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Broad Band ECE measuremenst in ECW heated plasmas

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Abstract

The Wendelstein 7-X (W7-X) experiment is equipped with an Electron Cyclotron Resonance Heating installation consisting of 10 gyrotrons capable of delivering upto 7.5 MW of Electron Cyclotron Wave power at the 140 GHz resonance in the plasma. Normally, the gyrotron power is delivered in a very narrow band of several 100 MHz around the gyrotron frequency and the gyrotrons are optimized to deliver power only at this frequency. In practice, the gyrotron central frequency will shift several 100 MHz during start-up while excitation of spurious modes inside the gyrotrons may lead to power at frequencies spaced several GHz away from the resonance. These effects do not hinder gyrotron operation, but the power at unintended frequencies is a problem for sensitive microwave receivers, typically measuring power levels in the sub μW range. For protection these generally employ notch filters such as fundamental mode interference cavities [1], [2]. This paper focuses on the effect of non-absorbed 140 GHz gyrotron power on the Michelson Interferometer at W7-X.

Keywords: ECE, Michelson Interferometer, Gyrotron, Stray radiation, Compression, Notch Filter, W7-X

1. Introduction

A Michelson Interferometer has been taken into operation at the Wendelstein 7-X Stellarator (W7-X) to complement data of the radiometer [3]. The instrument is being commissioned to cover the ECE spectrum in O-mode from 50 GH $\cdots$ 300 GHz. The principle heating scheme at W7-X is by means of 10 gyrotrons operating at 140 GHz with a combined power of 7.5 MW. The ECE power, in contrast, is many orders of magnitude lower. This will potentially damage the receiver or lead to non-linearity at other frequencies. A solution is to include a notch filter at the input of the instrument. But such filters are mostly based on single mode cavity filters and cannot be applied in the broad band transmission line required by the Michelson. Therefore a broad band notch filter based on multiple disks, is under developent [4].

2. Description of the Michelson

The Michelson instrument recently installed and commissioned at W7-X is a Martin-Puplett type interferometer similar as in use at JET [5]. In the W7-X case, the excursion of the moveable mirror is 15 mm and a round trip, taking two interferograms, takes 45 ms. The signal of both arms are combined and illuminate a Helium cooled InSb bolometer detector. According to the manufacturer the instrument has an optical response of 3 kV/W and a N.E.P. of 0.8 pW/ $\sqrt{Hz)}$ using a pre-amplifier gain of 1000. The signal is fed into a signal conditioning unit before it enters a MDSplus Data Acquisition System. This system is also used to provide user definable triggers.

The ECE signal from the vessel is collected with a 36 mm horn antenna by means of a set of quasi-optical in-vessel mirrors. The waveguide following the antenna is tapered to 4 mm where it enters a vacuum window made with a thin (order 100 μm) Mica disk designed for operation in D-band by the X2-mode Radiometer. The cut-off frequency of circular 4 mm waveguide is 44 GHz such that it should still pass the 1-st ECE harmonic (see Fig.1) but the margin is small and only one mode can pass. At the atmospheric side the waveguide is tapered to 28 mm circular and fed to a beam splitter which separates X-mode and O-mode. Both modes continue in 28 mm circular waveguide over 21 m and 9 mitre bends to the diagnostic hall. Here the X mode waveguide continues over approximately 3 m to the radiometer (120 $\cdots$ 160 GHz), while the O-mode continues over approximately 5 m to the Michelson. By means of waveguide switches the X- and O-mode can be interchanged. Transmission line losses measured with the multimode Michelson are 11.0 +/- 0.5 dB. By including in-vessel losses such as the vacuum window and losses in the front-end optics of the Michelson itself, the overall loss starting at the in-vessel antenna up to the input of detector is set at 15 dB.

