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# Electron Cyclotron Emission Measurements on JET: Michelson Interferometer, New Absolute Calibration and Determination of Electron Temperature

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*\* See annex of F. Romanelli et al, "Overview of JET Results",  
(23rd IAEA Fusion Energy Conference, Daejeon, Republic of Korea (2010)).*



## ABSTRACT

At the fusion experiment JET, a Michelson interferometer is used to measure the spectrum of the electron cyclotron emission in the spectral range 70-500GHz. The interferometer is absolutely calibrated using the hot/cold technique and, in consequence, the spatial profile of the plasma electron temperature is determined from the measurements. The current state of the interferometer hardware, the calibration set-up and the analysis technique for calibration and plasma operation are described. A new, full-system, absolute calibration employing continuous data acquisition has been performed recently and the calibration method and results are presented. The noise level in the measurement is very low and as a result the electron cyclotron emission spectrum and thus the spatial profile of the electron temperature are determined to within 5% and in the most relevant region to within 2%. The new calibration shows that the absolute response of the system has decreased by about 15% compared to that measured previously and possible reasons for this change are presented. Temperature profiles measured with the Michelson interferometer are compared with profiles measured independently using Thomson scattering diagnostics, which have also been recently refurbished and recalibrated, and agreement within experimental uncertainties is obtained.

## 1. INTRODUCTION

A Michelson interferometer diagnostic is capable of measuring broad band intensity spectra in the microwave and near infrared spectral range [1]. Therefore, the Michelson interferometer is dedicated to probe the full electron cyclotron emission (ECE) spectrum emitted by high-temperature plasmas in fusion experiments with magnetic confinement [2–4]. At the JET tokamak, the Michelson interferometer, designed and built in the early 1980s [5–7], operates to the present day as the cornerstone of the ECE diagnostic system. Justified by its absolute calibration using the hot/cold technique the interferometer delivers information about the electron temperature  $T_e$  independent of the Thomson scattering diagnostics [8–10]. The JET plasma is probed from the low magnetic field side, and the vacuum line of sight is perpendicular to the magnetic field. Most JET plasmas have a high optical thickness [11], i.e. above 3, for the second harmonic range in extraordinary mode (X2) polarization, which is therefore used to extract information about  $T_e$ . The Michelson interferometer with low spectral ( $\Delta f = 3.66\text{GHz}$ ) and temporal resolution ( $\Delta t \approx 17\text{ms}$ ) is complemented by a heterodyne radiometer ( $\Delta f = 0.25\text{GHz}$ ,  $\Delta t \geq 5\text{s}$ ) [12]. The radiometer probes the ECE subspectrum in ordinary (O) and extraordinary (X) mode polarization for the magnetic field range 1.7-4T. This flexibility requires the cross-calibration against the Michelson interferometer for each pulse [13]. In some cases the pedestal region of  $T_e$  can be probed on the in- and outboard sides simultaneously [14]. Hence, the necessity of the Michelson interferometer for the ECE diagnostic system at JET becomes clear: it is the basis for the independent determination of the absolute value of the electron temperatures by all the JET ECE diagnostics. In addition, the diagnostic is highly reliable because of its basic design and, if necessary, it can be maintained during plasma operation.

In addition to the standard application for the measurement of the  $T_e$  profile other diagnostic applications are possible. Since different harmonics have an individual dependence on plasma

parameters and the line of sight, the Michelson interferometer can reveal information about the magnetic field, wall properties of the vacuum vessel, and the electron distribution function  $f_e$  parameterized to first order by  $T_e$  and  $n_e$ . For example, choosing an oblique line of sight, electrons are probed which are located in different regions of the velocity phase space, and thus non-Maxwellian features can be studied. At JET such a diagnostic is installed and was recently independently calibrated [15,16]. Furthermore, the diagnostic potential allows the extraction of information about  $n_e$  from the optically thin part of the ECE spectrum, i.e. the broad spectral range for the 3rd and/or higher harmonics. The proof of principle [17] relies on ECE-tracing codes such as SPECE [18] and the Minerva Bayesian inference framework [19]. However, the reliability of the wider diagnostic application, including the testing of the plasma and wall model, depends strongly on the quality of the absolute calibration as does the determination of the  $T_e$  profile. A full system calibration was carried out in 2007. The measured system response was found to be different from that measured previously by about 25% [20]. Such a large change had not been measured before. Subsequent investigations indicate that the 2007 calibration suffered from several practical difficulties possibly including insufficient filling of the antenna pattern with the hot and cold sources mounted in the vacuum vessel. Therefore a new full system calibration was carried out in 2010 and measures were taken to overcome the earlier difficulties.

Despite the long operation time of the interferometer the diagnostic has not been described in detail from hardware and data analysis point of view. Thus, this paper starts with the comprehensive description for the diagnostic design (Sec. II) including the segments for the antenna, transmission line and interferometer back end. It presents the details of the 2010 absolute calibration and the hardware and the analysis technique employed (Sec. III and Sec. IV). Furthermore, the potential sources of systematic errors in the measurement are discussed and their possible magnitude estimated. Comparisons with  $T_e$  profiles measured with the refurbished Thomson scattering systems are included. Conclusions are drawn in Sec. V. For completeness, the general derivation of the calibration factors and their application to obtain the ECE spectrum for plasma operation are given in Appendix A.

## 2. DIAGNOSTIC DESIGN

The Michelson interferometer diagnostic at JET consists of three major segments: antennas, transmission line and back end (see Fig.1). The latter is located in the JET diagnostic hall. The in-vessel antenna is used with the associated transmission line for probing the plasma and absolute calibration. For measurements in the diagnostic hall, i.e. local measurements, for example to characterize a source spectrally, the local antenna with short transmission line is employed. The main elements of the back end are the interferometer unit, the bolometer detector, the post detection amplifier and the data acquisition system. Detailed descriptions of the different parts of the diagnostic follow. These summarize the information in [5–7, 21–29] and complete the diagnostic description by presenting additional facts.

### ***A. ANTENNAS AND TRANSMISSION LINE***

The aperture of the in-vessel antenna is located at the major radius  $R=4.126\text{m}$  and height  $z=0.353\text{m}$  (see component 1 in Fig. 2(a)) in octant 7 of the JET torus. The horizontal line of sight is at  $3.5^\circ$  with respect to the radial direction. The antenna with the length of  $1.6\text{m}$  incorporates in the middle one mitre bend at  $30^\circ$  and is manufactured from Inconel to withstand the temperature variation between ambient temperature and some hundreds Celsius. The rectangular antenna cross-section decreases from  $50\times 65\text{mm}$  at the plasma end to  $40\text{mm}\times 30\text{mm}$  at the inner JET wall. For the TE<sub>10</sub> mode the antenna pattern is characterized theoretically and experimentally by the acceptance angle of about  $3^\circ$  in the spectral range  $100\text{-}130\text{GHz}$  [21, 22].

The antenna ends at the double window with diameter  $68\text{ mm}$ . The window is secured with a high temperature vacuum seal and is made from two wedged disks of Z-cut crystal quartz. Outside the vessel the transmission line is about  $40\text{ m}$  long, which is filled entirely with air including water vapour, and comprises 12 mitre bends (4 in E plane, 8 in H plane) ending at the back end in the diagnostic hall. The attenuation of the transmission line as determined in 2010 drops from  $-10\text{dB}$  at  $100\text{GHz}$  to  $-21\text{dB}$  at  $500\text{GHz}$  (see Fig.2(b)). Immediately after the vacuum window the horizontal waveguide with crosssection  $40\times 30\text{mm}$  carries the grid with horizontal wires to transmit waves in X-mode polarization (see component 2 in Fig.2(a)). Close to the polarizer the waveguide falls vertically after the first two mitre bends and is connected to the TE<sub>10</sub> mode filter [22] with the length of  $2\text{m}$  shown by component 3 in Fig.2(a). From the filter output onwards the S band waveguide ( $72\times 34\text{mm}$ ) is used in tall mode, meaning that the E field vector of the wave is parallel to the long side of the waveguide, up to the diagnostic hall. Close to the inner wall of the torus hall the transmission line has an air gap of  $1\text{ cm}$  in length to insulate the waveguide electrically from the JET vessel. In the diagnostic hall the waveguide tapers to the rectangular cross-section  $40\times 30\text{ mm}$  along a length of  $1.20\text{m}$  (see component 2 in Fig.3). The last bend connects the vertical waveguide with the horizontal input port of the interferometer. A removable aluminium plate constitutes the last bend, and so when this switch (S1 in Fig.1 and Fig.3) is removed the horizontal part of the antenna is connected to the interferometer input port. This antenna is a waveguide of  $0.8\text{ m}$  in length with cross-section  $40\text{ mm} \times 30\text{ mm}$ . The antenna aperture points downwards via a mitre bend  $15\text{ cm}$  before the end.

### ***B. MICHELSON INTERFEROMETER***

The Martin-Puplett interferometer (see Fig.3) is sensitive to the difference in the source spectra held by its two input ports. Thereby, just one of the output ports is used for signal detection. The interferometer uses wire grids with the wire diameter  $10\text{m}$  and spacing  $25\text{m}$ . The first input port holds the permanent source made from ECCOSORB AN-72 [31] at ambient temperature. The second one holds the rectangular waveguide connected to the in-vessel or the local antenna. Behind the first grid the vertical and horizontal electric field carries the information of the permanent source and the one to be probed, i.e. the plasma or any locally placed source, respectively. The beam splitter transmits and reflects the same fraction for both polarizations. Therefore, its wires rising with the

angle  $33^\circ$  appear at  $45^\circ$  when the filter is rotated by  $45^\circ$  with respect to its central vertical axis. Each partial beam enters a separate arm holding a roof top mirror with aperture angle of  $90^\circ$ . By the double reflection at the mirror the beam polarization direction flips by  $90^\circ$ . Hence, each returning beam is affected in the opposite way by the splitter resulting in the reunification of the partial beams. After passing the last grid with horizontal wire orientation a lens made from Polymethylpentene (TPX) [32] with focal length of 15cm is used. The beam is focused into the aperture of the circular waveguide with diameter 25mm and length 0.5m. The circular waveguide ends at the entrance window of the cryogenic vessel holding the bolometer detector. During plasma operation an attenuating grid is inserted between the lens and the circular waveguide. As a consequence the power incident on the detector reduces by approximately 5dB, and the range for the linear detector response is extended. The grid with diagonal wire direction is placed almost perpendicular to the optical axis.

In the interferometer arms the change in the optical path difference between the partial beams is achieved by the direct movement of one roof top mirror. The mirror translator is connected to the shaker by a thin silver steel rod (see component 12 in Fig. 3) with 1mm in diameter at the ends tapering to 250 $\mu$ m in the middle section and 30 mm in length. The rod is introduced to break if the stress on the moving parts is increasing. The shaker oscillates with the frequency 30Hz. Its peak-to-peak amplitude is about 16.3mm covering mainly the single-sided interferogram region.

