A Michelson Interferometer for Electron Cyclotron Emission Measurements on EAST∗

LIU Yong (刘永)1, Stefan SCHMUCK2, ZHAO Hailin (赵海林)1, John FESSEY2, Paul TRIMBLE2, LIU Xiang (刘祥)1, ZHU Zeying (朱则英)1, ZANG Qing (臧庆)1, and HU Liqun (胡立群)1

1Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China
2CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK

Abstract A Michelson interferometer, on loan from EFDA-JET (Culham, United Kingdom) has recently been commissioned on the experimental advanced superconducting tokamak (EAST, ASIPP, Hefei, China). Following a successful in-situ absolute calibration the instrument is able to measure the electron cyclotron emission (ECE) spectrum, from 80 GHz to 350 GHz in extraordinary mode (X-mode) polarization, with high accuracy. This allows the independent determination of the electron temperature profile from observation of the second harmonic ECE and the possible identification of non-Maxwellian features by comparing higher harmonic emission with numerical simulations. The in-situ calibration results are presented together with the initial measured temperature profiles. These measurements are then discussed and compared with other independent temperature profile measurements. This paper also describes the main hardware features of the diagnostic and the associated commissioning test results.

Keywords: EAST, ECE, interferometer, calibration, electron temperature

PACS: 52.70.Gw

DOI: 10.1088/1009-0630/18/12/02

(Some figures may appear in colour only in the online journal)

1 Introduction

Electron cyclotron emission (ECE) diagnostics have proven to be extremely useful measurement techniques in magnetically confined plasmas since the 1960s [1−4]. The Michelson interferometer and the heterodyne radiometer are two examples of the ECE measurement systems which are routinely used [5−10]. Both systems have remarkable advantages and will be adopted for the ECE measurements on ITER [11]. The Michelson interferometer has a very wide frequency coverage, and thus probes the full spectrum spanning multiple ECE harmonics. Furthermore, the Michelson interferometer is relatively simple to set up and maintain, and its hardware is very robust. Therefore, for example the interferometer is calibrated independently at DIII-D and JET, and allows the cross-calibration of an additional heterodyne radiometer system [8,10]. Besides the electron temperature information which is generally deduced from the spectral range of the second harmonic in extraordinary mode (X-mode) polarization, information about the electron density, the electron velocity distribution and wall reflectivity can be inferred from an entire ECE spectrum [12−14].

A few ECE measurement systems have been commissioned on the experimental advanced superconducting tokamak (EAST): two radiometers [15−17] and a grating polychromator [18]. In order to improve the capability of the ECE measurements at EAST, one of JET’s Michelson interferometers has been relocated to EAST in 2012 under a loan agreement. This Michelson interferometer has been refurbished, commissioned, calibrated and used throughout the recent campaign at EAST. This paper is organized as follows: Section 2 introduces the hardware of the interferometer, the laboratory characterization and the in-situ absolute intensity calibration. First results for temperature profile measurements at EAST are presented in section 3. Section 4 contains the discussion.

2 Diagnostic system

For the EAST campaign in 2014, there are two ECE measurement systems in operation: a 32-channel heterodyne radiometer [16,17] and a Michelson interferometer.

This Michelson interferometer was originally

∗supported by National Natural Science Foundation of China (Nos. 11405211, 11275233), and the National Magnetic Confinement Fusion Science Program of China (Nos. 2013GB106002, 2015GB101000), and the RCUK Energy Programme (No. EP/I501045), partly supported by the JSPS-NRF-NSFC A3 Foresight Program in the Field of Plasma Physics (NSFC: No. 11261140328)
developed by SPECAC [3] in the 1980s for ECE measurements in magnetically confined plasmas. This system, formally located at JET, has been refurbished and tested before it was relocated and installed at EAST.

The diagnostic probes the ECE spectrum in X-mode polarization. The basic components of the diagnostic are the quasi-optical antenna, the transmission line and the interferometer in the diagnostic room.