At the time of writing a calibration using a hot source - cold source arrangement was not yet available, however, a calibrated RF source with variable attenuator at 140 GHz was used to align the instrument and to assess power levels. With this source a responsivity of 5 kV/W was found. Caution is required as the responsivity measured with a broad band source at relatively low power density is likely to deviate from that of a narrow frequency band source at relatively large power. With a total post detection gain of 10^6, a LP filter at 10 kHz and a HP filter at 100 Hz, it was determined that a power level of 60 nW originating from the 140 GHz source was at the lower limit what still could be detected with the naked eye on the oscilloscope, without coherent addition. At the other extreme, the manufacture of the detector deems a power level of 1 mW still acceptable before it gets damaged. This level is adapted here as maximum value during error conditions.

3. Expected power levels

To assess the effect of ECH power onto the Michelson, both a measure of the absolute ECH power, and the ratio of ECH to ECE power are required. These levels will vary with plasma conditions such as temperature and optical thickness and with the amount of ECH power launched. It is noted though that the instrument dynamic range is over several orders of magnitude in power such that these variations are absorbed in the assessment.

3.1. ECE

Fig. 1 shows an expected temperature profile for a 5 keV plasma with electron density $5 \cdot 10^{19} \mathrm{m}^{-3}$. The total expected power is the integral over the O1-mode in Fig. 1, as O2 is optically thin, and is of the order of 5 μW. Taking into account the 15 dB losses, the power at the input of the Michelson is estimated at 150 nW.

3.2. ECH

ECH power levels are expected to be largest during ECH start up. Once the plasma is present but 140 GHz goes in cut-off (can no longer propagate due to high density) the ECH beam could be refracted into the ECE antenna. Given the location of ECH antennas and the ECE

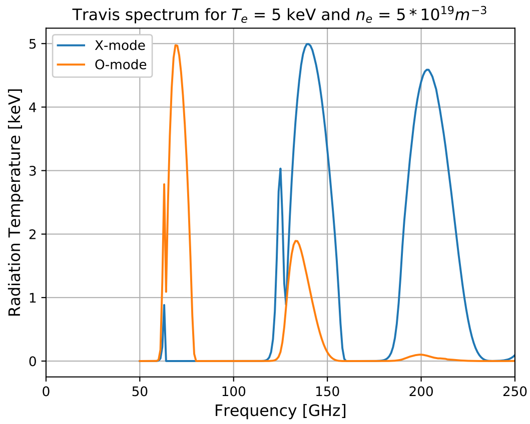

Figure 1: Expected ECE spectra from Travis for X-mode and O-mode.

antenna, a direct hit by a refracted beam is unlikely and is not considered. During the plasma phase of the discharge the ECH stray radiation levels are expected to be highest in O2-heated plasmas due to the incomplete ECH absorption in O2. In segment 4 the stray radiation in O2 heated plasmas is evaluated to be 2 $\mathrm{kW/m}^{-2}$ [6]. With the 36 mm diameter ECE antenna up to 2 W of power could be collected. In an oversized aperture about 700 modes are possibly at 140 GHz [7]. Upon passing the 4 mm diameter vacuum window, supporting 10 modes at 140 GHz, the power is reduced by a factor 700/10 = 70, giving 30 mW. At the input of the instrument, i.e. taking into account the 15 dB front-end losses, the expected power is then $\approx$ 1 mW.

4. Measurement data

During the work described in this paper the notch filter could not be used to it's full potential as the dedicated quasi-optical rig was not implemented at the instrument. As a result the rejection at 140 GHz was reduced to a factor of 15 and the notch width fairly broad, order 20 GHz, having an insertion loss of 10 dB. Drawing on previous work [8], in which measurenst with a single mode detector diode at the location of the instrument were analysed, the 15 dB reduction is still safe. To investigate the power at start up, the voltage gain in the video stage was reduced from a 10^6 to 10^4 to avoid saturation. Fig. 2 shows a measurenent of discharge 20180814.022 that used 5 gyrotrons for start-up. After the discharge a reference measurement was made with the 140 GHz RF-source injecting 0.6 mW power via the notch filter in to the instrument. The reference trace shows a response of $\approx$ 1 V resulting from an excitation of 0.6 mW/ 15 ≈ 40 μW at the input of the Michelson. Using this scaling it was determined that the power at start-up inclusive the notch filter was of the order of 0.14 mW (without the notch filter of the order of 2 mW).

