

# Assessment of ECH stray radiation levels at the W7-X Michelson Interferometer and Profile Reflectometer

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**Abstract.** Electron Cyclotron Heating and Electron Cyclotron Current Drive are key components for heating and control in magnetically confined fusion plasmas. The high power microwaves are not always completely absorbed leading to stray radiation [1], [2]. At W7-X, the total injected microwave power can be up to 7.5 MW @140 GHz while the entire Electron Cyclotron Emission picked-up by an observer at the edge of the plasma is a fraction of a mW. In the situation of a Michelson Interferometer, the principle measurement is the entire ECE spectrum. Thus, any stray radiation is bound to enter the spectrum. In this work initial stray radiation measurements without filters at the location of two microwave receivers - the Michelson Interferometer and the Profile Reflectometer - are discussed. The data is used to dimension a notch filter to be used with the broad band Michelson Interferometer.

## 1 Introduction

A Michelson Interferometer is being prepared for W7-X operations from campaign OP1.2b onwards, scheduled July - October 2018. The objective of the work reported here is to find both the absolute power at the input of the instrument as well as the ratio of ECH to ECE power to assess the impact of stray radiation. In support of this, stray radiation measurements at the location of Michelson Interferometer as well as at the location of the Profile Reflectometer have been carried out during the previous W7-X experimental campaign (OP1.2a). Spurious gyrotron mode have not been included in this work.

## 2 Instruments and waveguide system

Both the Michelson Interferometer and the Profile Reflectometer use in-vessel horn antennae. The signals are relayed from the vessel by means of oversized waveguide to the Diagnostic Hall. A sketch is given in Fig. 1.

### 2.1 Michelson Interferometer

The Michelson Interferometer is designed to operate from 50 ··· 300 GHz. The in-vessel antenna of the ECE diagnostic is located in module 4 (port 'AEE41'). It is constructed by a quasi-optic section of mirrors that project the collected beam onto a horn antenna with a diameter of 36 mm. The output of the horn is tapered to 4 mm circular waveguide and subsequently passes a single disk mica vacuum window. On passing the window the waveguide is tapered to 28 mm smooth walled circular waveguide and split into X- and O-mode by a wire grid. These waveguides then continue to the diagnostic hall where, by means

of switches, X-mode is coupled to the radiometer and O-mode to the Michelson Interferometer. The overall waveguide length between vessel and instrument is  $\approx 22$  m. The losses of waveguide up to the radiometer have been measured in advance of OP1.2a using a 140 GHz source and are 13.5 +/- 0.5 dB (waveguide relay in TE<sub>11</sub> mode). The losses starting at the input of the wire grid through the vacuum windows, tapers and up to the horn antenna are estimated to be 3 dB, resulting in an estimated overall transmission line loss of 16 dB.

### 2.2 Profile Reflectometer

The edge Density Profile Reflectometer is situated in module 2 (port 'AEA21') and is still under development. In the case of the profile reflectometer the in-vessel antennas consists of two horns with diameter 62 mm, located such that their beams intersect in the edge region of the plasma. The upper horn was used in the experiment. The horn guides the power into a section of circular waveguide that tapers to 4 mm diameter in order to pass the mica vacuum window. Following the window the waveguide is tapered up to 28 mm smooth walled circular waveguide and continues to the diagnostic hall. While the overall waveguide length is comparable to the ECE-system, the losses are lower. This can possibly be explained by fewer components in the Transmission Line (e.g. no X/O splitter, no polarisation tuner). The losses in the Tx-Line from window to instrument were measured, similarly as in Sec. 2.1, and are 8 +/- 0.5 dB. The loss from vacuum window up to the in-vessel horn aperture is estimated at 2 dB, such that the overall loss of the Tx-Line is set to 10 dB.

