Rapid scanning polarizing Martin Puplett type THz Fourier transform spectrometer (FTS) for ITER ECE measurements

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Abstract— **this paper gives a brief overview of the ITER Electron Cyclotron Emission Diagnostic system, outlining the design requirements for Fast scanning Fourier transform Spectrometer. The prototype Martin Puplett Interferometer and its associated data acquisition system are presented. The importance of interferometer characterization and calibration procedures is briefly discussed. Moreover, conventional data analysis techniques are discussed and implemented on the experimentally obtained interferogram from the prototype Martin Puplett interferometer.**

Keywords—THz Fourier transform spectrometer, Martin-Puplett Interferrometer, FTS data analysis, Electron cyclotron emission (ECE), International Thermonuclear experimental reactor (ITER)

I. INTRODUCTION

Electron Cyclotron Emission (ECE) measurement serves as an essential diagnostic tool, offering valuable insights into tokamak plasma, like electron plasma temperature profile with high spatial and temporal resolution, detection of high-frequency instabilities like Neoclassical tearing modes (NTM), and characterization of the non-thermal electron energy distribution function. This diagnostic technique involves an antenna, transmission line system and broadband instruments (like heterodyne radiometer and rapid scanning Fourier transform spectrometer). The antenna collects ECE radiation from the plasma and focuses it at the input of Transmission line consisting of oversized smooth walled circular waveguide. The transmission line transmits the collected ECE/calibration signal over a long distance and couples the ECE radiation to the detectors. For ECE measurements, heterodyne radiometers (comprising local oscillators, mixers, and power dividers) [1] [2], and rapid scanning Martin Puplett Interferometers FTS, which include focusing optics, input/output polarizers, beam splitters, a rapid scanning system, and a cryogenic THz detector, are commonly used in tokamaks.

The rapid scanning Martin Puplett [3] type FTS diagnostic stands as a standard tool for precise ECE measurements in tokamak plasma, primarily due to its capability to measure a broad spectrum range and its ease of calibration, which are facilitated by its high throughput characteristics. For the International thermonuclear experimental reactor (ITER) [4] [5] [6], both heterodyne radiometers (O/X-mode) and Martin Puplett interferometers have been adopted for ECE measurements. This paper is organized as follows: In Section 2, we will cover the Rapid Scanning FTS diagnostic. This includes details about the antenna, transmission line, the Martin Puplett interferometer, and the data acquisition system. In Section 3, we discuss FTS data analysis for the interferogram measured from the Eccosorb LN2 source, while Section 4 provides a discussion.

II. RAPDID SCANNING FTS DIAGNOSTIC SYSTEM

The Electron Cyclotron Emission (ECE) in Ordinary and Extraordinary Mode is collected using front-end optics which is a Quasi-optical antenna. The design details of this Quasioptical antenna are given in this paper [7].

In ITER [6] ECE Diagnostic, two Martin Puplett-type FTS systems are proposed to simultaneously measure the Ordinary mode (O-Mode) and Extraordinary mode (X-mode) polarizations. These spectrometers will measure the multiple harmonics of ECE radiation in a wide frequency range, from 70 GHz to 1000 GHz. This diagnostic consists of a quasi-optical antenna, an oversized smooth-walled circular waveguide having an inner diameter (72mm) and the two FTS systems located in the diagnostic room. The schematic of the ITER ECE diagnostic using FTS is as shown in Fig.1

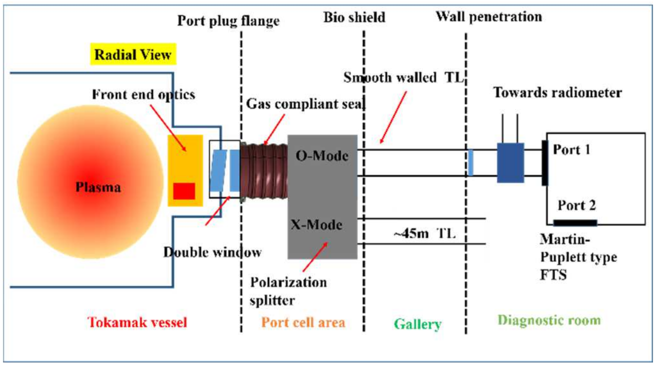

Fig. 1. Schematic of the ITER electron cyclotron emission diagnostic system; this picture shows only the radial view. However, there are two views; the other is an oblique view at approximately 10 degrees.