2.1 Quasi-optical antenna and transmission line

Three quasi-optical reflectors, an elliptical mirror and two flat mirrors, form the antenna (see Fig. 1). The antenna is located on the low magnetic field side, and the line of sight is along the major radius of the torus. The ellipsoidal mirror can be rotated for facing either the plasma or a hot source facilitated for online calibration. The ellipsoidal mirror is placed 2 m away from the plasma centre, and the distance to the waveguide is 1 m. This mirror has an effective focal length of 900 mm and forms a Gaussian beam along the line of sight inside the vacuum vessel. For example, the beam width is roughly 4 cm for the frequency 130 GHz which corresponds to the second harmonic of the electron cyclotron frequency at the plasma centre for the toroidal magnetic field of 2.3 T. A wire grid is placed between the high density polyethylene (HDPE) window and the waveguide to select the X-mode polarization.

The online calibration hot source shown in Fig. 1 was designed and fabricated by the Institute for Fusion Studies (IFS), the University of Texas at Austin. This source was fabricated using a different method from the one used in the calibration described in this paper (see section 2.3), and it needs to operate in vacuum. This kind of source is proposed to be a candidate for ITER ECE calibration [19,20]. The design and the spectral characterization of this source as its usage during the online calibration will be presented in an independent paper.

Low-loss corrugated waveguides (as low as 0.05 dB per 100 m) [21] with inner diameter of 63.5 mm are used for constructing the transmission line. Roughly, the total length of the transmission line is 45 m having 8 miter bends (the mode in this kind of waveguide is HE_{11}). In the laboratory, the transmission line houses a power divider (wire grid) with variable splitting ratio to feed the interferometer and the radiometer [16,17].

2.2 Michelson interferometer

This diagnostic is a Martin-Puplett type interferometer with two inputs and two outputs, and the schematic is illustrated in Fig. 2. In our case, to the input 1 the emission from the plasma or calibration sources is fed, and a microwave absorber at ambient temperature is placed at the input 2. At the moment, output 1 is recorded with a detection unit composed of a detector, a pre-amplifier, a post-amplifier and the data acquisition (DAQ) system. The scanning mirror is driven by a motor system, and an air bearing reduces the friction. Throughout the EAST campaign in 2014, the mirror moved at a frequency of roughly 15 Hz which determines the temporal resolution of roughly 33 ms.

Fig.1 Quasi-optical antenna for the horizontal ECE measurement on EAST
where \( G \) and \( S \) are expressed as \( \tilde{\nu} \) is the gain of the post-detection electronics, and \( I \) is the sensitivity of the interferometer. The equation with removed part of Eq. (2) is independent of the OPD, and it is DC, and it is removed by the amplifiers. The equation with removed DC is one-half of a cosine Fourier transform pair, and the other is

\[
B(\tilde{\nu}) = \int V(\delta) \cos(2\pi \tilde{\nu} \delta) d\delta, \tag{3}
\]

which is the basic principle of a Michelson interferometer. To be noted is that the deduced spectral quantity \( B(\tilde{\nu}) \) is attributed to the intensity difference of the two inputs.

### 2.2.2 Detector and electronics system

At the moment the diagnostic has one detection channel connected to output 1 (see Fig. 2). The channel comprises a fast InSb Liquid Helium cooled detector and an associated electronics system which includes a pre-amplifier and a post-amplifier. Table 1 lists the technical specifications of the amplifier electronics. The gain setting for the pre-amplifier is fixed at 40 dB (×100). The post-amplifier gain is set to be 62 dB for the \textit{in-situ} calibration, and it varies for the plasma measurements depending on the plasma parameters.

