Design of a correlation electron cyclotron emission diagnostic for Alcator C-Mod


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A Correlation Electron Cyclotron Emission (CECE) diagnostic has been installed in Alcator C-Mod. In order to measure electron temperature fluctuations with amplitude lower than the intrinsic thermal noise level, this diagnostic uses a spectral decorrelation technique. Constraints obtained with nonlinear gyrokinetic simulations using the GYRO code guided the design of the optical system and receiver. The CECE diagnostic is designed to measure temperature fluctuations which have \( k_\perp \leq 4.8 \text{cm}^{-1} (k_\perp \rho_s < 0.5) \) using a well-focused beam pattern. Because the CECE diagnostic is a dedicated turbulence diagnostic, the optical system is also flexible, which allows for various collimating lenses and antenna to be used. The system overview and the demonstration of its operability as designed are presented in this paper.

I. INTRODUCTION

In magnetic fusion plasmas, it has been observed that electron heat conductivity is higher than the neo-classical level, and turbulent fluctuations are believed to be responsible.\cite{1} In order to understand this turbulent transport, we need to measure the fluctuations of electron density, temperature, magnetic field and electrostatic potential when possible.\cite{2} Though radiometry of Electron Cyclotron Emission (ECE) is a useful diagnostic for electron temperature measurements, it is hard to measure broadband turbulent temperature fluctuations due to thermal noise. The thermal noise level is typically much higher than the fluctuation level, which is around 1% in the core plasma. We can remove thermal noise through cross correlation of two ECE radiometer channels with uncorrelated thermal noise. This method has been successfully used in several toroidal confinement devices\cite{3-5}. In the Alcator C-Mod tokamak (\( R=0.67 \text{m}, a=0.21 \text{m} \), \( \kappa=1.6 \)), past attempts to measure electron temperature fluctuations using correlation ECE did not resolve broadband fluctuations above the sensitivity limit.\cite{6} Nonlinear gyrokinetic simulations using the GYRO code \cite{7} were used to reexamine reasons for this, and the results motivate a new CECE diagnostic in C-Mod.\cite{8} In this paper, the system overview and first results from the new CECE diagnostic on C-Mod are presented.

II. DESIGN OF CECE DIAGNOSTIC IN C-MOD

Gyrokinetic simulations have provided several constraints on the design of CECE for C-Mod.\cite{8} First, the optical system should provide a small beam diameter (1/e electric field diameter) of 1cm at the measurement position to measure low wavelength (\( k_\perp \rho_s < 0.5 \)) fluctuations in the core. The beam diameter determines poloidal spatial resolution of CECE, and a large beam diameter will result in filtering out of high frequency fluctuations. A large final beam diameter (~4cm) is considered to be the main reason original attempts to measure temperature fluctuations with CECE on C-Mod were unsuccessful.\cite{8} Second, the gyrokinetic simulations predict that the radial correlation length of the turbulence is less than 1cm. This gives a constraint in the IF (Intermediate Frequency) bandwidth and on the spacing of neighboring IF filters. Third, the receiver should be able to measure high frequency fluctuations, which can extend up to 0.5-1.0MHz in the core of C-Mod plasmas, due to the effects of ExB flow that Doppler shift the measured laboratory-frame fluctuation power spectrum. This sets limits on the video bandwidth. Last, sensitivity of CECE diagnostic should be less than 0.5%, since fluctuations are predicted to be between 0.5-2.0% in the core (0.4<\( p < 0.9 \)).

Figure 1 CECE diagnostic with C-Mod plasma (shot 1120221014, t=1.0 sec). The 1/e beam width along the line of sight is shown as blue curve. Flat and parabolic mirrors are installed in the vessel.
and HDPE lens, antenna and high frequency receiver components (RF section) are installed outside the vessel.

Following the above constraints, a CECE diagnostic for C-Mod was designed. The CECE radiometer collects 2nd harmonic X-mode electron cyclotron emission, viewing the plasma from the low field side near the midplane. For the initial set-up, 4 channels have been installed to measure turbulence near \( \rho = 0.8 \) when \( B_\phi = 5.4T \). In order to obtain the temperature fluctuation data, the spectral decorrelation technique will be used. This method uses the fact that thermal noise on two radiometer channels will be uncorrelated if the channels are separated in frequency space[3]. The antenna pattern overlaid on a contour plot of flux surfaces for a typical C-Mod plasma is shown in Figure 1. The optical system (drawn to scale) consists of two in-vessel stainless steel mirrors (flat and parabolic mirror, effective focal length, \( f=23.4cm \)), and outside the vessel a HDPE collimating lens with focal length \( f=10cm \) and corrugated, high gain scalar horn antenna (230-270GHz).

![Figure 2 Gaussian beam calculation for optical system design (a) The calculation of Gaussian beam propagation in the designed optical system (b) The change of focal point depending on the different collimating lenses](image)

In order to estimate the final beam diameter, Gaussian beam calculations were used as shown in Figure 2. We can consider this optical system as a 1D system. This calculation method was verified experimentally for similar optical arrangements at DIII-D[9]. The final beam diameter is about \( 2w=1.3cm \) at \( \rho = 0.2 \) \( (2w=1.5cm \) at \( \rho = 0.5 \)), where \( w \) is 1/e electric field radius. This value sets the poloidal resolution of CECE to \( k_\theta \leq 4.8cm^{-1} \). In the calculation, it was also found that we can change the focal point of Gaussian beam by changing the collimating lens. Depending on the focal length of the collimating lens, beam spreading on the parabolic mirror can be varied. When the beam size on the parabolic mirror is increased, the focal point moves radially deeper into the plasma. Thus, we can adjust the focusing point by changing the ex-vessel lens without changing the in-vessel components. One possible configuration is shown in Figure 2 (b). By changing the focal length of collimating lens from 10cm to 7.6cm, the focal point moves 3.2cm further into the plasma.