A. Antenna and Transmission Line

The Quasi-optical antenna, based on a Gaussian beam telescope, is utilized for collecting Electron Cyclotron Emission from the plasma [7]. This antenna subsequently focuses the beam at the input of a polarization splitter unit. ECE comprises of two polarizations, namely O-mode and X-mode, which are separated using the polarization splitter unit located within the interspace structure (near to the closure plate of the port plug flange).

The polarization splitter unit consists of a wire grid polarizer, ellipsoidal and flat mirrors. The design of the Polarization splitter unit is based on the principles of the Gaussian beam telescope. To transmit the ECE signal or thermal radiation over a long distance, long transmission having length approximately 45 meters are required in case of ITER ECE diagnostic system. In the current ITER ECE Diagnostic design, a smooth-walled circular waveguide made of Al 6061T6 is selected for this purpose. The waveguide possesses an inner diameter of 72mm and an outer diameter of 88mm and waveguide joints are vacuum compatible.

A downscaled mock-up of the smooth-walled transmission setup has been tested using a prototype Rapid Scanning FTS and LN2 Source. The outcome of these tests are detailed in this paper [8]

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B. Martin-Pupleet Interferrometer FTS

The Martin-Puplett-type interferometer [3] based FTS diagnostic (employed in ITER) is widely popular and is utilized as a diagnostic tool in various magnetic fusion machines, including JET [9] [10], EAST [11], and W7-x [12]. The Martin-Puplett interferometer consists of two input and two output ports. This device measures the difference in intensity between sources positioned at the input ports, providing complementary output characteristics.

These two ports are kept to select horizontal or vertical polarization of the beam coming from plasma or calibration source. The port 1 will be either open for calibration or plasma emission and the microwave absorber sheet is kept at input port 2 or vice versa. The output of the Interferometer is detected using a THz cryogenic detector, preamplifier and data acquisition system. The scanning mirror is being moved using an electromechanical system i.e. a voice coil.

To fulfil the ITER measurement requirements, a prototype Martin Puplett-type FTS has been designed and developed through a close collaboration between ITER-India, IPR and M/s Bluesky spectroscopy Pvt. Ltd [13] [14].This prototype FTS employs two Gaussian beam telescopes to achieve optimal performance, and its optical schematic is depicted in Fig.2. The frequency resolution depends on the scanning length (or maximum optical path difference) and temporal resolution is determined by scanning rate. The main design requisites for the FTS are as follows: Firstly, the FTS should incorporate a rapid scanning mechanism to determine the time resolution of the ECE spectrum measurement. Secondly, to mitigate water vapor absorption of millimeter-wave radiation, the FTS must be effectively shielded from the atmosphere. Lastly, the interferometer's throughput enables absolute calibration within a reasonable timeframe.

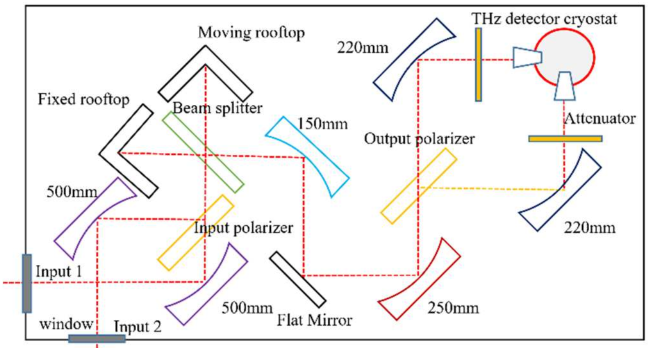

Fig. 2. Layout of prototype ITER Martin Puplett type Fourier transform spectrometer having a dual channel THz detector system.

The actual photograph of the prototype FTS with dual channel detector and DAQ is shown in the Fig.3 and achieved parameters shown in Table 1. The achieved temporal resolution is 10ms and the frequency resolution is ~ 10GHz for the double-sided interferogram. The scanning length is 15mm and the resonance frequency of the scanning system is 50Hz.