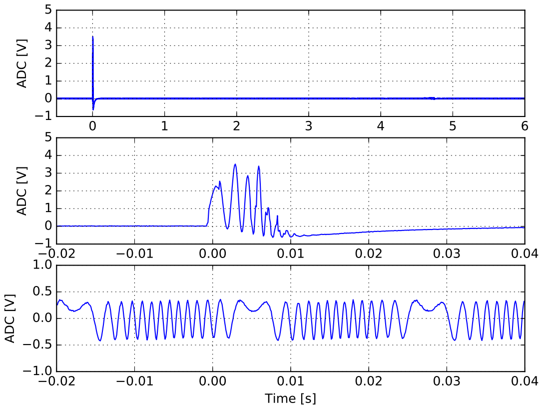

Figure 2: Upper two traces: Michelson detector for discharge 20180814.022 with 5 gyrotron start-up. Lower trace: calibrated reference signal recorded directly afterwards. The peak-to-peak level corresponds to 0.6 mW/15 (notch filter atteunates a factor 15) = 40 μW. Using this scaling, the power at start up into the Michelson is ≈ 0.14 mW with the notch filter and ≈ 2 mW without the notch filter.

While remaining at reduced gain (10^4) an assessment of O2 heated plasmas was carried out. Fig. 3 shows pulse 20180814.027 with O2 heating and terminated by a gyrotron interlock. During the pulse no stray radiation is seen at the reduced gain setting, but towards the end of the pulse there is a very high stray radiation and a gyrotron interlock. This ECH power becomes clearly visible in the Michelson signal but the gyrotron power is cut at ≈ 10% of the power at ECH plasma start up.

Based on the above data, for which a larger data set is available, is was decided to operate the Michelson with a mechanical shutter that opens 100 ms after plasma breakdown. This ensures protection during start-up and optionally allows the notch filter to be removed.

At the time of writing there was not yet an opportunity to use the instrument at high gain (i.e. normal operation) in O2-heated plasmas. But data in X2-heated plasma's is available. An illustration is given in Fig. 4 for pulse 20180822.30. This was a 20 s long discharge, 3 MW ECH heating and an electron density around $2 \cdot 10^{19}$ m^{-3}. The total video gain of the Michelson was 10^6. The notch filter was in place during the first 10 seconds and was then removed.

To assess the impact of the 140 GHz component on the time trace recall that the mirror frequency is 22 Hz, resulting in a sweep (half a period time) of ≈ 23 ms.

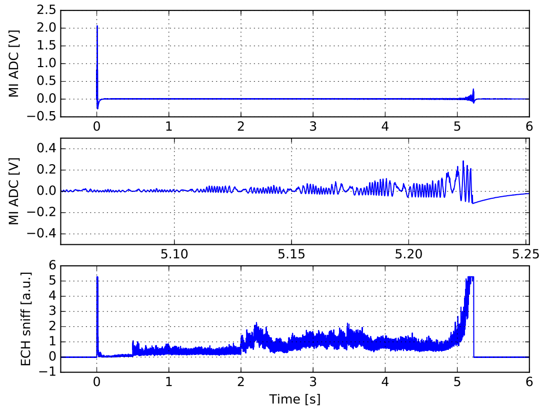

Figure 3: Upper two traces: dischare 20180814.027, O2-mode heated and terminated by a gyrotron interlock. Lower trace: ECH sniffer probe. The scaling is the same as in Fig. 2 from which it is concluded that the power entering the Michelson in such accidental cases is limited to fractions of a mW.

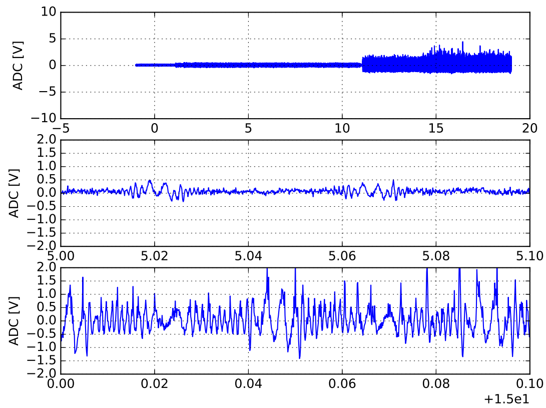

Figure 4: Discharge 2080822.030, 20 s discharge with 3 MW ECH and electron density around $2 \cdot 10^{19}$ m^{-3}. The notch filter was included in the first half of the discharge (detail in box 2), and removed in the second half (detail in box 3)

