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ABSTRACT

The measurement of accurate temperature profiles is critical for transport analysis and equilibrium reconstruction in the DIII–D tokamak. Recent refinements in the Michelson interferometer diagnostic have produced more precise electron temperature measurements from electron cyclotron emission and made them available for a wider range of discharge conditions. Replacement of a lens-relay with a low-loss corrugated waveguide transmission system resulted in an increase in throughput of 6 dB and reduction of calibration error to around 5%. The waveguide exhibits a small polarization scrambling fraction of 0.05 at the quarter wavelength frequency and very stable transmission characteristics over time. Further reduction in error has been realized through special signal processing of the calibration and plasma interferograms.

INTRODUCTION

Michelson interferometers have been a standard diagnostic for measuring electron cyclotron emission (ECE) from tokamak plasmas.[1,2] Their broad spectral coverage and ease of calibration make them attractive for obtaining electron temperature and other information about the electron distribution. On the DIII–D tokamak, ECE is the only means available for determining central electron temperatures of many discharges; hence, it is important that these measurements be as accurate as possible. Several techniques have been tried to increase the precision of the Michelson ECE measurement, and the results of these efforts are reported here.

I. THE MICHELSON INTERFEROMETER

The fast-scanning Michelson interferometer (FSMI) has been operating at DIII–D since 1987. It is configured as a Martin-Puplett polarizing type, manufactured by Specac, UK, and is a twin of the instrument that has been operating at the TFTR tokamak since 1984.[3] For the DIII–D instrument, the center 2 cm of the 5 cm stroke is recorded with 40 μm spacing, yielding an unapodized frequency resolution of 4 GHz. For both calibration and plasma interferograms, Norton-Beer[4] apodization is typically used, increasing the minimum spectral width by about 50%. The scanning motor can be run up to a speed of 35 Hz, but is typically run at 20 Hz giving an integration time for each scan of ~6 ms.

Lenses at the input and output of the FSMI form a gaussian telescope so that the beam waist through the instrument is independent of frequency. After the output lens the radiation is passed through an aperture at the edge of the optics table which is used to mount high-pass dichroic plate filters. Another gaussian telescope section consisting of a lens and parabolic mirror surrounds a two-stage attenuator which is used to reduce the transmission to the detector during plasma experiments. The detector is a LHe cooled InSb wafer at the end of a compound parabolic concentrator.

II. TRANSMISSION LINE

Originally the transmission line for the FSMI was a quasi-optical lens system of four confocally spaced gaussian telescopes consisting of nine lenses and three flat mirrors covering a distance of 18 m. The components were prone to being bumped thus the system had to be checked for alignment frequently, a tedious and time consuming task, and the system had a large attenuation (≈11 dB) to boot. To obtain greater transmission efficiency and reduce maintenance time the system was replaced with a broad-band low-loss corrugated waveguide.[5]

For typical DIII–D magnetic fields of 1.0–2.2 T the range of interest for ECE frequencies is 60–300 GHz, encompassing harmonics two through six. To pass radiation in this frequency range the corrugated waveguide was constructed in 63.5 mm ID aluminum tubing with corrugations of 0.25 mm depth and 0.38 mm period. The line is 21 m in length and contains 7 miter bends. At the input and output of the waveguide, optical components are employed which form a gaussian beam waist at the waveguide aperture with radius $0.64a$, where a is the aperture radius, in order to maximize the fundamental mode coupled power.[6] At the Michelson end this is accomplished with the proper focal length in the TPX lens of the first gaussian telescope. At the input end near the tokamak, shown in Fig. 1, the gaussian beam is formed with an ellipsoidal mirror, field stop and TPX lens. The front end has the additional characteristic that the gaussian beam does not fully fill the ellipsoidal mirror, a design which lessens the sensitivity of the system to small misalignments.

