokinetic simulation and synthetic CECE modeling to determine the optimal spot size for measurement of core temperature fluctuations. All upgrades to the original system were performed to achieve smaller spot sizes and higher poloidal resolution in the desired radial range. These upgrades now allow for resolution of poloidal wavenumbers of $k_\theta < 9.8$ cm$^{-1}$ or $\sim k_\theta \rho_s < 0.3$, the range typically associated with long wavelength Ion Temperature Gradient (ITG) and Trapped Electron Mode (TEM) turbulence.

The design and construction of a tunable IF section, to complement the originally installed, four-channel, fixed filter system, had two primary objectives: 1) Provide the ability to remotely tune the CECE measurement location on a shot by shot basis 2) Double the number of measurements (4 to 8) providing effective profile measurement of temperature fluctuation profiles (in the range $\rho = 0.7 - 0.9$) during a single plasma discharge. These objectives were achieved using the hardware setup detailed in Figure 2 and described here.

FIG. 2. (Top) a block diagram of the tunable IF section for a typical setup is shown. (Bottom) A photograph of the system is shown.

To improve signal strength, upon entering the tunable IF section, signals from the CECE RF section are amplified using a MITEQ 39dB, 2-18 GHz, low-noise (1.8-2.2dB) amplifier. A power divider is used to split the input signal into four distinct channels. Two of these channels feature fixed filters with center frequencies typically in the range of 4-14 GHz, and a 3dB bandwidth of 200 MHz. For standard plasma discharges on Alcator C-Mod ($B_T \sim 5.4$ T), IF filters with center frequencies in the 8-8.5 GHz range are commonly employed. Signals
from the additional two channels are run through Yttrium Iron Garnet (YIG) band pass filters manufactured by Micro Lambda Wireless. These filters are remotely tunable with a center frequency range of 6-18 GHz with a 3dB bandwidth of nominally 200 MHz across the tunable frequency range. Input voltages from 0-10 V DC are used to remotely tune the center frequency of both YIG filters. These voltages are digitized and remotely monitored for consistency between input and output. Currently, two web-interfaced function generators are used for remote tuning of the filters on a shot to shot basis. Due to cable losses and spatial constraints, the new IF section was installed approximately 3 meters from the tokamak field coils, exposing the tunable filters to stray fields (estimated at ∼100 G) which can significantly alter the YIG filter’s center frequency. Quarter inch, low-nickel stainless steel was used to create a magnetic housing for both filters (seen in Figure 2). These housings were verified to sufficiently shield the filters to fields up to ∼ 10× (1 T) those present at the location of the IF section.

After passing through the band pass filters (fixed and tunable), each channel is fed into Schottky diode detectors, measuring the power in each channel before being passively high pass filtered at approximately 10 kHz and sent through 6.5 MHz video amplifiers. The high pass filtering eliminates the low frequency, DC component of the signal (associated with the background temperature), allowing for increased sensitivity to the low amplitude (AC component) temperature fluctuations. Output from the video amplifiers is sent via BNC outputs on the IF section to a D-TACQ (ACQ216CPCI-16-50) digitizer where the signals are digitized typically at 6 to 10 M samples/s. The theoretical sensitivity of this system to detection of temperature fluctuations is given by the formula

\[ \frac{T_c}{T_e} > \sqrt{\frac{1}{N} \frac{2 B_{vid}}{B_{IF}}} \]  

Where \( N = 2 B_{vid} \Delta t \), the number of samples used for the correlation, \( \Delta t \) is the averaging time, and \( B_{IF} \) and \( B_{vid} \) are the Intermediate Frequency (IF) section and video bandwidths respectively. As stated above, the upgraded C-Mod system features 200 MHz bandwidth for the IF section and a video bandwidth of 1 MHz (obtained by digitally low-pass filtering the measured signal). Given an increase in sensitivity with increased averaging time, attempts were made to maximize the stationary periods of the discharge, thus allowing for increased sampling periods. 500 ms averages were typically used for analysis resulting in sensitivity levels of ∼ 0.3%.