In the 100 ms shown four interferograms are present. The optical path of one sweep is ≈ 15 mm, which is traversed twice in the system (to the mirror and back). The wavelength at 140 GHz is 2.1 mm and one expects ≈ 30/2 = 15 interference fringes due to stray radiation in a sweep of the mirror. These fringes indeed dominate in box 3 (no notch filter). In box 2 the 140 GHz fringes are less pronounced, but a penalty is the 10 dB insertion loss of the filter and the additional bandwidth that the filter removes.

The *absolute* power level of the ECH in the signal is of the order of several μW recalling that an additional video gain of 100 has been used. Without the notch filter, the ECE power is below the ECH power and therefore masked by it. But in discharges where the electron temperature is high and where the plasma confinement time is sufficient, there is an oppurtunity to observe data without ECH after the the ECH is switched off. Such an example is given in Fig. 5

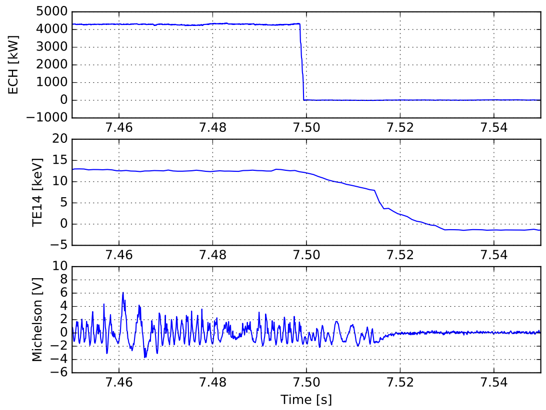

Figure 5: Discharge 2080823.044, 5 MW ECH, n_e around $2 \cdot 10^{19}$ m^{-3} and high electron temperure. At 7.5 s the ECH is switched off and the power is zero within a ms. But the plasma requires time to cool as illustrated by central ECE-channel TE14 and the interference after t = 7.50 s contains no ECH component.

The discharge in Fig. 5 shows an amplitude of the ECE induced interference of 2 V. Comparsion to the reference in Fig. 2 (lower trace) a 2 Volt signal corresponds to 80 μW. With the additional video gain of a factor 100 in the measurement in Fig. 5, the ECE power scales to about 0.8 μW. In this X2 heated discharge this leads to ECE and ECH levels within an order of magnitude without the notch filter used.

There are example of discharges in X2 heated plasmas where the absolute ECH level is a considerably larger, judging at the current data set by a factor 5 to 10. Evaluation of the spectra shows the 140 GHz component also at such magnitude above the ECE suggesting a linear response. Measurements on O2-heated plasmas - where large ECH power in the spectrum is expected - were at the time of writing not available yet. Recalling that the detector is linear over several orders of magnitudes, the relatively large ECH levels will not cause a problem as long as it does not reduces the response at other frequencies ('compression'). This will be studied in subsequent work by preforming a hot source calibration while injecting a strong 140 GHz signal.

5. Summary

Initial measuremenst with the Michelson Interferometer at W7-X show ECH levels at the input of the instrument lower then expected. By using a mechanical shutter that blocks the receiver waveguide during ECH plasma start-up this may, in X2-heated plasmas, allow a mode of operation without the notch filter. A calibration including a compression test is scheduled to investigate whether a strong 140 GHz component in the spectrum in such case does lead to compression. The lower ECH stray radiation levels as measured at the input of the instrument also lead to reduced demands on the notch filter. The current prototype, when used with the dedicated quasi-optiocal rig, could readilly suffice. But a mark II notch filter with superior materials, drawing on the experience with the current design, could also be conceived. The front-end losses of the instrument of 15 dB, excluding the notch filter insertion loss, are high and should be reduced.

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