After installation the transmission system was tested to measure its efficiency. The results of this test are shown Fig. 2 where it can be seen that the average loss is 4 dB, a gain of 7 dB over the old lens-relay

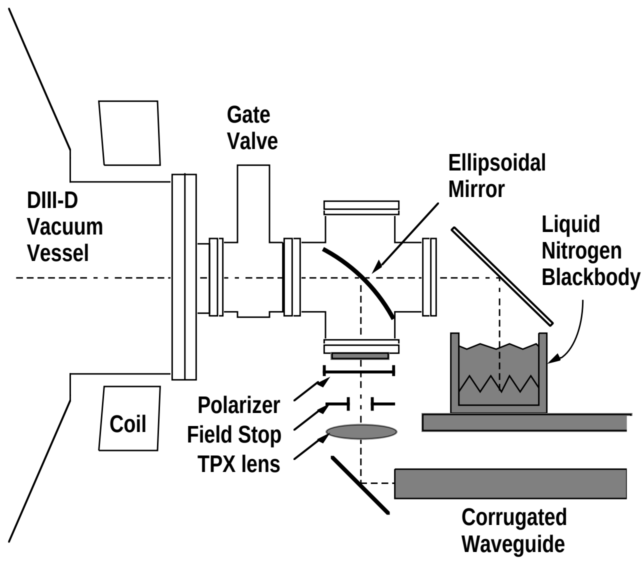

Fig. 1. The front-end optics configuration for the Michelson interferometer.

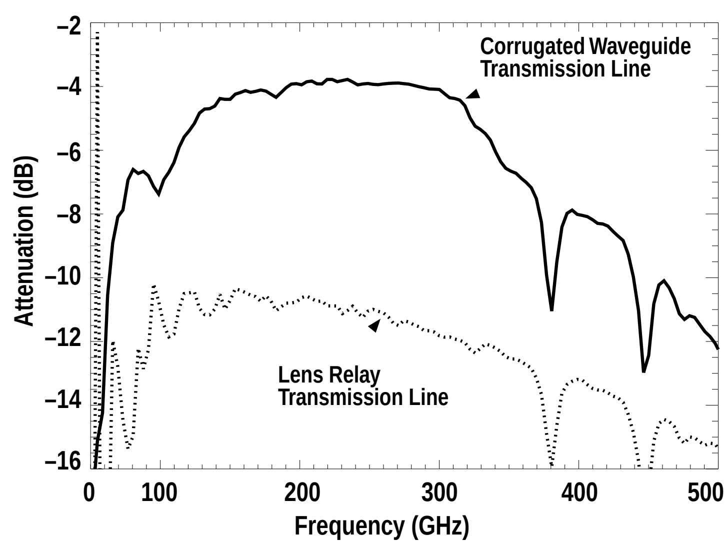

Fig. 2. Comparison of the attenuation of the old lens-relay system to the new corrugated waveguide line.

system. The results were obtained by taking the ratio of the spectrum of a LN blackbody source at the input to the ellipsoidal mirror to the spectrum at the input to the Michelson. The transmission loss includes the loss in the front end of the transmission system, e.g. the lens attenuation, which is about 20%, and the losses due to incomplete coupling of the radiation to the waveguide.

Another test was done to check the polarization scrambling occurring in the waveguide. This can happen because of imperfect angles in two successive bends in orthogonal planes or because of ellipticity in the waveguide. The tests were first done without the ellipsoidal mirror and front end optics to check the waveguide line by itself. A LN blackbody source was placed at the input to the waveguide either without a polarizing grid or with a polarizing grid set to pass either X–mode or O–mode polarized radiation. These three measurements were made with the FSMI polarizer set for X–mode radiation. Taking the ratio of the resulting spectra gives the polarization scrambling coefficient. It was found that at the $\lambda/4$ frequency (300 GHz) the polarization is retained to 96% while at much lower frequencies, around 80 GHz, only 60% polarization is observed. Foreseeing this possibility, the front end optics were designed to include a polarizing grid, which selects the desired polarization before the radiation is coupled to the input of the waveguide. The grid, which is mounted on the window flange located below the ellipsoidal mirror, is normally set to pass vertically polarized radiation leaving the plasma.