### 2.2.3 Data acquisition system

The specifications of this Michelson interferometer are listed in Table 2. The frequency coverage ranging from 80 GHz to 350 GHz is determined by the sampling OPD increment \( \Delta x = 40 \mu \text{m} \) of the interferogram and is limited by the diagnostic calibration (see section 2.3). The spectral resolution 2.7 GHz depends on the maximum OPD of roughly 86.5 mm. The temporal resolution determined by the scan rate of the scanning mirror, is roughly 33 ms.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum OPD:</td>
<td>86.5 mm</td>
</tr>
<tr>
<td>Scan rate:</td>
<td>15 Hz</td>
</tr>
<tr>
<td>OPD increment ( \Delta x ):</td>
<td>40 \mu m</td>
</tr>
<tr>
<td>Frequency coverage:</td>
<td>80–350 GHz</td>
</tr>
<tr>
<td>Spectral resolution:</td>
<td>2.7 GHz</td>
</tr>
</tbody>
</table>

### 2.3 Characterization and calibration

#### 2.3.1 Characterization

The Michelson interferometer has been fully characterized in laboratory conditions. The linearity of the detector and electronics system is extremely important because the gain settings of the post-amplifier are different for the \textit{in-situ} calibration (62 dB) and the plasma measurements (a few dB). A
linearity test for a fixed gain setting was performed by using a monochromatic source (Gunn oscillator at the frequency of 138.5 GHz) and an adjustable attenuator both placed in front of the detector unit. Considering the frequency response of the electronics, a chopper is adopted and placed between the source and the detector unit. The result for the linearity test is shown in Fig. 3.

![Fig.3 Linearity test result for the detection unit (detector, pre- and post-amplifier)](image)

The gain of the post-amplifier is measured by fixing the input intensity. The measured gains are defined as the output divided by the input (same as the output for the gain of 0 dB) of the post-amplifier. The measured gains agree with the expected values very well, and the difference is within 1%. The linearity of the detector and electronics system is confirmed by this measurement together with the linearity test for a fixed gain setting.

The spectral resolution is verified with a measurement for a monochromatic source, and determined to be about 2.7 GHz. This test also indicates a very good agreement between the frequency of the source and the measured centre frequency of the main peak of the inverse Fourier transform of the interferogram data.

The long-term stability is monitored by recording the interferograms obtained by placing the calibration hot source (see section 2.3.2) in front of the in-lab antenna day by day for a week. The variation of the spectra is within a few percent.

### 2.3.2 In-situ calibration

In order to provide an independent measurement of the electron temperature profile, the Michelson interferometer needs to be calibrated absolutely. In-situ calibration is performed to calibrate the whole diagnostic system including the quasi-optics, the window, the transmission line, and the Michelson interferometer. The hot/cold load method is adopted, and the calibration procedure will be briefly described here. The calibration procedure and the data analysis applied have been described in a detailed way in Ref. [10].

The cold source, which is assumed to behave like an ideal blackbody radiator, is made of the microwave absorber Thomas-Keating (TK) tiles [24]. This source is at ambient temperature (roughly \( T_{\text{cold}} = 313 \) K). The hot source used is one of JET’s ECE calibration sources. This source is electrically heated and controlled such that its surface temperature is held at 873 K. The emissivity of the hot source has been characterized by comparing its spectrum with the spectra emitted by the TK tiles at room and LN2 temperature, and it is roughly 0.84 in the frequency range of our interests.

The interferograms of the hot load and the cold load are measured alternately. In total, 14 cycles are completed for the calibration. In order to improve the signal-to-noise ratio (SNR), individual interferograms for each load are acquired for 10 min continuously and processed later. Besides the amplified detector signal, the reference signal is acquired simultaneously. Both signals are shown in Fig. 4(a) for some mirror scans. Individual interferograms (roughly 9000 pairs interferograms) are averaged coherently guaranteed by the recorded reference signal. Two averaged interferograms are obtained separately for the forward and backward scanning direction of the mirror. An averaged interferogram for the hot source is shown in Fig. 4(b), and that for the cold source is given in Fig. 4(c) together with the difference interferogram. The averaged interferogram for the hot load has a maximum-minimum difference of 335 mV around the ZPD. The noise for the individual interferograms is described by the standard deviation 62 mV (see Fig. 4(a)), and it is around 1 mV for the averaged interferogram. Therefore, the SNR for the individual interferograms is about 5.4:1 around the ZPD position and is increased by the averaging to around 335:1. Comparing with the results for JET given in Ref. [10], the SNR is improved (see Fig. 4(b)) and it is believed that this is attributed to the lower transmission loss on EAST. Then, the difference spectrum shown in Fig. 4(d) is recovered from this difference interferogram following the same procedure described in Ref. [10].