The corresponding maximum optical path difference achieved is about 27mm. The air-bearing stage (not shown) ensures the linear movement of the gliding mirror translator and reduces friction.

### ***C. BOLOMETER DETECTOR AND AMPLIFIER***

The semiconductor Indium Antimonide bolometer detector<sup>25,26</sup> is designed to operate at the ambient temperature of liquid Helium (4.2 K). Therefore, the back of the detector is attached to a reservoir of liquid Helium (6.5 l) in the centre of a cylindrical cryogenic vessel [25] (not shown). In addition, a vacuum chamber and a reservoir with liquid Nitrogen (6.5 l) surround the vessel centre for insulation from the laboratory environment.

The radiation leaving the circular waveguide (see Sec. II B) passes through a window embedded in the cryogenic vessel. Inside the vessel the Winston cone [33] with aperture diameter 26mm concentrates the radiation along 42 mm to its exit with diameter 6.5mm where the bolometer detector is located. At the window Fluorogold foil is placed to limit the spectral range to about 1.0THz [26] which can enter the vessel.

At 4.2 K the detector absorbs incident photons which increases the conductivity (hot electron effect). The corresponding voltage change across the detector, i.e. the output voltage, is measured. For operation a bias current needs to be applied to the detector, the magnitude of which affects the detector sensitivity. To minimize electrical noise, the bias current of about 60 $\mu$ A is provided by rechargeable long-life batteries (10V) via a high resistance ( $\approx$ 164 k $\Omega$ ) acting as a constant current source. The detector sensitivity provided by the supplier exceeds 500V/W and 1000V/W for the spectral ranges 60-1000GHz and 100-250GHz, respectively. The detector has a recovery time of

1s and the noise-equivalent power (n.e.p.) of  $2 \times 10^{-12}$  W/Hz<sup>0.5</sup> for the first amplifier stage with bandwidth 600kHz and fixed amplification of 40 dBV. For the second stage the bandwidth is set to 30kHz realized by a first order resistor-capacitor filter, and the amplification used is 14dBV and 50dBV for plasma and calibration operation, respectively. For radiation up to 1THz, which marks the cut-off frequency of the Fluorogold foil, the Fourier components of the detector signal are all below 10kHz. This value is sufficiently exceeded by the chosen cut-off frequency (30kHz) of the second amplifier ensuring that the induced phase shift is insignificant. The linearity of the detector response including the amplifier stage has been confirmed [23].

The rapid reciprocating motion of the roof-top mirror can induce vibrations in the interferometer supporting structure and these, in turn, can produce vibrations of the detector. Since the detector is microphonic at a low level, decoupling of the interferometer unit and the detector is necessary. This is achieved by using separate metal frames.

#### ***D. DATA ACQUISITION***

The acquisition of the detector output voltage (see Sec.IIC) synchronized with the optical path difference (see Sec.IIB) is essential for achieving an accurate spectrum by processing the interferogram data. Since the mirror position and thus the optical path difference change sinusoidally with time, the sampling at a fixed frequency deforms the acquired interferogram. Therefore, an incremental linear encoder [34] is used to sample the interferogram equidistantly in the spatial domain. On top of the mirror translator a micrometer scale with an additional reference marker is fixed and probed by a scanning head (see components 10 and 11 in Fig.3). The encoder electronics generates individual transistor-transistor logic (TTL) signals, when the reference marker passes the optical head, which happens once per interferogram scan, and the direction of the mirror motion changes at the turning points. Furthermore, a TTL signal is available which encodes the spatial position of the mirror. The latter are used to trigger the data acquisition for the detector output voltage when the mirror moves by 10, 20, 40 or 80m depending on the chosen setting.

Historically, the data acquisition systems differ for plasma and calibration operation. For the former the spatial increment 80m is used corresponding to the average and maximum sampling frequency of about 11kHz and 17 kHz, respectively. The ADC with 12 bit resolution used since the 1980's covers the dynamical range of 10 V and has limited memory storage for 216 data words. For the spatial increment 80m, giving about 200 data words per interferogram, the memory fills up in 5.5s. Therefore, most interferograms must be omitted during a JET pulse with 30s duration which is handled by the diagnostic control program.

For calibration operation the situation changes completely. Since broad band sources are used with temperatures below 1000K, the signal-to-noise ratio (SNR) is low and the main interferogram located around the zero-path difference position is narrow. Hence, the interferogram is sampled with the spatial increment 20m determining the sampling frequency with the average and maximum value of about 44kHz and 70kHz, respectively. The SNR is increased by averaging individual interferograms coherently. Before 2010 diverse daq systems averaged the output voltage of the detector in real-time

for several minutes coherently. Thereby, the information about individual interferograms was lost and numerical instabilities could arise. On the contrary, the daq system applied for the calibration in 2010 stores all raw data to hard disc enabling post-measurement treatment. Thereby, the daq card [35] used has 16 bit ADC resolution and covers the dynamical range 10.5V. Due to the permanent storage, individual interferograms, which are corrupted by spikes possibly picked up from radio and mobile emission (see Fig.5(a)), can be identified and removed. Besides the detector output voltage, the TTL signal for the reference marker is acquired to check and therefore guarantee the coherent averaging procedure. To reduce the physical hard disc memory the ADC level is stored in binary format. The conversion to voltages is achieved using the coefficients for the fourth order polynomial specific for the daq card. Removing faulty interferograms, checking the interferogram coherence and converting the unitless raw data to voltage for a data file with 250MB, corresponding to measurements for 20 minutes, takes less than 30 seconds with the averaging software developed. For each data file the analysis results in two averaged interferograms one each for the forward and backward direction of the mirror motion. In addition, for each mirror position the standard deviation is stored. This feature allows the identification of the interferogram region which is averaged coherently.

Recently, a conversion factor was found between the daq systems used for plasma and calibration (2010) operation. Local and plasma measurements show that the daq system for plasma operation gives a signal which is reduced by about 2%. Probably, this conversion factor is present since the construction of the interferometer, and it is nowhere corrected.

Since the daq system used during the calibration session in 2010 has proven its reliability it is used for plasma operation from JET pulse 83144. Besides removing the conversion factor the temporal resolution (660Hz) of the diagnostic limited by the shaker frequency (see Sec. IIB) is achieved.

### ***E. DIAGNOSTIC PROTECTION***

The diagnostic design includes several aspects for protecting the diagnostic hardware. In general, a detected malfunction results in the interlock of the power supply for the shaker stopping the mirror movement which happens once a month or less. Causes for interlocking are the changing shaker characteristic, the breaking of the connector between shaker and mirror translator and the drop in air flow to the air bearing.

The shaker characteristic changes after several hours of running time, and thus the maximum amplitude and the centre of the sinusoidal movement for the mirror vary. To keep the movement in a well-defined range the air bearing supporting the mirror translator has a limiting micro switch at either side. The translator (see component 10 in Fig.3) has small arms one on each side which can activate the micro switch stopping the Michelson interferometer.

If the stress is increasing on the moving parts the steel rod (see component 12 in Fig.3) breaks causing the activation of the micro switches.

In case the pressure in the air bearing system falls below a threshold, which is set manually by an air flow indicator, the electronics recognizes a malfunction.

## ***F. MAINTENANCE***

During plasma operation little effort is needed for the diagnostic maintenance. The cryogenic vessel (see Sec.IIC) is refilled with liquid Helium in 20 minutes with two persons once every two weeks. The Michelson has been equipped with an automatic liquid Nitrogen (LN2) refilling system. The system operates between set points using a probe for the LN2 level and a meter system and takes around 15 minutes to refill the system from 30% to 100%. The 250 litre LN2 Dewar connected lasts for around 10 days. Since 2011 the bias voltage for the detector (see Sec. II C) is monitored on a daily/weekly basis. When the voltage drops to the 9V level the batteries are recharged for 12 hours during non-plasma operation time. The adaptation of the rod length, i.e. the distance between shaker and mirror extension, and/or the replacement takes 10 minutes and happens every some 10 hours of running time for the shaker. The replacement of the shaker after the running time of about 200 hours takes approximately 60 minutes. The main maintenance work is demanded by the preparation and execution of the absolute calibration which is described separately in the chapters 3 and 4 for the session in 2010. The absolute calibration is complemented by the relative calibration using JET pulses for which the magnetic field ramps down from 3.5T to 1.7 T [36]. The JET operation limits mean that two pulses are needed to perform the full ramp. These ramp pulses are carried out about once a year.

## **3. CALIBRATION SET-UP**

The absolute calibration of the Michelson interferometer at JET utilizes the hot/cold technique. The calibration sources are integrated in the stand-alone setup which is remotely controlled via the network. Due to JET radiation protection regulations the placement of the mounting structure together with both sources needs to be carried out by the remote handling system MASCOT [37]. Once the deployment is completed, the calibration set-up requires no additional auxiliary resources. The continuous operation of the set-up was achieved without malfunction for several days. Details about the stand-alone set-up are described below.

### ***A. COLD-SOURCE***

Typically for absolute emission measurements in the microwave range the cold-source is realized by a microwave absorber material at the temperature of LN2 (77K). However, because of safety considerations, the use of cryogenic fluids at JET is limited and so a material at ambient temperature with black body properties needs to be used. The microwave absorber material TK, which has black body properties from at least 100GHz upwards [38], meets the regulations for contamination hazards of the JET vessel and is therefore used. Individual TK tiles form the active surface with an area of about 17×20cm. The cold-source is attached to an aluminium plate of equal dimension (see Fig. 4 left). Between the tiles and the plate a thermocouple is mounted to measure the temperature.

### ***B. HOT-SOURCE***

The hot-source is a remote device electronically heated (see Fig.4 left). Its principal component is a copper plate, in which twelve cartridge heaters are inserted capable of heating the plate uniformly to

the physical temperature of 873K within about 40 minutes. The radiating surface is situated on top of the copper plate with an area of 20×20cm and has a moth-eye structure with a SiC grit suspended in an inorganic binder. The radiating plate is housed in an aluminium alloy box and insulated with a high temperature refractory board. The outer box has been designed specifically to aid remote handling by MASCOT within the JET torus. The control electronics are mounted on the rear of the outer box. The only connections are a 110 Volt power supply and a UTP Ethernet cable that connects the in-built web server to the local area network. Six mineral insulated thermocouples are embedded uniformly within the radiating screed. One central thermocouple is used to lock the plate temperature via the closed loop control of a PDI controller.

### ***C. SWITCHING BETWEEN SOURCES***

The periodical switching between the sources is achieved by the mechanical up/down movement of a vertical aluminium plate (see Fig.4 left) which carries the cold-source (see Sec. III A). A horizontal aluminium plate of length 830cm connects the switch and the outer box surrounding the hot-source. Switching between the sources is applied every 20 or 30 minutes, and the process itself takes less than 30s.