III. CALIBRATION

The increased throughput of the transmission line resulted in improved calibration mainly through increase in signal to noise. For the lens-relay system, typically 160,000 scans had to be taken using a LN blackbody source to get a satisfactory response function for the instrument, and even then the calibration was very poor below 120 GHz. With the new corrugated waveguide system, a very good calibration was obtained with only 80,000 scans, recorded in groups of 10,000, and the response curve was relatively smooth down to 80 GHz. One measure of the quality of the calibration is the standard deviation of the response over the 8 blocks of scans and this is plotted with a typical response curve in Fig. 3. For frequencies above 120 GHz the standard deviation is around 2%. For the range of frequencies for which second harmonic optically-thick ECE is usually measured from the tokamak, 85–150 GHz, the average standard deviation is 5%.

More important than increased signal to noise for calibration was the increased stability of calibration gained by having a rigid waveguide transmission line. During the first full year of operation with the waveguide, the front-end optics were disturbed five times, either due to a scheduled vent of the DIII–D vessel or tests of the optics system. A calibration was performed after each of these events to check the change in the transmission line and it was found to vary little over time. In

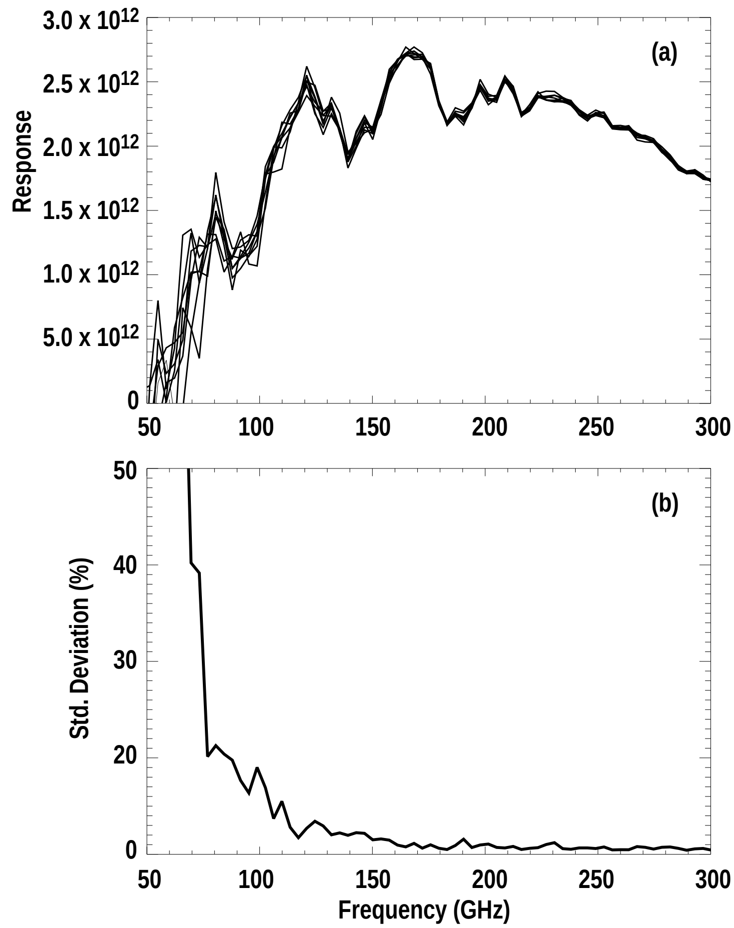

Fig. 3. Calibration response data for the Michelson interferometer with the corrugated waveguide system: (a) eight response curves from blocks of 10,000 scans each, (b) the percent standard deviation for the eight response functions.

general it has been found that small alterations in the positioning of the front-end components have very little effect on the system response, on the order of the standard deviation, or about 2%. In contrast, a realignment of the Michelson components and detector optics on one occasion produced a systematic variation of 10%–20%.

IV. DATA PROCESSING

Further improvements in the quality of the calibration have been realized by taking care with the recording and manipulating of the interferograms. For example, a source of 60 Hz noise was eliminated by moving the power supply transformer out of the preamplifier box. However one source of noise that is consistently difficult to eradicate is the microphonics from the vibrating Michelson instrument which is picked up on the InSb detector. Even though both the FSMI table and the optics table are on vibration dampening mounts, the coherent signal is still of the order of 5% of the interferogram amplitude during calibration. Originally a high pass filter was employed to cut out much of this low-frequency signal but this was observed to be differentiating the signal and creating asymmetric interferograms.