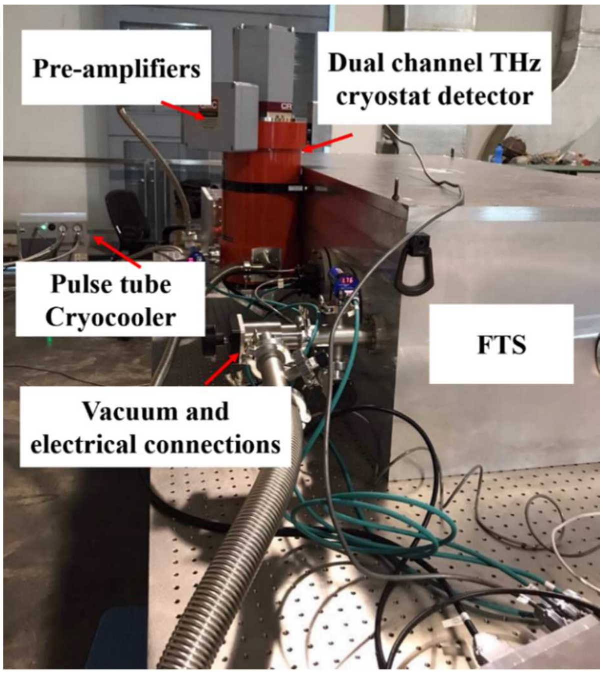

Fig. 3. Photograph of physical prototype Martin-Puplett type Interferrometer FTS located at ITER-India, Diagnostics laboratory

TABLE I. PARAMETERS ACHIEVED FOR PROTOTYPE FTS [15]

Parameters	Value
Spectral range	70 GHz-1THz
Frequency resolution	~ 10GHz
Linear path scan	~ 15mm
Path difference sample rate	Variable in steps of 10/20/40/80 µm
Scanning repetition rate	≤ 20 ms
Etendue (or Throughput)	>4x 10^{-5} m^2 Sr
Transmittance	≥ 70%
Stability	~1%

The achieved frequency resolution is ~ 10GHz. However, the ITER FTS has a frequency resolution requirement of around 5 GHz. Typically, Martin Puplett interferometers used in tokamaks [9] [11] [12] have a single-sided configuration (-L1 to +L2); however, the ITER prototype is designed to produce a double-sided interferogram (-L to + L). The resolution could be improved by adopting the single-sided configuration. R & D efforts are underway to meet the ITER requirement.

C. *Waveguide Coupling with FTS*

An Oversized Smooth-Walled circular waveguide with a diameter of 72 mm is connected to the input ports of the FTS. Efficient coupling between the waveguide and FTS optics is crucial to achieve a good Signal-to-Noise Ratio (SNR). For optimizing the coupling between the Waveguide and the focusing mirror, the dimensions of the waveguide and the beam waist radius (w) at the input of the waveguide are related by a constant factor [16].This relation can be used for determining the dimensions of the quasi-optical components. In the case of a smooth-wall circular waveguide, the optimum coupling is 87%, and the ratio of the beam waist radius (w) to the waveguide's radius is 0.76. Consequently, the beam waist radius (w) is calculated to be 27.36 mm for a smooth walled circular waveguide. The Gaussian beam analysis has been performed to estimate the size of quasi-optical components.

D. *THz broadband detector and pre-amplfier*

The dual-channel detector system consists of two Indium Antimonide (InSb) Hot Electron Bolometers (HEB) mounted at 90 degrees to each other on the 4 K cold plate attached to the PT403 cold head. InSb has intra-band free electron absorption of long wavelengths below 6 K resulting in changes to its electron mobility. The electron-electron interaction time is orders of magnitude shorter than that of the electron-phonon interaction by which energy is lost to the lattice. Therefore electrons come into thermal equilibrium at a temperature above the lattice. This change in temperature and the resulting change in electron mobility, known as the hot-electron response. The electron-phonon relaxation time constant is highly temperature dependent and is measured to be 300 ns at 4.2 K [17].