### ***D. MOUNTING STRUCTURE***

The mounting structure is designed to guarantee reproducibility for the localization of the sources with respect to the in-vessel diagnostic antenna. The positioning is realized by a plug inserted into another waveguide below the diagnostic antenna. The mounting structure carries the assemblage of the cold- and hot-source such that the diagnostic line of sight crosses the centre of both active surfaces (see Fig.4 right). The distance from the antenna aperture to the cold- and hot-source is less than 5cm and 33cm, respectively. After placing the mounting structure and the sources with MASCOT within three hours, no resources are needed for support.

### ***E. OVERALL CONTROL AND MONITORING PROGRAM***

During the absolute calibration the software developed with Labview@ controls the main parameters, automatizes all necessary steps and monitors the state of the set-up. After reaching the requested physical temperature for the hot-source, the initial shutter position is set. The acquisition starts to take data for the time interval specified by the user, in doing so the durations 20 and 30 minutes have been used. When the time interval has elapsed, the data acquisition stops and the switch moves. Afterwards the data acquisition starts for having the complementary source in place. This hot/cold cycle is repeated automatically. At the same time, online monitoring of the main parameters, i.e. the current physical temperatures of both sources and the switch position, is available describing the calibration set-up extensively. In addition, these parameters are stored on hard disc every five seconds. Throughout the calibration of four days the state of the stand-alone set-up was always defined and sufficiently steady. In total, about 600 Gigabyte of data for the interferogram and reference marker were continuously acquired.

#### 4. ANALYSIS TECHNIQUE

The absolute calibration of the Michelson interferometer at JET has been carried out since the 1980's by different diagnosticians each having its own approach. General information and specific details for each approach can be found in [39,40]. In the following the analysis technique of the calibration session in 2010 is described. The evaluation of the absolute calibration factors, and how they are used in the analysis during JET plasma operation, requires measured and/or derived quantities like the difference interferogram, recovered difference spectrum, difference input intensity and the grid transmission. After the definition of the calibration factors is given the detailed description for the derivation of each relevant quantity follows. In addition, the corresponding uncertainty for the quantity at hand is evaluated for the spectral domain expressed by the standard error of the mean. Therefore, the uncertainties of the calibration factors can be captured by Gaussian error propagation. All results presented rely on measurements carried out in 2010 with the Michelson interferometer to be calibrated and the continuous daq system including the post-measurement digital averaging technique (see Sec. II D). Each measurement reflects the integration time of several hours, at least. The necessary switching between different sources is realized every 20 or 30 minutes.

##### A. DEFINITION AND APPLICATION

A general derivation of the calibration factors including units can be found in the appendix A. For JET conditions a grid attenuator with transmission  $T$  is inserted during plasma operation (see component 8 in Fig.3). Therefore, the calibration factors  $C_f$  defined by equation (A5) need the modification

$$\begin{aligned} C_f &= A_C^{-1} \frac{PC (DFFT^{-1} \{g(V^{Hot} - V^{Cold})\})}{\Delta I} T \\ &= \frac{\Delta S}{\Delta I} T \end{aligned} \quad (1)$$

where the ratio of the recovered difference spectrum  $\Delta S$  to the difference input intensity  $\Delta I$  enters.  $\Delta S$  is evaluated using the post detection amplification  $A_C$ , the phase correction method  $PC$ , the inverse discrete fast Fourier transformation routine  $DFFT^{-1}$ , the apodization function  $g$  and the difference interferogram  $V^{Hot} - V^{Cold}$ . During plasma operation the amplification  $A_P$  is reduced with respect to  $A_C$  by some orders of magnitude. The linearity of the diagnostic sensitivity necessary to apply  $C_f$  to processed data measured during plasma operation has been confirmed [23]. The calibrated spectrum, i.e. the ECE spectrum, is evaluated by

$$I_{ECE} = A_P^{-1} \frac{PC (DFFT^{-1} \{g(V^{ECE})\})}{C_f} = \frac{S^{ECE}}{C_f} \quad (2)$$

from a measured interferogram  $V^{ECE}$  processed to give the recovered spectrum  $S^{ECE}$ . Thereby, the coherence between  $C_f$  and  $S^{ECE}$  is ensured by using the same implementation for  $PC$ ,  $DFFT^{-1}$  and  $g$  in equation (1) and (2).

## ***B. DIFFERENCE INTERFEROGRAM***

To increase the SNR the detector output voltage is amplified by the factor  $AC=104:5$ , stored permanently and averaged afterwards. Thereby, the stored raw data trace for 20 minutes (see Fig.5(a)) consists of about 35103 individual interferograms for each mirror direction. Occasionally, spurious signals in the range 10V perturb the measurements (see Fig.5(a)). Since in the worst case a single spike of 10V corrupts the measurements of 20 minutes, the averaging method rejects affected interferograms to ensure the data quality. Typically, at the zero-path difference (ZPD) position, at which all spectral components interfere constructively, the averaged interferogram has its maximum of about 6mV (see Fig.5(b) and Fig.5(c)) when the hot-source is in place. At the same time the noise at a fixed optical path length is described by the standard deviation 17.5mV (see Fig.5(b)). Therefore, the SNR is about 1:3 at the ZPD position and is increased by averaging for the duration of 20 minutes to 60:1. Note, at nodes where the interferogram vanishes the SNR is decreased by several orders of magnitude. The average of each raw data trace, i.e. the average interferogram  $V^{Cold}$  or  $V^{Hot}$ , represents the continuous interferogram by 724 samples in the optical path difference range from -2.54 mm to 26.38 mm. The interferograms  $V^{Cold}$  and  $V^{Hot}$  remain slightly noisy, and the asymmetry around the ZPD position is obvious (see Fig.5(c)). The latter feature reduces considerably for the difference interferogram  $V^{Hot} - V^{Cold}$  (see Fig.5(c)).

In total 208 difference interferograms are available corresponding to about 8.6106 individual interferograms and 3.4 days of integration duration per source (see Fig.5(d)). Thereby, subsequent interferograms  $V^{Cold}$  and  $V^{Hot}$  are used for the difference. The overall average for the difference interferogram  $\langle V^{Hot} - V^{Cold} \rangle$  (see Fig.5(d)) clearly shows structures for large optical path differences and a high degree of symmetry around the ZPD position. In addition, the reduction of the ratio of the noise level to the ADC resolution (0.325mV) to 1:35 is achieved.

## ***C. RECOVERED DIFFERENCE SPECTRUM***

The recovery of the difference spectrum  $\Delta S$  from the difference interferogram  $V^{Hot} - V^{Cold}$  uses standard techniques like apodization, zero-padding, discrete fast Fourier transformation and phase correction [41]. The corresponding processing is given in equation (1). Thereby, the apodization window function  $g$  is a linear ramp in the double-sided region ( $|x| \leq 2.54$  mm) and the first quarter period of a cosine function bringing the single-sided region ( $2.54 \text{ mm} < x < 26.38$  mm) smoothly to 0. Zero-padding above 26.38mm increases the spectral resolution from 5.68GHz to 3.66GHz.

Processing  $\langle V^{Hot} - V^{Cold} \rangle$  (see Fig.5(d)) gives the smooth recovered difference spectrum (see Fig.6(a) and (b)). Non-vanishing components are present in the spectral range 30-525GHz and 600-700GHz, and the maximum is located around 200GHz. The processing of the 208 individuals  $V^{Hot} - V^{Cold}$  (see Fig.5(d)) maps the uncertainties from the spatial to the spectral domain (see Fig.6(a) and (b)). The averages for both approaches coincide below 500GHz. The uncertainty  $\sigma_{\Delta S}$  in the spectral domain remains almost constant above 30GHz (see Fig. 6(c)) and, thus, is independent on the signal itself. Nevertheless, the relative uncertainty  $\sigma_{\Delta S} = \Delta S$  varies with frequency (see Fig.6(d)) and certifies the spectral range 50-500GHz for calibration. Furthermore, inside the range 100-

350GHz the relative uncertainty remains below 1%. Two peaks at 380.2GHz and 440GHz indicate the influence of water vapour absorption lines resulting in high uncertainties at these frequencies. The determination is not affected by the water vapour absorption line at 183.31GHz.

#### ***D. DIFFERENCE INPUT INTENSITY***

In order to derive the difference input intensity  $\Delta I = I_f^{\text{Hot}} - I_f^{\text{Cold}}$  the spectrum of each source, i.e.  $I_f^{\text{Cold}}$  for the cold-source (see Sec.III B) and  $I_f^{\text{Hot}}$  for the hot-source (see Sec.III C), needs to be characterized. Thereby, the spectrum is parameterized by the radiative temperature using the Rayleigh-Jeans law ( $I_f = (k_B/c^2)f^2 T_{\text{Rad}}$ ).

For the cold-source, realized by the microwave absorber material TK, the radiative temperature  $T_{\text{Rad}}^{\text{Cold}}$  equals the physical temperature  $T^{\text{Cold}}$ , which is measured by a thermocouple (Sec. III B) every five seconds during the absolute calibration. A periodical variation in  $T^{\text{Cold}}$  during the hot/cold-source cycles is present. For example,  $T^{\text{Cold}}$  rises from about 307K to 312K in 20 minutes, when the TK material is placed between the in-vessel antenna and the hot-source, and drops accordingly, when removed. For the complete calibration session  $T^{\text{Cold}}$  averages to 309.8K, and, in addition, the standard deviation  $\sigma_{T^{\text{Cold}}}$  reads 1.24K.

The hot-source is characterized at the physical temperature 873K by the hot/cold technique using the TK material at 77K (LN2) and at 296K (room temperature) as references. For the characterisation each source is placed in front of the local antenna (see Sec.II A) at the distance less than 15 cm, which is assumed to be close enough to fill the antenna pattern sufficiently. The determined radiation temperature  $T_{\text{Rad}}^{\text{Hot}}$  is smaller by about 100K with respect to its physical temperature in the spectral range 70-725GHz (see Fig.7(a) and (b)). Furthermore,  $T_{\text{Rad}}^{\text{Hot}}$  decays from 800K to 760K. The uncertainty  $\sigma_{T_{\text{Rad}}^{\text{Hot}}}$  is less than 3 K/6 K for 150-350GHz/100-500GHz (see Fig.7(c)). Since the corresponding relative uncertainty  $\sigma_{T_{\text{Rad}}^{\text{Hot}}}/T_{\text{Rad}}^{\text{Hot}}$  is less than 1% (see Fig.7(d)),  $T_{\text{Rad}}^{\text{Hot}}$  is determined with high precision for a broad spectral range. However, since somewhere below 100GHz the TK material loses its black body property,  $T_{\text{Rad}}^{\text{Hot}}$  suffers from a systematic error emphasised by the strong increase to 860K around 60GHz. Using the spectral characterisations described above, at the aperture of the in-vessel antenna the difference input intensity  $\Delta I$  is present (see Fig.7(e) and (f)). Due to the square law in frequency  $\Delta I$  covers two orders of magnitude for the spectral range 60-725GHz. Using Gaussian error propagation the relative uncertainty  $\sigma_{\Delta I}/\Delta I = \sqrt{\sigma_{T^{\text{Cold}}}^2 + \sigma_{T_{\text{Rad}}^{\text{Hot}}}^2}/(T^{\text{Hot}} - 309.8\text{K})$  becomes available (see Fig.7(c) and (d)). Compared with  $\sigma_{T_{\text{Rad}}^{\text{Hot}}}/T_{\text{Rad}}^{\text{Hot}}$  the ratio  $\sigma_{\Delta I}/\Delta I$  is increased by a factor two but is still below 1% above 110GHz. The absorption lines of water vapour at 556.94 GHz and 752.03GHz substantially restrict the derivation of  $\Delta I$  at these frequencies.