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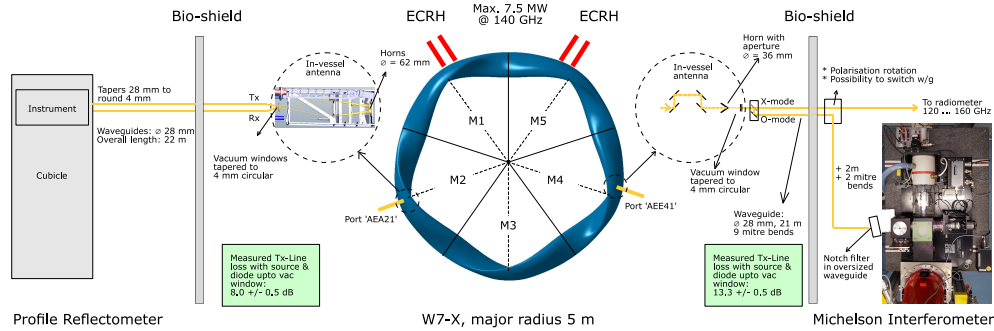


Figure 1: Michelson and Profile Reflectometer waveguide systems at W7-X

### 2.3 Stray radiation probe

The stray radiation measurements were carried out close to the entrance of the instruments, i.e. directly behind the tapers from circular 28 mm diameter to fundamental. For the stray radiation measurements the 28 mm circular waveguide was tapered to D-band (110 ··· 170 GHz). The signal was - by means of a variable attenuator - terminated on a single mode Schottky detector diode. The detectors were calibrated with a 140 GHz source using an isolator and a variable attenuator. With the attenuator set to 0 dB, the output power was measured as 0.6 mW, corresponding to 10 V at the ADC. The combination of detector diode and pre-amplifier resulted in a sensitivity of the sniffer probe of 17 V/mW at low power. The lowest power level that could be detected without additional video conditioning was around - 35 dB below 0.6 mW (i.e. 0.2  $\mu$ W). In the Michelson configuration the probe measured O-mode and in the Profile Reflectometer configuration the probe measured X-mode.

## 3 Expected power levels

### 3.1 ECH

In-vessel stray radiation levels are obtained from [3]. For over-dense plasmas (O2-heating) stray radiation levels as measured by bolometers are of the order of 10 kWm<sup>-2</sup> for module 2 (Reflectometer) and 4 kWm<sup>-2</sup> for module 4 (Michelson). This data is for injection of 5 MW ECH. For X2 heated plasmas, optically thick and not in cut-off, stray radiation will predominantly originate from the ECH launchers and mismatches in polarisation launch, and these levels will be lower. In the presence of a plasma a more or less isotropic and homogeneous power density is found in the volume between the plasma surface and the vessel components. In such case, the stray radiation is present under all angles and polarisations and the absolute ECH power coupled into the horn is obtained by multiplication of the physical antenna aperture with the power density but reduced by the antenna directivity. In this assessment the antenna directivity of the horns is taken to be 20 dB, compared to the ideal situation of an omni-directional sniffer probe at 0 dB. The power that reaches the detector is subsequently reduced by i) rejection of modes, and ii) attenuation of the waveguide for stray radiation. The

reduction of modes is here taken to be the ratio of all modes that can propagate to those reaching the detector, i.e. one mode in this case (single mode detector). An estimate considering all possible modes in circular oversized waveguide is given by:  $N = 0.85 \left(\frac{f}{f_0}\right)^2$  [4], with  $f_0$  the fundamental cut-off frequency in the waveguide (here TE<sub>11</sub>). For the Michelson horn antenna one finds of the order of 700 modes while for the Reflectometer horn one finds of the order of 2000 modes. Expressed in decibels the ratios multi-mode at horn aperture to single mode at detector are -28 dB resp. -33 dB. The attenuation of the waveguide for stray radiation is here taken to be the same as that measured with the RF-source and diode in section 2.