E. *Data Acquisition System*

The acquisition of a correct interferogram is very important to retrieve the actual spectrum profile since the velocity of the scanning system is sinusoidal in nature with time. Acquiring data at uniform time intervals will distort the interferogram, and therefore, it needs to be acquired with a uniform optical path difference. To achieve this, a Position Metrology system is required, providing a clock to the Data Acquisition System (DAQ), which then digitizes the detector signal according to the clock frequency. The prototype FTS has two DAQ systems: one is a high-speed acquisition (DT9832), and the other is a slow-speed DAQ (DT9804). The high-speed DAQ employs the DT9832 [18] Module, which provides a maximum sampling rate of 2 MSamples per channel with 16-bit resolution. On the other hand, the slow-speed DAQ utilizes the DT9804, offering a sampling rate of 100 kSamples/s and a 16-bit resolution.

The high-speed acquisition is clocked with negligible latency based on the clock signal from the position metrology using a laser interferometer. Fig.5 illustrates the data and communication connections between various FTS subsystems. The control software, written in IDL, is responsible for communicating and controlling the FTS subsystems. The detector signal is sampled at a constant optical path difference by the high-speed acquisition module using laser interferometer position metrology. The recorded signal is known as an interferogram (signal versus optical path difference). This interferogram is then Fourier-transformed using appropriate data analysis techniques to recover the spectra. The standard data analysis is described in this paper. Parameters such as the temperature and pressure of the FTS will be acquired using the slow-speed acquisition module.

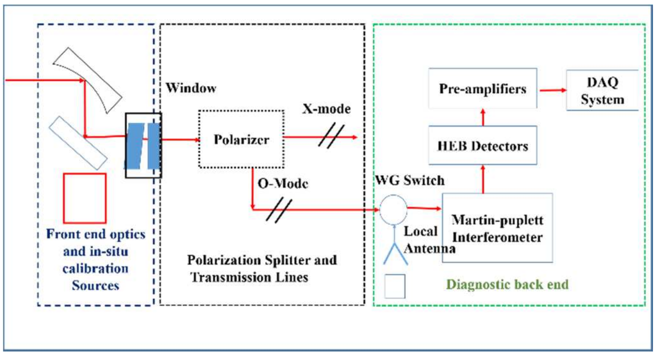

Fig. 4. Schematic of Martin Puplett Interferrometer back end diagnostic

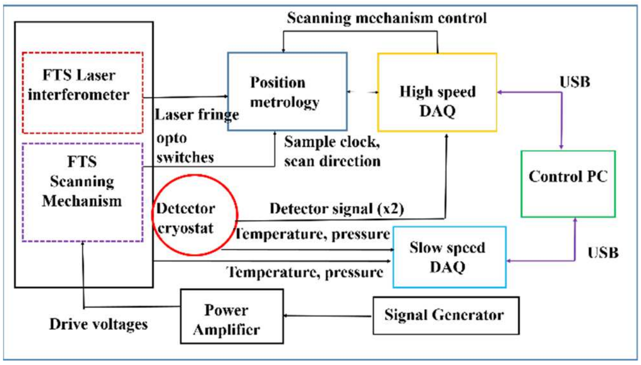

Fig. 5. Data and communication connection between various FTS subsystem

F. Interferrometer Characterization and calibration procedure

Characterizing the Martin Puplett Interferometer is crucial for ensuring the optimal performance of the diagnostic system. The Interferometer is characterized by measuring the frequency resolution, stability, and transmission of the system. The characterization of the Interferometer is reported in this paper [19]. Absolute calibration of the ECE diagnostic is essential for deriving accurate temperature profiles. The accuracy of the temperature profile depends on the calibration accuracy. Calibration accuracy relies on several factors, such as the accuracy of the known spectrum of the blackbody source, system stability, and the back-end sensitivity of the system. The hot/cold technique is a well-known method used to calibrate the ECE diagnostic system, including the antenna, window, transmission line system, and Martin-Puplett-type Interferometer.

Typically, two types of sources are used in calibrating the interferometer. One is the cold (or intermediate) source, composed of TK RAM tiles [20], kept at LN2 temperature (or ambient temperature), and acting as a black body source in the millimetre-wave frequency range. The other source is the hot source, an electrically heated source operating at 500 degrees Celsius to increase the signal-to-noise ratio. This source needs to be well-characterized in terms of emissivity. The development of a hot source for laboratory conditions is underway. Once this source is developed, the prototype Martin Puplett Interferometer will be characterized as a whole. The detailed calibration procedure is given in this paper [9].