#### ***E. GRID TRANSMISSION***

The transmission of the attenuator grid inserted in the interferometer back end during plasma operation (see component 8 in Fig.3) is determined by local measurements using two broadband sources. For practical reasons the TK material at ambient temperature and liquid Nitrogen temperature is chosen. The interferograms are acquired for both sources with the grid (G) and without the grid (NoG) in

place. The ratio of the corresponding recovered difference spectra gives the grid transmission  $T = \Delta^{SG}/\Delta^{NoG}$ . In the spectral range 70-700GHz the transmission oscillates in the range 0.31-0.35 (see Fig.8(a) and (b)). By the uncertainty  $\sigma_T$  (see Fig.8(c)) and the relative uncertainty  $\sigma_T/T$  (see Fig.8(d))  $T$  is identified with high reliability in the spectral range 70-725GHz neglecting the intervals around water absorption lines at 556.94 GHz and 752.03GHz.

### F. CALIBRATION FACTORS

In general, equation (1) defines the calibration factors  $C_f$  using the recovered difference spectrum  $\Delta S$ , the difference input intensity  $\Delta I$  and the grid transmission  $T$  (see Sec. IV B-E). In the following the year of the derivation is used as upper index to distinguish different calibration factors sets. Since the relative uncertainty of  $C_f^{2010}$  evaluated by  $\sigma_C = C_f^{2010} = \sqrt{(\sigma_{\Delta S}/\Delta S)^2 + (\sigma_{\Delta I}/\Delta I)^2 + (\sigma_T/T)^2}$  remains below 10% (see Fig.9(c)), the spectral range 60-525GHz is qualified to be presented (see Fig.9(a)). Around 90 GHz  $C_f^{2010}$  has a maximum. Below 90GHz the sensitivity reduces strongly by about one order of magnitude over 30GHz as does the reliability. From 90GHz to 525GHz  $C_f^{2010}$  drops globally by more than one order of magnitude but shows locally minima and maxima pointing to resonances. The relative uncertainty is at the 1% level and increases from 350GHz onwards.

Compared with to the calibration factor set  $C_f^{1996}$  (see Fig. 9(a)), the spectral shape of  $C_f^{2010}$  is similar, especially for the second harmonic range 100-200GHz which is most important for the determination of the  $T_e$  profile at JET. However, on absolute scale the set  $C_f^{1996}$  exceeds  $C_f^{2010}$ . Thus, the diagnostic has become apparently less sensitive assuming that both sets have been determined correctly. This reduction can be found as well above 125GHz for the set  $C_f^{2007}$  ([20], see Fig. 9(a)). The ratio  $C_f^{1996}/C_f^{2010}$ , expressing the relative change for each spectral channel, reveals a general increase of the detected intensity and thus the radiation temperature by about 15% in the spectral range 100-200GHz (see Fig.9(b)). For the third harmonic range a stronger variation of  $C_f^{1996}/C_f^{2010}$  between 1.05 and 1.3 is present. Thus, the calibration in 2010 affects the spectral range of the 2nd and 3rd harmonic in different ways. The application of  $C_f^{2010}$  and  $C_f^{1996}$  to JET pulse data using equation (2) is shown in Fig.9 (d). Thereby, the intensity is presented in terms of radiation temperature  $TRade$ . The data chosen is recorded for a plasma with low magnetic field (Pulse No: 79777,  $t = 17.28s$ ,  $B_{vac} = 1.83T$ ,  $n_{e0} = 3 \times 10^{19} m^{-3}$ ) and high magnetic field (Pulse No: 79759,  $t = 14.04s$ ,  $B_{vac} = 3.42T$ ,  $n_{e0} = 7 \times 10^{19} m^{-3}$ ). For both cases the ratio of the 2nd (at 100GHz and 190GHz) to the 3rd harmonic remains at the same level for the plasma centre. For the high field case, the wiggly structure is removed in the spectral range 275-350GHz within the uncertainties by using  $C_f^{2010}$ . In addition, the 4th harmonic is available above 350GHz. However, the high frequency range suffers from the influence of the water absorption lines.

### G. DISCUSSION

The difference between the two calibration sets,  $C_f^{1996}$  and  $C_f^{2010}$ , is about 15% on the absolute level showing a reduced sensitivity for the latter. Therefore, the application of the sets to the same uncalibrated plasma spectra results directly in an increase of the  $T_e$  values of that order. Unfortunately,

the change in the sensitivity of the instrument cannot be resolved temporally, since no sessions at the absolute calibration have been performed between 1996 and 2007. The latter delivered the calibration set  $C_f^{2007}$  (see Fig.9 (a)), which was also reduced with respect to  $C_f^{1996}$  above 125GHz but in this case by approximately 25% [20]. However, it is likely that  $C_f^{2007}$  suffered from problems like uncertain placing of the calibration sources in front of the in-vessel antenna, insufficient integration time and interferogram data superimposed with spurious signals as revealed by the approach for the session in 2010 (see Fig.5(a)). Nevertheless, an apparent considerable change in the system response as first indicated by the calibration measurements in 2007 has been confirmed by the calibration in 2010 although to a lesser extent. As a consequence the data taken by the Michelson interferometer and the heterodyne radiometer have been reprocessed from the JET campaign C20, which started in 2008, using  $C_f^{2010}$ .

The determination of the spectral variation of  $C_f^{2010}$  is very precise in the main spectral range 100-350GHz due to the low level of noise in the measurement (see Fig. 9(c)). However, the accuracy of the absolute level of  $C_f^{2010}$  could suffer from the influence of systematic errors. The potential causes of systematic errors are listed below and whenever possible an estimate of their magnitude and a strategy for a further investigation are given.

- i) Amplifier setting: The ratio  $C_f^{1996}/C_f^{2010}$  (see Fig.9(a)), which is around 1.15 except for minor spectral regions, suggests that if a systematic error is the cause of the difference, then it must affect all spectral channels equally. Such an effect can be caused by the amplifier setting. Since the setting increment is constant at 2dBV (26%), a wrongly noted amplification seems unlikely.
- ii) Bias voltage: The detector sensitivity is dependent on its bias voltage  $V_{Bias}$  supplied by batteries. Local measurements show that the sensitivity has a maximum around  $V_{Bias} = 7$  V for all spectral components. The corresponding increase in sensitivity is  $\sim 7\%$  compared to  $V_{Bias} = 10$  V which was used during the session in 2010. The decrease in the sensitivity by about 15% is possible if  $V_{Bias}$  is set to less than 4 V, which is eliminated for the calibration session in 2010. Furthermore,  $V_{Bias}$  needs to be held at the same level, which is 10 V, for plasma and calibration operation. Therefore, since 2011  $V_{Bias}$  is monitored, and if mandatory the batteries are recharged.
- iii) Linearity of diagnostic sensitivity: The application of  $C_f^{2010}$  in the equation (A2) to analyse plasma data is justified if the diagnostic response remains linear even for input signals which are some orders of magnitude larger than those during calibration. Subsequent to the calibration a full linearity check of the detector together with both amplifier stages has not been done. Nevertheless, the linearity was checked in 198423. In addition, recent tests of a detector unit with attached first amplifier stage, which are both similar to the equipment used by the calibrated interferometer, and the second amplifier stage (see Sec. III C) confirm a linear response characteristics even after some decades of usage.
- iv) Separate daq systems for plasma and calibration operation: Measurements verify that a conversion factor between the two daq systems (see Sec. II D) exists. In the branch for the

plasma daq system a slight attenuation is present at the 2% level. Hence, strictly speaking,  $C_f^{2010}$  need to be decreased by that fraction. Instead of doing that, the calibration daq branch is used for plasma operation from Pulse No: 83144 as well.

- v) Black body property of TK material: Below 100 GHz the TK material loses its black body property. Since it is expected, that the absorption remains close to unity below the frequency 100GHz, the effect on the spectral characterisation of the hot-source and the calibration factors for the Michelson is estimated to be below the 5% level for the spectral range 60-100GHz. However, since the determination of the  $T_e$  profile at JET relies mainly on the spectral range 100-200GHz, the effect of this systematic error is of minor interest. Nevertheless, another type of the TK material<sup>38</sup> could possibly be used to cover the spectral range above 50GHz.
- vi) Spectral characterisation of hot-source: As long as the antenna pattern is filled by the sources, which are placed at the distance of 15cm to the antenna during the measurements in the diagnostic hall, and for the spectral range of interest the black body property of the TK material holds, the spectral characterisation of the hot-source is valid. The former condition is presumed to be fulfilled, but if it is not, then, in principle, an under- or an overestimation of  $T^{\text{Hot}}$  by 10% is thinkable dependent on the radiation temperature of the lab and the actual shape of the local antenna pattern. As stated in v) the characterisation is systematically affected below 100 GHz, because of the changing properties of the TK material.
- vii) Filling in-vessel antenna pattern by hot- source: Simulations of the in-vessel antenna pattern for the spectral range 70-500GHz and the modes TE10 and TE01 confirm that the hot-source is placed close enough at the distance 33cm from the antenna. However, potentially this could be a source for a systematic error. Because of the TE10 mode filter (see section 2.1) higher order modes should not play a major role, at least not at the level of 15%. The experimental investigation of the antenna pattern is planned during the JET shut-down phase starting in 2012. Ideally, the antenna pattern should be determined by a set-up which is able to scan the two-dimensional plane perpendicular to the line of sight employing a monochromatic source. This would be difficult to do but scans of the distance between the hot-source and the antenna are foreseen.

Besides the possible systematic errors listed above the comparison of the electron temperature profile  $T_e$  measured independently by the Michelson interferometer (ECE diagnostic) and the Thomson scattering (TS) diagnostics at JET gives confidence in the calibration made (see Fig.10(a) and b). Thereby, for both TS diagnostics, which comprises the time-of-flight diagnostic LIDAR<sup>8,9</sup> and the high-resolution TS diagnostic HRTS<sup>10</sup>, the recent calibrations are used which were determined independently subsequent to refurbishments in 2010/2011.