A solution was found through manipulating the interferograms in software. To perform the FFT of the interferogram the dc offset of the signal is first removed. This is usually accomplished by finding the average value of the interferogram and subtracting it. A better way to do this, however, is to fit a low order polynomial, typically of order 3 to 5, to the interferogram. This effectively removes the low frequency noise in the interferogram and gives a much cleaner inverted spectrum at the long wavelength end. For the calibration interferograms, removing the offset by using a polynomial of degree 5 instead of subtracting the mean value reduced the response variation by several percent in the 65–85 GHz range, a difficult region to calibrate this instrument.

Another problem that frequently occurs with the interferogram signals is noise spikes. One type of spike that is seen is one that saturates the digitizer for one point of the interferogram and these are removed automatically by the software that handles the plasma data. Another type of spike that often occurs has a long time constant and may last for several points in the interferogram. These are usually due to some transient fluctuation in the plasma such as a sawtooth crash or other MHD event. They are very difficult to take care of in software since they do not always exhibit derivatives much larger than the normal interferogram fluctuations. However, for the case where the event occurs near the end of the scan, good spectra have been obtained by zero-filling the remainder of the interferogram after the event. This naturally reduces the frequency resolution for the spectra but for smooth temperature profiles the effect will not be noticed. An example of this technique is shown in Fig. 4.

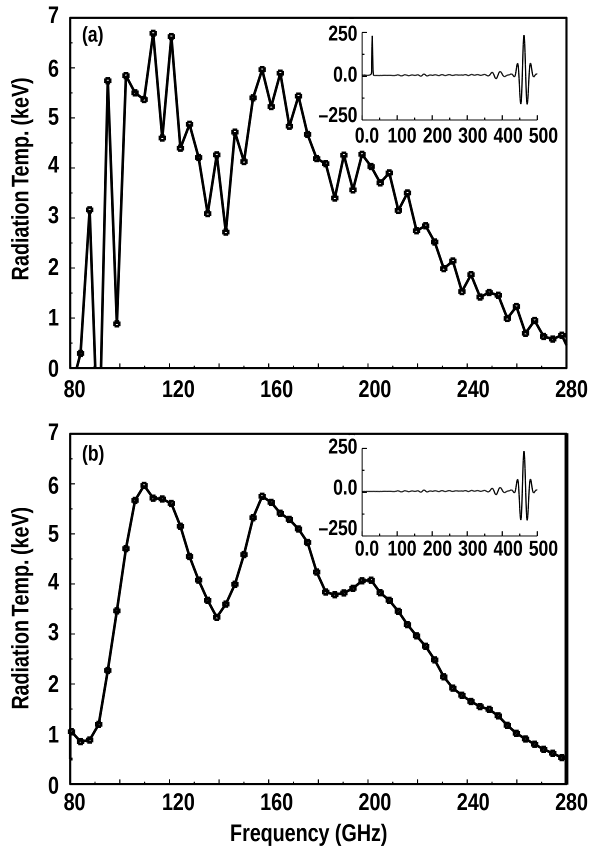

Fig. 4. Plot showing results of interferogram repair (a) interferogram with noise spike near point 40 and resulting spectrum, (b) interferogram with spike removed by zero-filling the first 50 points and spectrum.

V. CONCLUSIONS

The accuracy of the Michelson interferometer ECE spectra on the DIII–D tokamak has been significantly increased, especially at the long wavelength end of the spectrum which is important for low field operation of the tokamak. The major change responsible for this improvement is the installation of low-loss corrugated waveguide transmission line which increased the calibration signal-to-noise ratio and reduced the average calibration error from 15% to 5%. The new transmission line demonstrated long term stability which could be useful for next-generation tokamaks which will need low-maintenance systems. Further enhancements to the quality of the data has been realized through better signal analysis techniques, again which effect most strongly the low-frequency end of the spectrum. The improvements have made it possible to check the calculated magnetic equilibrium of the plasma using the ECE data and have reduced the chi-square error on fits to electron temperature profiles used in transport calculations.

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