III. MEASUREMENT OF TEMPERATURE FLUCTUATIONS ON THE ALCATOR C-MOD TOKAMAK

The improvements to the original CECE system and the new, tunable IF section were operational during the 2012 experimental campaign on Alcator C-Mod. The versatility of this system was clearly demonstrated as electron temperature fluctuation measurements were obtained in a wide range of plasma conditions, spanning ohmic, L-mode, I-mode, and H-mode plasmas at a range of fields, densities, and plasma currents. Most notably, these upgrades have made possible the study of electron temperature fluctuations across the ohmic confinement transition. Measured fluctuation levels and frequency spectra are currently being compared with nonlinear gyrokinetic simulations, in an attempt to validate the gyrokinetic model. In order to demonstrate the capability of the tunable CECE system in measuring turbulent electron temperature fluctuations, we plot an example of measurement obtained from a 1.6 MW Ion Cyclotron Resonance heated, L-mode plasma from Alcator C-Mod in Figure 3.

Cross Power Spectrum from Tunable Filter Channels

![Cross Power Spectrum from Tunable Filter Channels](image)

FIG. 3. (Color Online) The cross power obtained from the two tunable CECE channels is plotted versus frequency. Below 200 kHz, we see clear evidence of temperature fluctuations in this discharge.

The measured cross power spectrum obtained from correlation of the two tunable channels centered at 6.0 and 6.6 GHz (approximately \( \rho = 0.84 \) for the plasma conditions studied) is shown. Data from this discharge was obtained from a stationary period of the discharge corresponding to \( t = 0.8 \) to 1.3 seconds, resulting in a sensitivity limit (Equation 2) of ∼ 0.3%. As the plasma is clearly optically thick at the measurement location (\( \tau \sim 5.0 \)), clear evidence of temperature fluctuations above the statistical noise level is found in the range 0-200kHz, with contributions from 200kHz to 1MHz representing statistically insignificant contributions to the temperature fluctuation level and thus confirming the ability of the new system to measure electron temperature fluctuations. From the cross power spectrum, we determine that the electron temperature fluctuation level in this plasma condition is approximately 1.5 ± 0.15%, with the dominant uncertainty in this quantity arising from uncertainty in the IF bandwidth. For an in-depth
The description of the analysis technique used to determine the cross power spectrum and the rms fluctuation level from the raw data, we refer the reader to reference 28.

FIG. 4. (Color Online) The profile of the electron temperature fluctuation levels from \( \rho = 0.7 - 0.9 \) is shown for an L-mode discharge on Alcator C-Mod. The new upgrades to the CECE system and the tunable IF section make this measurement easily attainable.

The addition of the tunable IF section increased the CECE system to a total of eight channels, allowing for determination of temperature fluctuation levels at four radial locations during a single plasma discharge. This upgraded capability allows for the determination of 4-point temperature fluctuation profiles (in the range \( \rho = 0.7 - 0.9 \)) within a single shot, and slight Bt scans shot by shot can be used to reconstruct more detailed radial profiles. Figure 4 demonstrates a profile of the electron temperature fluctuations in an Alcator C-Mod L-mode discharge during the 2012 campaign. Data in this plot were obtained using both the tunable IF section as well as the originally installed IF section with four of the measurement locations obtained during a single discharge. Slight (< 5%) changes in the magnetic field were applied to these repeat discharges to shift the radial location of the fixed frequency filters. Using the new CECE system, temperature fluctuation levels and frequency spectra have been measured in a wide range of plasma conditions\(^{21}\). This collection of measurements has provided an invaluable set of data for comparison with emerging turbulence models. Currently, work is in progress to try to reproduce the quantitative fluctuation levels and qualitative trends of the fluctuations using gyrokinetic simulations and synthetic CECE diagnostics\(^{25,26}\).

\(^{7}\) C. Sung et al. Proceedings of 18th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, To be Published.