Starting from Eq. (3) we define the calibration factor for a given frequency by

\[
C(\nu) = \frac{\Delta B(\nu)_{\text{hot,cold}}}{\Delta T_{\text{hot,cold}}} G_{\text{calibration}}^{-1}
\]

\[
= \frac{FT_{\text{hot,cold}}^{-1}(V_{\text{hot}} - V_{\text{cold}})}{\Delta T_{\text{hot,cold}}} G_{\text{calibration}}^{-1}
\]

\[
(4)
\]

where \( FT_{\text{cos}}^{-1} \) represents the cosine Fourier transform, \( T_{\text{hot}} \) is the physical temperature of the hot source corrected by its emissivity, and \( G_{\text{calibration}} \) states the gain. Accordingly, for plasma measurements the radiation temperature is recovered by

\[
T_{\text{rad}} = \frac{B(\nu)_{\text{plasma}}}{C(\nu) G_{\text{plasma}}} G_{\text{calibration}}^{-1}
\]

\[
(5)
\]

where \( G_{\text{plasma}} \) marks the gain settings chosen. Here, since \( I_{\text{IT}} \gg I_{\text{IR}} \) holds for probing the plasma (see Eq. (1)), the contribution of the second input is neglected.
Fig. 4 Data analysis procedure for the in-situ calibration. (a) The individual interferograms and the reference signal over the time scale of a few periods, (b) The averaged interferogram for a continuous 10 min measurement of the hot source at 873 K, (c) The averaged interferogram for the cold source at ambient temperature (313 K) and the difference interferogram, (d) The difference spectrum $\Delta B(\tilde{\nu})_{\text{hot,cold}}$ for the difference interferogram in (c).

The calibration factors dependent on frequency are given in Fig. 5 together with their uncertainties which are estimated from the standard deviations of the recovered difference spectra. The diagnostic sensitivity rises in the frequency range of 60–200 GHz and has a plateau from 300 GHz which is attributed to transmission losses due to Bragg scattering [21]. As the results show, the relative uncertainty is around 5% in the frequency range 100–350 GHz which is adequate for probing the second and third harmonic range of the ECE spectrum at EAST. Below 80 GHz the relative uncertainty increases to about 15%.

3 Plasma measurements

3.1 Commissioning for the plasma operation

The Michelson interferometer has been calibrated absolutely before the EAST campaign in 2014. During this campaign the interferometer has been commissioned such that interferogram data are acquired automatically for a pulse. After initializing the settings, the software will acquire the pulse number and the envisaged pulse duration sent by the plasma control system (PCS). Subsequently, a DAQ task is created and the motor which drives the scanning mirror is started. The data acquisition is triggered by a TTL pulse sent by the PCS 0.5 s before the plasma start-up, and stops when the acquisition duration has reached the pulse length. Afterwards, the DAQ task is cleared and the motor is stopped, and the software waits for the next discharge. For the plasma operation, the amplified signal of output 1 and the reference signal are acquired simultaneously.

3.2 Derivation of the electron temperature profile

The Ohmic pulse #46542 ($B_0$: 1.8 T @ 1.85 m) is chosen to demonstrate the derivation of the electron temperature profile. Fig. 6(a)–(c) illustrate...
the temporal evolution of some plasma parameters: the plasma current, the line averaged electron density measured by a HCN interferometer [25], and the electron temperature around the major radius 1.77 m measured by a heterodyne radiometer [16,17]. At the beginning of the pulse (t < 0.2 s), the lower hybrid wave heating (LHW) of roughly 200 kW is adopted for pre-ionization. This heating scheme results in high radiative temperatures (> 3 keV), i.e., intensities in the microwave range indicated by the saturated radiometer output. The Fig. 6(d) shows the waveforms of the interferograms measured by the Michelson interferometer. The behaviour of the interferograms’ baseline at the beginning is influenced by the LHW as well.