III. FTS Data analysis

The detector gives the interferogram signal, and the spectrum is obtained by performing a Fourier transformation on the interferogram signal. Standard data analysis techniques [21] are employed to recover the spectrum. These techniques include applying an apodization function, zero padding, Fourier transformation, and phase correction.

The apodization function is utilized to reduce secondary lobes in the spectrum, which can arise due to the finite scanning length. Zero padding enhances the artificial spectral resolution, resulting in a smoother plot, and phase correction is applied to eliminate asymmetry in the interferogram. These methods have been implemented on the raw interferogram obtained from the prototype FTS, as illustrated in Figure 6. The processed interferogram and the spectrum following phase correction are displayed in Figure 7 and Figure 8, respectively.

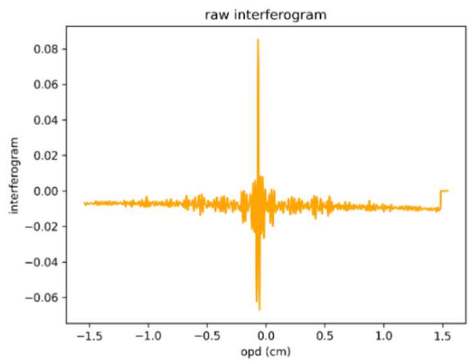

Fig. 6. coherent average of 30,000 interferograms for the FTS setup where port 1 is set at ambient temperature and port 2 is maintained at LN2 temperature.

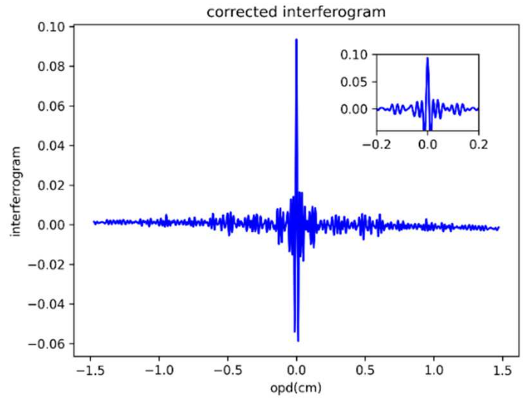

Fig. 7. Phase corrected interferogram signal

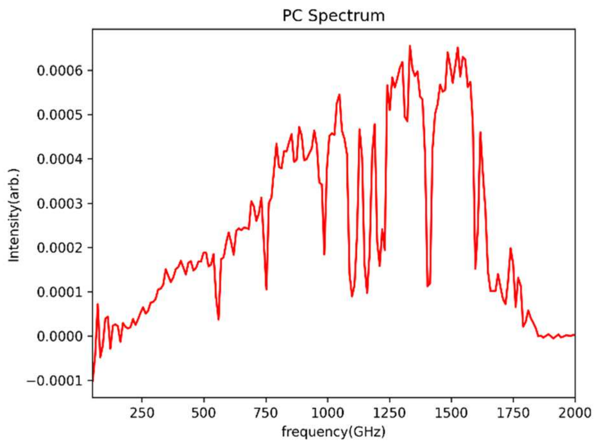

Fig. 8. LN2 spectra computed from the average of 30,000 interferograms taken over 300 seconds. The interferogram is recorded for a setup with a short smooth walled waveguide with a 90-degree miter bend and a Microwave Eccosorb immersed in LN2 temperature (77K)

Various apodization functions [22] such as boxcar, triangle, Gaussian, and Norton & Beer etc., are available to process the interferogram. However, the selection of the apodization and its impact on the ECE spectrum requires further investigation, which is currently being studied.

IV. Discussion

This paper provides an overview of the prototype Martin Puplett Interferometer diagnostic developed for electron cyclotron emission measurements in ITER. The sub-systems of the FTS diagnostic, such as the antenna, transmission line, interferometer, and DAQ system, are described. The significance of instrument characterization and calibration procedures is also discussed. The standard data analysis techniques for recovering the broadband spectrum are presented as a whole system overview. Additionally, it was mentioned that R&D efforts are underway to improve the frequency resolution in order to meet ITER requirements. The assessment of the effect of apodization functions on the ITER ECE spectrum is currently being studied.

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