## CONCLUSIONS

Several aspects of the hardware, absolute calibration and analysis techniques for the Michelson interferometer diagnostic at JET have been extensively described. The diagnostic benefits from a simple design and robust hardware components, especially for the back end, which makes faults

unlikely. In case of a hardware fault, which is limited to components located in the diagnostic hall, the down-time is kept to a minimum. In addition, in-built protective measures reduce possible damage to the diagnostic. Therefore, during plasma operation maintenance work becomes minimal and the diagnostic has excellent reliability. The major operational task is the preparation and analysis for the absolute calibration using the hot/cold technique. The current implementation of the calibration procedure at JET, which employs the stand-alone set-up and the specially developed digital averaging technique, demonstrates the derivation of the calibration factor set with high precision from high quality raw data. Since the in-vessel session data has been acquired on consecutive days and nights without malfunction of the equipment, the influence of changing ambient temperature along the transmission line is included. The set-up parameters like the physical temperatures of the sources used have been monitored throughout the session. No abnormal behaviour was found.

For the spectral range 80-500GHz the calibration factor set is derived statistically with relative uncertainty below 5%. Especially, the spectral range 100-350GHz, which is the most important for the JET plasma parameter range, the relative uncertainty is less than 2%. The most significant potential systematic error is probably the extent to which the in-vessel antenna pattern is filled with the hot-source. To investigate this further, during the next JET shut-down the distance between the electronically heated source and the antenna will be scanned. Thereby, an antenna extension will be employed to reduce the distance to less than 33cm.

Below 100GHz the TK material, which is essential for the calibration, starts to lose its property of being a good microwave absorber material<sup>38</sup>. Therefore, a systematic error is introduced whose effect has not been investigated so far.

Compared to the previous calibration factor set derived in 1996 the spectral shape is similar but on absolute scale the recent set shows that the sensitivity of the instrument has decreased by about 15%. Accordingly, for plasma operation the ECE spectrum and, therefore, the electron temperature increase. The exact cause of the reduction in sensitivity is not understood so far, but ageing of the detector element is a possibility.

Since the Michelson is the cornerstone of the ECE diagnostic system at JET, frequent application of the calibration procedure is recommended as carried out in the early years of operating the ECE diagnostic. This enables a future study of the sensitivity for several years as done in the timeframe 1984-1994. In addition, the monitoring of important parameters like the bias voltage supplying the detector is already on-going.

The calibration of the Michelson in 2010 led to a general improvement of the determination of the  $T_e$  profile at JET and agree well with the profiles measured independently by the TS diagnostics LIDAR and HRTS.

Besides its reliability the Michelson interferometer at JET demonstrates that continuous operation for days is achievable during calibration operation, and therefore it is applicable to the future tokamak ITER which has a pulse duration of less than 30 minutes. In addition, in principle, an interferometer enables the probing of the ECE spectrum even in the Terahertz range. However, it is essential that frequent calibrations can be carried out, and to make this calibration possible sources should be

included in the system design. The calibration needs to be carried out up to 1 THz, at least. The Michelson at JET has shown by local measurements to be sufficiently sensitive to characterize the hot-source and the grid transmission up to the frequency 0.7THz. By removing the filter inserted to limit the infra-red spectrum to enter the cryogenic vessel, and improving the attenuation of the transmission line between the in-vessel antenna and the interferometer back end, it is believed that the sensitivity of Michelson would be suited for a successful absolute calibration up to 1THz on ITER.

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## APPENDIX A: GENERAL DERIVATION OF CALIBRATION FACTORS

The diagnostic of type Michelson interferometer translates the intensity spectrum at the input into the interferogram at the output according to the intrinsic sensitivity. The corresponding diagnostic model can be expressed by

$$\begin{aligned} V(x) &= A \int I_{\sigma} C(\sigma) \cos(2\pi\sigma x) d\sigma + V_{BG}(x) \\ &= A \text{ FT}_{\cos} \{I_{\sigma} C\} + V_{BG} \end{aligned} \quad (\text{A1})$$

assuming that the post detection amplifier with amplification A removes the DC part  $\int I_{\sigma} C d\sigma$ . The model links the interferogram V with the cosine transform  $\text{FT}_{\cos}$  of the product of the input intensity or spectral radiance  $I_{\sigma}$  and the diagnostic sensitivity C. To be clear, V with unit Volt varies with the optical path difference x,  $I_{\sigma}$  with unit  $\text{W}/(\text{m}^2 \text{sr m}^{-1})$  and C with unit  $\text{m}^2 \text{sr V/W}$  depend both on the inverse wavelength  $\sigma$ . Furthermore, the model (A1) comprises the background voltage signal VBG which is present for an arbitrary input spectrum. For the Michelson interferometer at JET VBG is negligible when ECE spectra are probed emitted by plasmas with typical temperature well above 10eV. Therefore, once the sensitivity C is specified via an absolute calibration, i.e. the experimental determination of C, the inversion delivers the ECE spectrum by

$$I_{\sigma} = A^{-1} \frac{\text{FT}_{\cos}^{-1} \{V\}}{C} = \frac{S}{C} \quad (\text{A2})$$

using the recovered spectrum S in the nominator. However, if the calibration technique like at JET relies on sources with temperatures below 1000K (<0.1eV),  $V_{BG}$  becomes important. The

background is removed for using the hot/cold technique. Thereby, two different sources, a cold and a hot one with corresponding spectra  $I_{\sigma}^{Cold/Hot}$ , are placed in front of the diagnostic antenna. As a consequence the difference interferogram

$$A^{-1} (V^{Hot} - V^{Cold}) = FT_{cos} \{ (I_{\sigma}^{Hot} - I_{\sigma}^{Cold}) C \} \quad (A3)$$

becomes proportional to the cosine transform of the product of the difference input intensity and the sensitivity. The inverse operation reveals the sensitivity

$$\begin{aligned} C &= A^{-1} \frac{FT_{cos}^{-1} \{ V^{Hot} - V^{Cold} \}}{I_{\sigma}^{Hot} - I_{\sigma}^{Cold}} \\ &= \frac{A^{-1} FT_{cos}^{-1} \{ V^{Hot} - V^{Cold} \}}{c \frac{I_f^{Hot} - I_f^{Cold}}{c}} \\ &= \frac{1 \Delta S}{c \Delta I} = \frac{C_f}{c} \end{aligned} \quad (A4)$$

as the ratio of the recovered difference spectrum  $\Delta S$  to the difference input intensity  $\Delta I$  with unit W/(m<sup>2</sup>sr Hz) multiplied with the speed of light  $c$ . Alternatively to  $C$  the quantity  $C_f$  with unit (Vm m<sup>2</sup>sr Hz/W) is introduced which plays a role for the Michelson interferometer at JET. Theoretically, the absolute calibration obtains the calibration function which represents the sensitivity for the spectral range with sufficient SNR. However, the previous derivation of the calibration function needs to be adapted to real world interferometers. In practice, the interferogram is sampled at a finite number of data points. Therefore, the continuous operation  $FT_{cos}$  is replaced by the discrete operation  $DFT_{cos}^{-1}$ . In addition, the information about the zero-path-difference (ZPD) position at which the optical path difference vanishes is uncertain, and dispersion in the diagnostic might be present. Hence, phase correction (PC) needs to be applied to the recovered spectrum for which the operation  $DFT^{-1} \sin$  is mandatory. Other common techniques or tricks are used: zero-padding to increase the frequency resolution and to meet the conditions for discrete fast Fourier transformation  $DFFT^{-1}$  routines; apodization of the interferogram data by window function  $g$  to reduce spectral leakage. Altogether the continuous calibration function is represented by a set of calibration factors calculated by

$$\begin{aligned} C_f &= \frac{\Delta S}{\Delta I} \\ &= A^{-1} \frac{PC (DFFT^{-1} \{ g (V^{Hot} - V^{Cold}) \})}{\Delta I}. \end{aligned} \quad (A5)$$

The calibration factors  $C_f$  become dependent on the specific implementation of how the difference interferogram is processed, but the impact is expected to be small. However, the implication is that the coherence between  $C_f$  and the recovered spectrum  $S$  calibrated in equation (A2) is only guaranteed when the interferogram  $V$  is processed like the difference interferogram in (A5).

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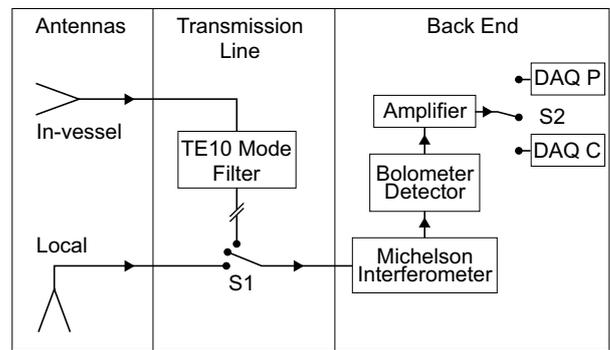


Figure 1: Scheme of Michelson interferometer diagnostic at JET with major segments: antennas, transmission line and back end. For the in-vessel antenna the transmission line (~40m) includes a TE10 mode filter. Via the switch S1 the source in front of the in-vessel antenna or the local antenna with short transmission line (~0.8m) located in the diagnostic hall is chosen. The transmission line ends at the input port of the back end which comprises the Michelson interferometer unit, the bolometer detector, the amplifier stage and the data acquisition system. For plasma (P) and calibration (C) operation the daq system is chosen with switch S2.

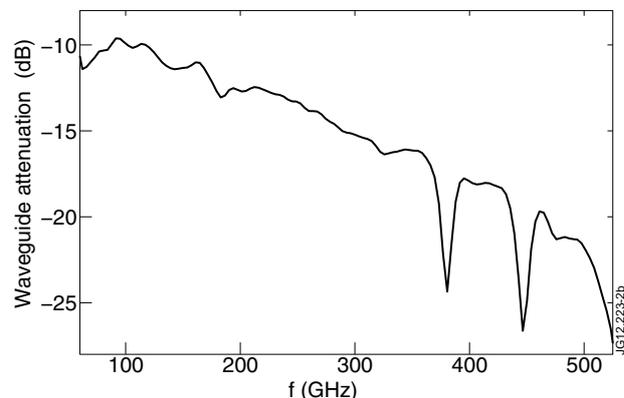
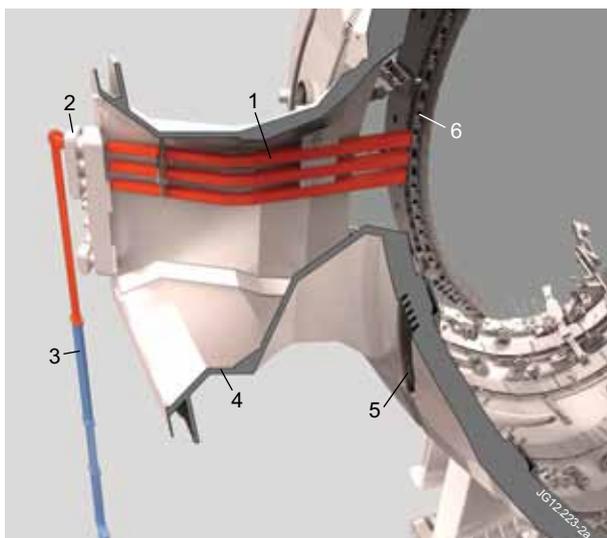


Figure 2: (a) Diagnostic front end according to JET model 30. 1) In-vessel antenna, 2) Location of polarizer with horizontal wires, 3) Transmission line (red) including TE10 mode filter (blue), 4) Cross-section of diagnostic port in octant 7, 5) Outer wall of JET vessel, 6) Limiter structure at inner wall of JET. (b) Attenuation of transmission line for in-vessel antenna for spectral range 60-525GHz. Around the frequencies 380.20GHz and 440GHz absorption by water vapour increases the attenuation.