![Fig.6 Waveforms for an Ohmic discharge (Pulse number: #46542) in 2014 EAST campaign. (a) Plasma current, (b) Line averaged electron density (HCN interferometer), (c) Electron temperature (heterodyne radiometer), (d) Interferograms (Michelson interferometer)](image)

3.3 Comparison with results of other diagnostics

In general, good agreement of the electron temperature profiles from the Michelson interferometer and an independent calibrated heterodyne radiometer has been achieved. A detailed comparison is given in Ref. [17], and the deviation is around 15%. Fig. 8 shows the comparison of the electron temperature profiles measured by the Michelson interferometer and the Thomson scattering (TS) diagnostic [26] for an ICRF heated pulse (#48272, B\textsubscript{t}: 2.25 T @ 1.85 m, I\textsubscript{p}: 400 kA, n\textsubscript{e}: \(2.5 \times 10^{19} \text{ cm}^{-3}\)). The line of sight for TS is along a vertical chord, and the normalized effective radius \(\rho\) (\(\rho = \sqrt{\psi_N}\), where \(\psi_N\) is normalized toroidal flux) is used. Within the diagnostic uncertainties the profiles have a similar shape. However, the TS profile is systematically higher than the interferometer one. The difference is smaller than 15% for \(\rho < 0.7\), but considerably higher (~40%) at the plasma edge. In addition to the intrinsic difference of the diagnostic principle, the flux surface mapping (Equilibrium reconstruction with constraint of magnetic measurements (EFIT) is adopted in this paper) can contribute to the discrepancy as well. The optical thickness of the second harmonic ECE at \(\rho = 0.8\) is estimated to be around 1, and this may have a contribution to the discrepancy at the plasma edge. Systematic comparison between electron temperature profiles from TS and ECE diagnostics will be presented elsewhere, and it is out of the scope of this paper.
Comparison of the electron temperature profiles measured by the Michelson interferometer and the TS diagnostic ($\rho = \sqrt{\psi N}$, where $\psi N$ is normalized toroidal flux). The profiles are for an ICRF heated pulse (#48272) at two time slices (Ohmic phase at 3.06 s, and ICRF phase at 3.46 s). The dotted lines are indicating the error bar of the profiles measured by the Michelson interferometer.

4 Discussion

A Michelson interferometer loaned from JET has been refurbished and commissioned on EAST in 2014 for the ECE measurements in the frequency range of 80–350 GHz. The system has been fully characterized in the laboratory. The linearity of the detector unit was verified, and the gain of the post-amplifier was measured. The in-situ absolute intensity calibration was carried out for providing an independent electron temperature profile measurement. The SNR is better than at JET because of the lossless corrugated waveguide adopted at EAST. For the frequency range of our interests, the calibration uncertainty is around 5%. The determined profiles are compared with those measured by the Thomson scattering diagnostic, and the agreement is fairly good.

Acknowledgments

One of the authors (Y. Liu) would like to express his thanks to Dr. Alan Costley, designer of this Michelson Interferometer, for introducing him to the interferometer world. Y. Liu also would like to thank Dr. Elena de la Luna for organizing the loan agreement and many fruitful discussions on ECE measurements.

References

22. APE 371 by HEIDENHAIN, http://www.heidenhain.de/
24. Tesselating Terahertz RAM radar absorbing material by Thomas Keating Ltd., http://www.terahertz.co.uk/

(Manuscript received 19 January 2016)
(Manuscript accepted 9 May 2016)
E-mail address of corresponding author ZHAO Hailin: zhaohailin@ipp.ac.cn