### 3.2 ECE

The ECE power is emitted in two modes (X- and O-mode). The circular in-vessel antenna has been arranged such that the antenna pattern is completely illuminated by the ECE in either of these two modes. Under such condition, and with the plasma optically thick, the power coupled into the waveguide is  $\approx$  kTB per mode using the Rayleigh-Jeans approximation for black body radiation, with k Boltzmann's constant, T the electron Temperature and B the bandwidth [5]. The TRAVIS code [6] was used to verify the ECE spectrum for typical temperatures (5 keV) and densities ( $5 \cdot 10^{19}$ m<sup>-3</sup>), see Fig. 2. It is seen that the power in the 2-nd harmonic O-mode is less than that in the 2-nd harmonic X-mode. As the Michelson probe measures in O2-mode, less power than based on kTB may be expected. When calculating the power over the entire spectrum, one should take the particular electron temperature profile into account as the central electron temperature would result in an over-estimate. In this estimate a parabolic electron temperature profile has been assumed which results in a reduction of the overall power by a factor of 1.5 with respect to a 'top-hat' profile.

### 3.3 Estimate

Table 1 gives the expected power as found using the data in sections 3.1 and 3.2.

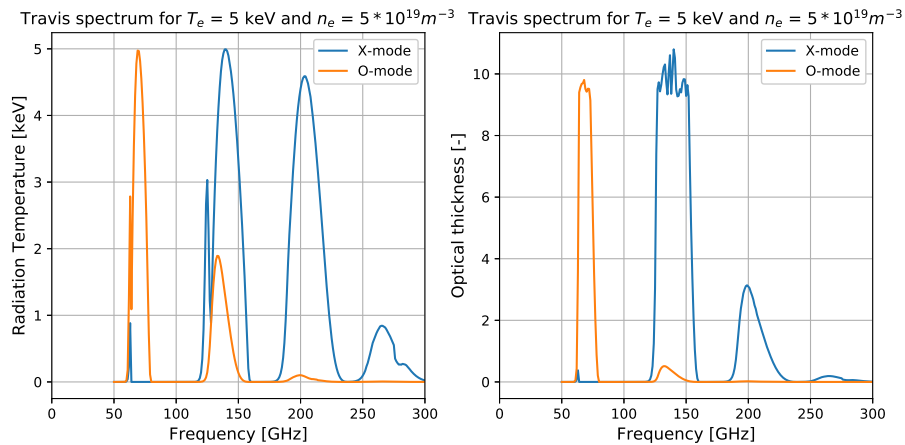


Figure 2: Data from Travis, left: radiation spectrum and right: optical depth.

	Power Density [Wm <sup>-2</sup> ] / 5MW	System	Ant. dia. [mm]	P_ant. [W]	P <sub>ECE</sub> (kTB) [μW]	ECH/ECE @ Ant. [dB]	ECH/ECE on Det. [dB]
Module 2	12000	PR	61	0.35	32	40	7
Module 4	4000	MI	36	0.04	32	31	3

Table 1: Expected power levels. The column  $P_{ant}$  gives the maximum ECH power coupled into the antennae: the power density multiplied with the antenna aperture but reduced by the antenna directivity. PR stands for Profile Reflectometer and MI for Michelson. The column  $P_{ECE}$  is the ECE power over D-Band, taking a central electron temperature of 5 keV and assuming a parabolic profile. Next the power ratio ECH to ECE in-vessel is calculated. The last column gives this ratio in front of the Michelson: here the stray radiation is strongly reduced due to the transition from oversized horn antenna to single mode detector.