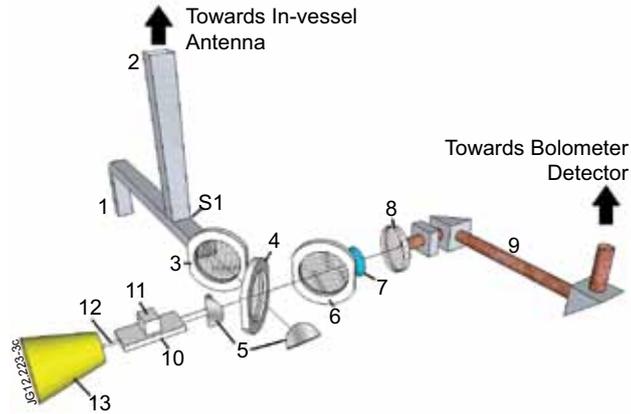


Figure 3: Design of Michelson interferometer unit using switch S1 (see Fig.1). 1) Local antenna with transmission line (0.8 m), 2) Taper for transmission line of in-vessel antenna, 3) Vertical polarizer, 4) Beam splitter, 5) Roof top mirrors, 6) Horizontal polarizer, 7) TPX lens, 8) Grid attenuator (in place for plasma operation), 9) Circular waveguide, 10) Mirror translator (air-bearing) with micrometer scale on top, 11) Scanning head, 12) Silver steel rod, 13) Linear shaker.

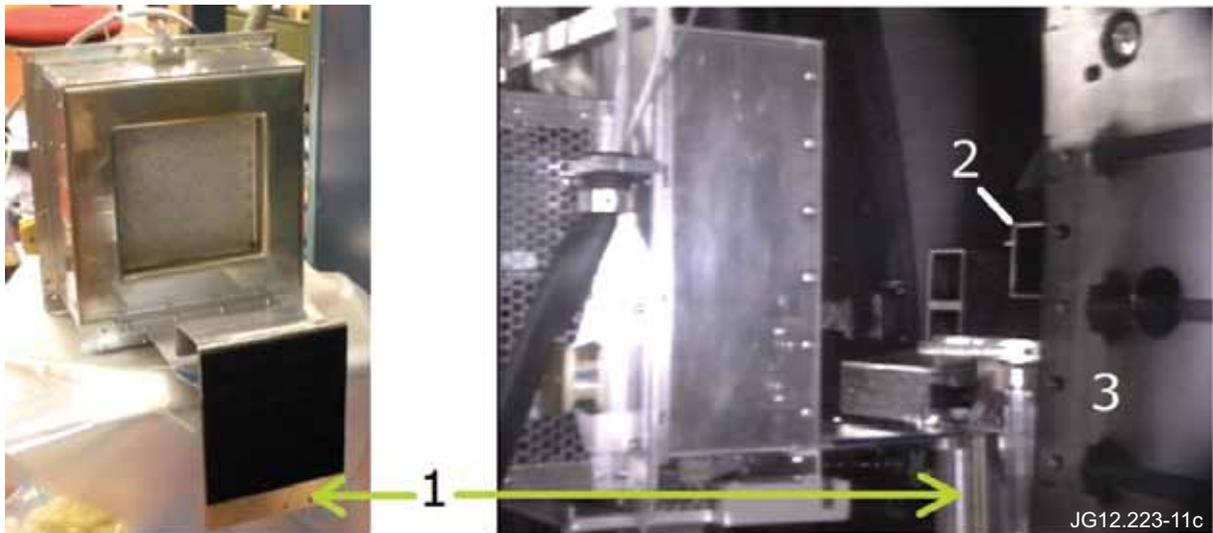


Figure 4: Left: Front view of cold- and hot-source. The coldsource realized by the microwave absorber material TK38 sits on the aluminium switch (1) moving up- and downwards. The active surface (black) of the TK material covers 17cm×20cm. The hot-source is located behind the cold-source having the active surface (grey) with area 20cm×20cm. An aluminium plate connects both sources. Right: Side view of cold- and hot-source placed in front of in-vessel antenna (2). The position of the switch (1) is down, thus the diagnostic antenna, partly hidden by the limiter (3, also see component 6 in Fig.2(a)), faces the hot-source. The diagnostic line of sight crosses almost the centre of each source (top view not shown). The distance from the active surface of the hot-source to the antenna is less than 33cm.

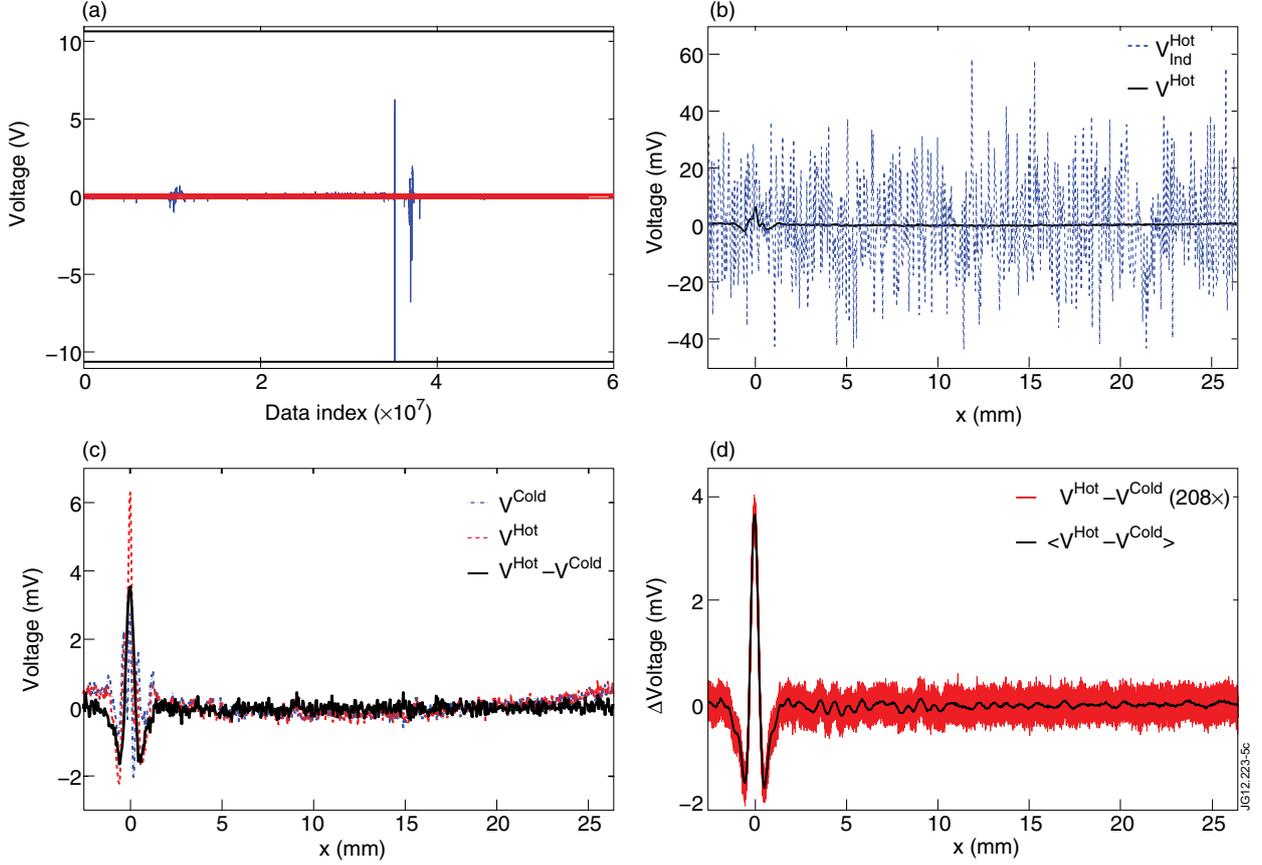


Figure 5: Processing steps for derivation of difference interferogram  $V^{\text{Hot}} - V^{\text{Cold}}$  from raw data taken during absolute calibration in 2010. (a) Raw data trace (blue). In 20 minutes of continuous data acquisition almost  $6 \times 10^7$  voltage values ( $\sim 70000$  individual interferograms) are stored on hard disc permanently. Spurious signals can exceed the interferogram data by more than three orders of magnitude, for example around data index  $3.5 \times 10^7$ . The post-measurement averaging method neglects individual interferograms which are outside the acceptance region  $\pm 100$  mV (red). The ADC covers the dynamical range  $\pm 10.5$  V (black). (b) Interferogram data  $V^{\text{Hot}}$  dependent on optical path difference  $x$ . Individual interferograms (blue) each acquired in 17ms suffer from in the noise with standard deviation 17.5mV. The averaged interferogram (black) is strongly asymmetric around the ZPD position ( $x=0$ mm). Digital averaging of a raw data trace acquired for 20 minutes increases the SNR from about 1:3 to about 60:1 around the ZPD position. (c) Digitally averaged interferograms  $V^{\text{Cold}}$  for cold-source (blue) and  $V^{\text{Hot}}$  for hot-source (red). The difference interferogram (black) removes the asymmetry around the ZPD position and the back ground voltage signal which is obvious for  $x > 25$  mm. (d) 208 difference interferograms  $V^{\text{Hot}} - V^{\text{Cold}}$  (red) and overall average  $\langle V^{\text{Hot}} - V^{\text{Cold}} \rangle$  (black). The latter reflects  $8.6 \times 10^6$  individual interferograms and integration time of 3.4 days per source. The final SNR at  $x=0$  mm is about 430:1.