The CECE receiver block diagram is shown in Figure 3. The high frequency components (RF section: LO at 250GHz, subharmonic mixer, and first amplifier (2-18GHz)) are installed in front of the port. After the scalar horn antenna, the input RF frequency range is chosen to be 232-245GHz by a band pass filter, and the IF frequency range is 2-18GHz. The IF signal is amplified 33dB by the first low noise amplifier. The signal is then transmitted to the relatively low frequency components (IF section) through a 6.1m low loss SMA cable. In the IF section, the signal is amplified 39dB by a second low noise amplifier, and attenuation can be varied. The signal is split into 4 channels, and in each channel, the signal is filtered by IF band pass filter. These filters have the fixed center frequency (8-8.5GHz), and 3dB bandwidth \( B_{IF}=100MHz \). This bandwidth is conservatively selected in order to ensure that two filters can measure emission in disparate frequency bands within a radial correlation length (<1cm) of the turbulence. The power of these signals is measured by square-law detector, and is amplified by a video amplifier with bandwidth 6.5MHz. This signal is digitized at 10Msamples/sec. The signal can be digitally filtered using standard signal analysis methods. The noise temperature of this IF section is less than 6eV.

![Figure 3 Block diagram of CECE receiver](image)

The lowest temperature fluctuation level of CECE is given as,[2]

\[
\frac{T}{T_r} \geq \sqrt{\frac{1}{N^{1/2}}} \frac{2B_{IF}}{B_{IF}}
\]

Where \( N \) is the number of samples used in correlation, given by \( N = 2B_{IF} \Delta t \). \( \Delta t \) is the averaging time. With the IF and video bandwidth values, \( B_{IF} = 100MHz \) and \( B_{IF} = 1MHz \), respectively, we need 0.32 sec averaging time to measure 0.5% fluctuation level. Increasing the averaging time, reducing the video bandwidth or increasing the IF filter bandwidth, all reduce the sensitivity level.

III. THE PREMINARY RESULTS FROM CECE IN C-MOD

Before the turbulence measurement, it is required to verify that the CECE radiometer is working properly. The first goal is to measure the electron temperature. The data from CECE in C-Mod was cross-calibrated to the independent profile ECE radiometer diagnostic in C-Mod, which has 32 channels. As a
result, a calibration factor of 2-3keV/N for each channel was obtained. This value agrees within experimental error with the independently estimated calibration factors obtained in laboratory tests. The cross-calibrated CECE data were compared to other temperature measurements (Grating Polychromator (GPC) and Thomson Scattering). Figure 4 shows the comparison for C-Mod shot 1120221014. As shown in Figure 4, the electron temperature of CECE diagnostic agrees well with the other temperature diagnostics in C-Mod.

![Figure 4](image_url)

Figure 4 Electron temperature measured with CECE compared well with other diagnostics (GPC, GPC2, FRC-ECE and core Thomson scattering) in C-Mod.

The spectral decorrelation was verified with a noise source in the laboratory. Figure 5(a) shows the cross correlation coefficient function using noise source from three pairs of channels. As expected, the cross correlation value is decreased as overlapped frequency is reduced. In Figure 5(b), we can observe that the cross correlation coefficient at lag time equal to zero, $C_\nu(0)$ is a low value when the separation of the center frequency of IF filters, $\Delta f$ is larger than the 3dB bandwidth 100MHz. The results in Figure 5(b) indicate that thermal noise in EC emission signal from CECE receiver can be removed by using spectral decorrelation techniques. Separate from the thermal noise (which is intrinsic to radiometer measurements), there can also be noise in the radiometer electronics that can possibly mask true temperature fluctuations. The measured auto power spectrum with plasma is compared to the one without plasma in Figure 5(c). As shown in this figure, the electronics noise level is small compared to the plasma signal. Therefore, the effect of electronics noise will be ignorable in the real measurements.

IV. CONCLUSIONS

A new CECE diagnostic in C-Mod was designed using several constraints guided by nonlinear gyrokinetic simulations.[8] The new radiometer, which has high poloidal resolution and flexible optical system is constructed and is installed at C-Mod and has been successfully used to measure electron temperature. This diagnostic is designed to measure long wavelength, $k_\parallel$≤4.8cm⁻¹, broadband (500-1000kHz) temperature fluctuations above 0.5% for typical video bandwidth and averaging times. During the 2011 run campaign, it was verified that the CECE radiometer is working properly, that thermal noise decorrelates as expected, and that electronics noise can be reduced to insignificant levels. It is expected that this diagnostic will obtain turbulence data in the next campaign and contribute to understanding of transport phenomena in Alcator C-Mod.

![Figure 5](image_url)

Figure 5 (a) Cross correlation coefficient from three pairs of CECE channels with noise source. Channel 01-04 have different IF filters whose center frequency is 8, 8.05, 8.08, 8.15GHz respectively, bandwidth 100MHz. (b) Absolute value of cross correlation coefficient at lag time=0, $C_\nu(0)$ depending on the frequency separation between channels with statistical level. (c) The comparison of auto power spectrum of CECE ch3 before plasma breakdown (black) and after plasma start-up (red)

VI. REFERENCES