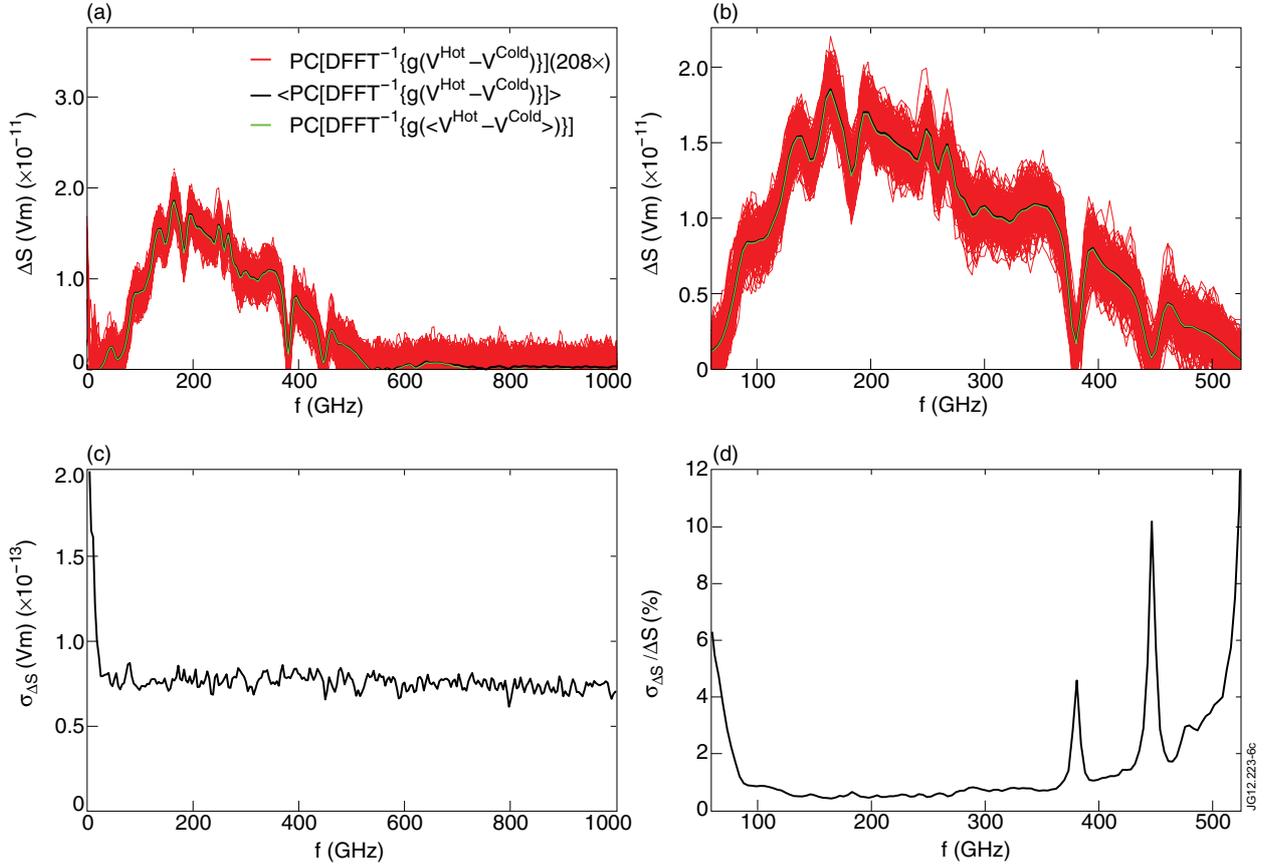


Figure 6: Recovered difference spectra  $\Delta S$  (first row) with uncertainty  $\sigma_{\Delta S}$  and relative uncertainty  $\sigma_{\Delta S} = \Delta S$  (second row). (a) Spectral range 0-1000GHz. The average in the spectral domain (black) arises from 208 individuals (red) and agrees with the result for the overall difference interferogram (green) within 2% below 500GHz. (b) Spectral range 60-525GHz. The dips at 183.31GHz, 380.20GHz and 440GHz indicate water absorption lines. (c)  $\Delta S$ . The uncertainties are almost constant on absolute scale for a broad spectral range ( $f > 30$ GHz). (d)  $\sigma_{\Delta S} = \Delta S$ . Clearly, the Michelson can be calibrated for the inbetween 60-525GHz. For the spectral range 100-350GHz  $\sigma_{\Delta S} = \Delta S$  falls below 1%. The water absorption lines at 380.20GHz and around 440GHz influence the relative accuracy far more than the one at 183.31GHz.

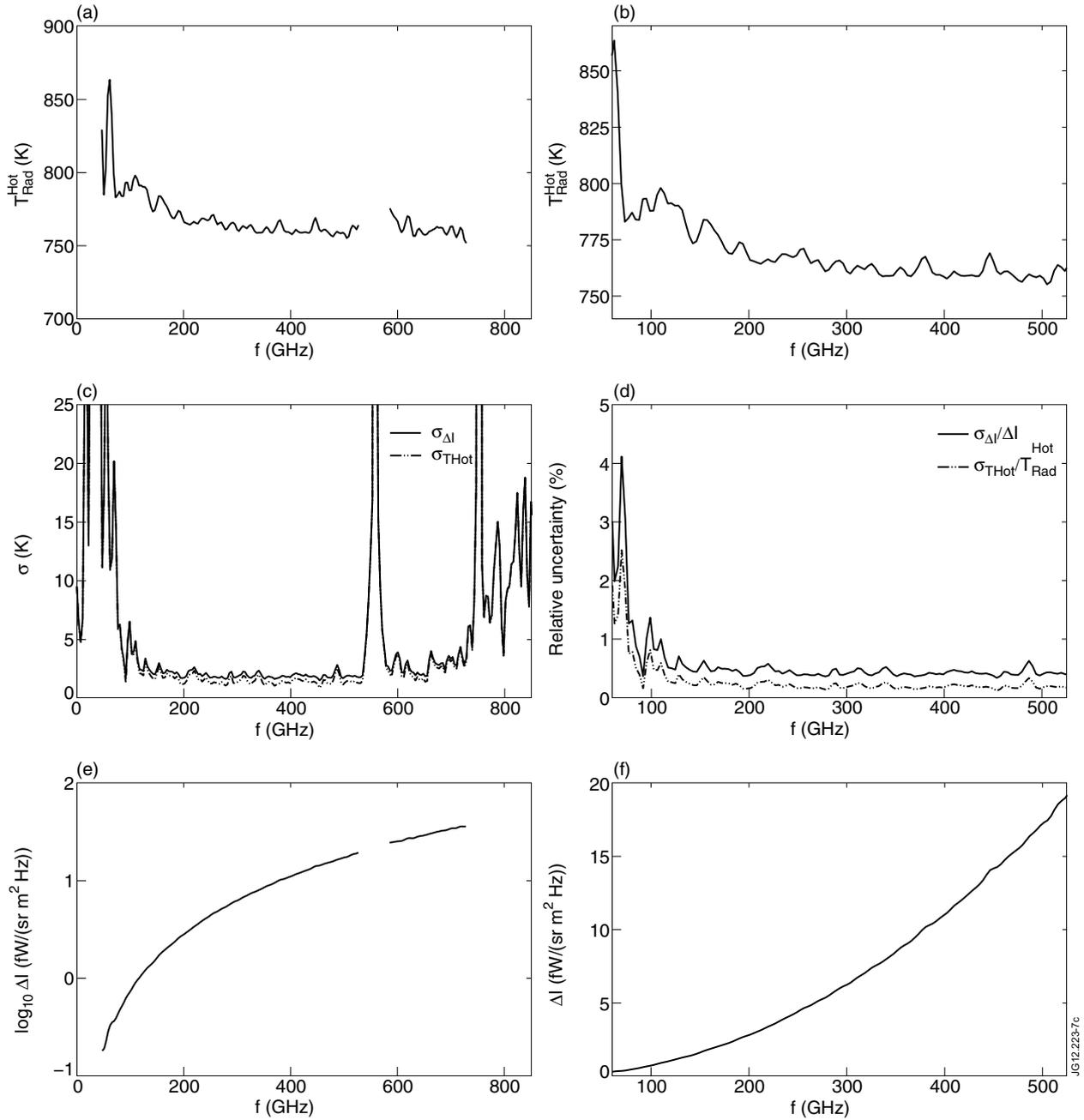


Figure 7: Radiative temperature of hot-source  $T_{Rad}^{Hot}$  (first row) with absolute and relative uncertainties (second row) and difference input intensity  $\Delta I$  (third row) for spectral ranges 0-850GHz (left column) and 60-525GHz (right column). (a)  $T_{Rad}^{Hot}$ . From 70-700 GHz  $T_{Rad}^{Hot}$  varies smoothly but is decreased by about 100K with respect to its physical temperature 873K. The characterization is corrupted at the water absorption lines around 556.94GHz and 752.03GHz. Below 70GHz and above 700GHz the poor SNR affects the characterization. (b) From 100GHz onwards  $T_{Rad}^{Hot}$  decays from 800K to 760K at 500GHz. (c) Uncertainties  $\sigma_{T_{Hot}}$  (black) and  $\sigma_{\Delta I}$  (red). Neglecting water absorption lines around 556.94GHz and 752.03GHz both uncertainties are small for a broad spectral range: 6K at 100GHz, 2K at 300GHz and 3.5K at 700GHz. Below 70GHz and above 700GHz the poor SNR increases the uncertainties. (d) Relative uncertainties  $\sigma_{T_{Hot}} = T_{Rad}^{Hot}$  (black) and  $\Delta_{\sigma I} = \Delta I$  (red). Both ratios fall below the 1% level above 100GHz. (e)  $\Delta I$  on logarithmic scale. (f)  $\Delta I$  on linear scale.

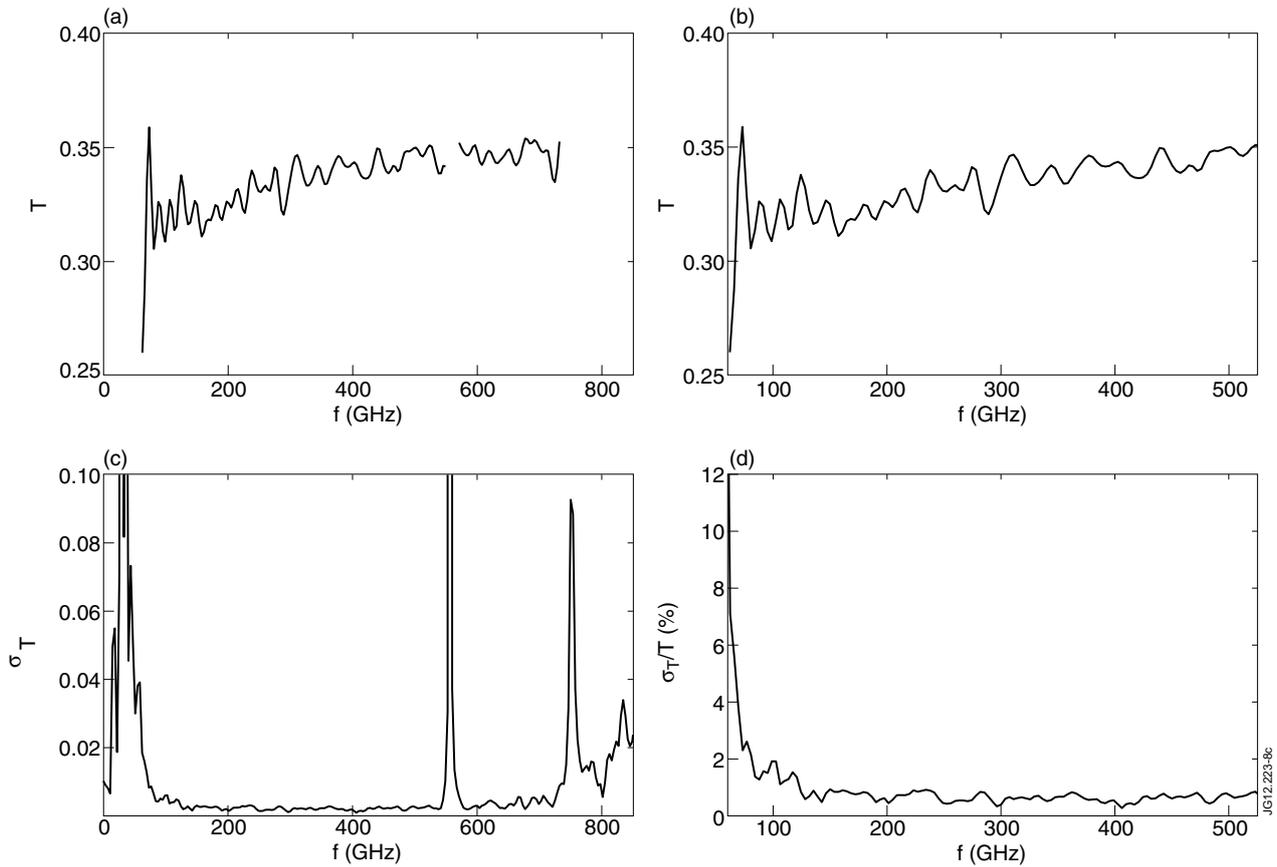


Figure 8: Spectral characterization of grid transmission  $T$ . (a)  $T$  up to 850GHz.  $T$  oscillates in the range 0.31-0.35 ( $\sim 5$ dB) for 70-700GHz. (b)  $T$  for spectral range 60-525GHz. (c) Uncertainty  $\sigma_T$ .  $T$  is determined with high precision from 70-700GHz neglecting spectral ranges for water absorption lines. (d) Relative uncertainty  $\sigma_T/T$  for spectral range 60- 525GHz. Above 80GHz  $\sigma_T/T$  falls below 2%. Below 70GHz the characterization becomes unreliable.

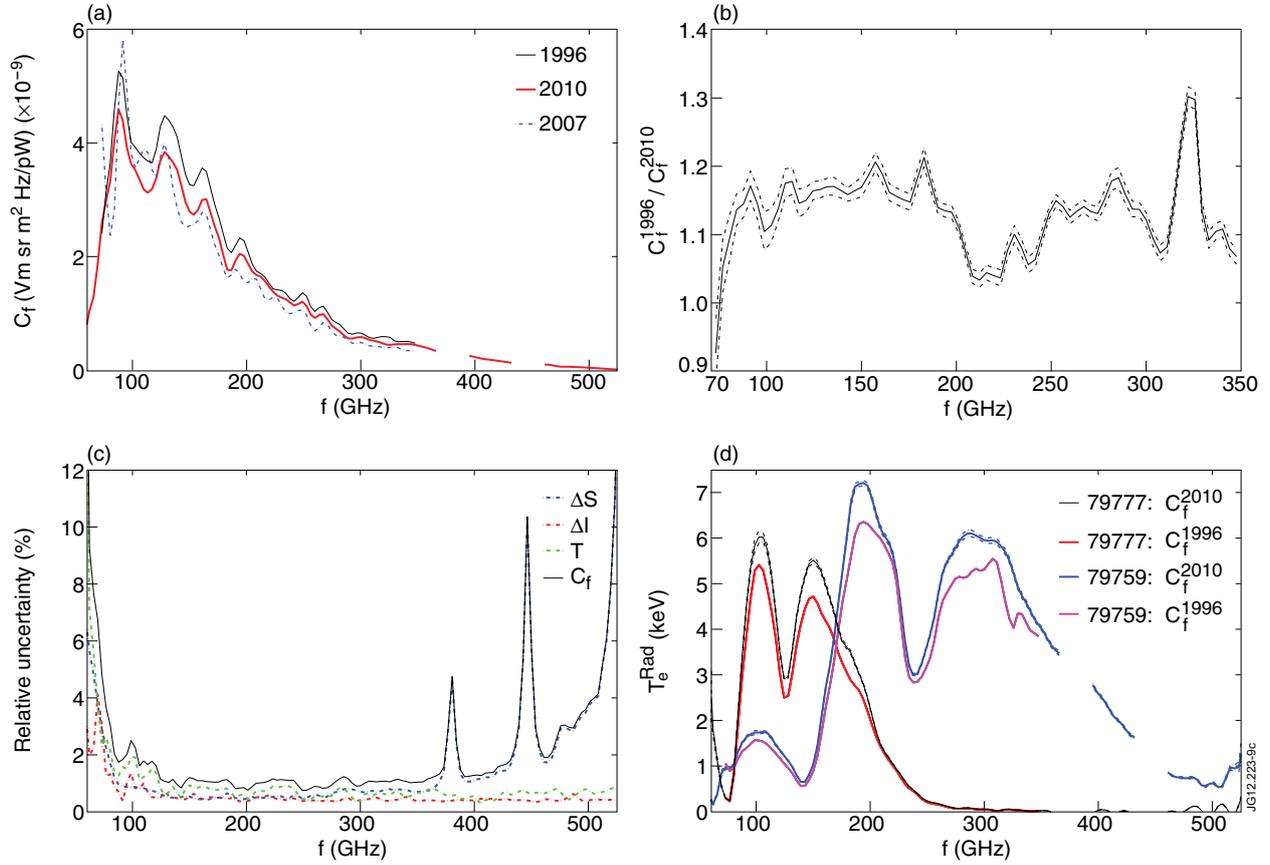


Figure 9: Results of absolute calibration for JET Michelson interferometer carried out in 2010. (a) Absolute calibration factor sets  $C_f^{1996}$  (black),  $C_f^{2010}$  (red) and  $C_f^{2007}$  (dashed, blue) derived in 1996, 2010 and 2007, respectively. For the spectral range 73-347GHz  $C_f^{2010}$  and  $C_f^{1996}$  have a similar spectral shape but differ on absolute scale. Hence, the diagnostic has become less sensitive. The session in 2007 follows mainly the spectral trend. (b) Relative change expressed by ratio  $C_f^{1996} = C_f^{2010}$  (solid). In the spectral range used for plasma temperature measurements (100-200GHz) the radiation temperature for  $C_f^{2010}$  is increased by about 15%. The uncertainty of  $C_f^{2010}$  (see (c)) translates into a narrow band (dashed). (c) Relative uncertainties for grid attenuation  $T$  (green, dashed), difference input intensity  $\Delta I$  (red, dashed), recovered difference spectrum  $\Delta S$  (blue, dashed) and calibration factors  $C_f^{2010}$  (black). The latter is evaluated by Gaussian error propagation. Below 100GHz  $T$  and above 350GHz  $\Delta S$  drive the overall uncertainty. (d) Measured ECE spectra in terms of radiation temperature  $T_e^{Rad}$  using sets  $C_f^{2010}$  (black, blue) and  $C_f^{1996}$  (red, magenta). JET plasmas with low toroidal magnetic field ( $B = 1.83T$ ,  $n_{e0} = 3 \times 10^{19} m^{-3}$ ,  $t = 17.28s$ , Pulse No: 79777) and high toroidal magnetic field ( $B = 3.42T$ ,  $n_{e0} = 7 \times 10^{19} m^{-3}$ ,  $t = 14.04s$ , Pulse No: 79759) are chosen.

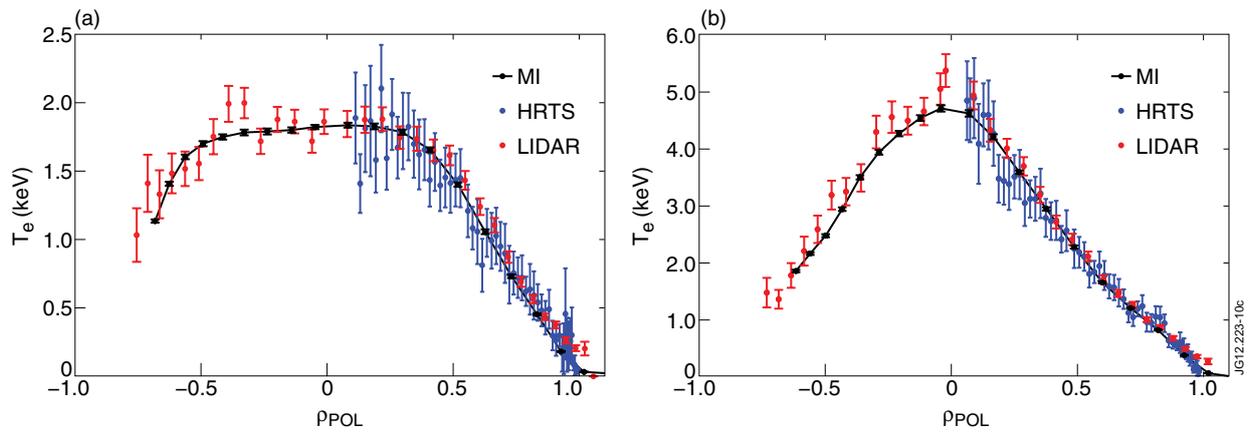


Figure 10: Typical  $T_e$  profiles measured independently by ECE and Thomson scattering diagnostics (TS). The profile for the Michelson interferometer (MI, black), the high-resolution Thomson scattering diagnostic (HRTS, blue) and the time-of-flight TS diagnostic (LIDAR, red) is mapped using equilibrium information provided by EFIT<sup>42</sup>. The uncertainties for the profile relying on the Michelson interferometer arise from the uncertainties of the calibration factors (see Fig.9(c)). Thereby, the uncertainty in the absolute level is estimated to  $\sim 5\%$ . For HRTS and LIDAR the uncertainties are purely statistical obtained from photon noise for the plasma measurement. Within the uncertainties the profiles are in good agreement. (a) JET Pulse No: 83200 at  $t = 11.87s$ . (b) JET Pulse No: 83361 at  $t = 19.38s$ .