## 4 Experiment

Availability of waveguides - in demand for other diagnostic data - restricted the measurements to a number of days towards the end of campaign. Nevertheless useful data was obtained but in X2 heated plasmas only. It was found that RF-attenuation before the diode could be reduced to below a factor 10 before the ECH signal during *start-up* approached 1 mW on the detector. During the *plasma phase* the stray radiation power was mostly too low to detect but note that only X2-heated plasmas were available. Fig. 3 shows a panel with time traces, the left hand column shows the overall pulse, the right hand column a zoom during start-up. The first row (a & b) shows signals for the total ECRH power, the second row (c & d) the Michelson stray radiation probe ('MI-probe'), and the third row (e & f) the Profile Reflectometer stray radiation probe ('PR-probe'). In this discharge the central electron temperature was around 5 keV. The central density was varied, but between 1 to 4 seconds it was in the range of  $5 \cdot 10^{19}$  electrons  $m^{-3}$ . The attenuation in front of the MI-probe was 4 +/- 1 dB while for the PR-probe it was set to 0 dB. It is seen that the stray radiation probes, on the 10 V scale of the ADC, only show signal during the plasma start-up, i.e. when ECRH power is injected but there is no absorption by the plasma yet.

The experimental program was not dedicated to stray radiation measurements. However, polarisation scans with

the probes themselves were carried out and the W7-X program required various ECH launcher angles. An initial assessment shows no large deviation from the presented data, however, a systematic analysis of launcher angles and polarisation - requiring additional measurements - is planned.

During start-up the data shows a large standing wave pattern of stray radiation that varied with launching angle and polarisation. But the amplitude rarely clipped the limit of the ADC, and if it did so, only just. During the plasma phase, limited stray radiation (below the levels at start-up) is observed during a number of pulses where the density is too high or too low.

The relatively low waveguide attenuation for the PR-probe, the 0 dB setting of the attenuator and possibly the X-mode measurement opposed to O-mode, made it possible to see a finger-print of the ECE during the plasma-phase of the discharge on the PR-probe. This is shown in Fig. 4, now with a *vertical* zoom on the PR-probe and as a reference a central radiometer EC-channel (# 14, 138.085 ... 138.435 GHz).

## 5 Discussion

Both probes show strong ECH stray radiation during plasma start-up. As the power fluctuates wildly, and is made up out of standing waves, it is not possible to give an accurate estimate of the power. But the signal very rarely

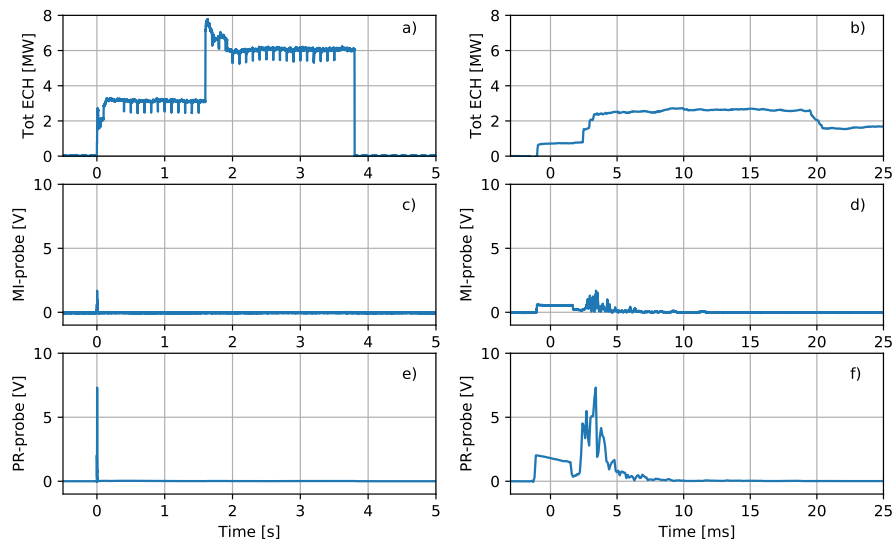


Figure 3: Data for # 171207009. Traces in the left hand column show the overall discharge, traces in the right hand column a zoom on plasma start-up. Top: ECRH total power, center: the Profile Reflectometer stray radiation probe and lower the Michelson Interferometer stray radiation probe.

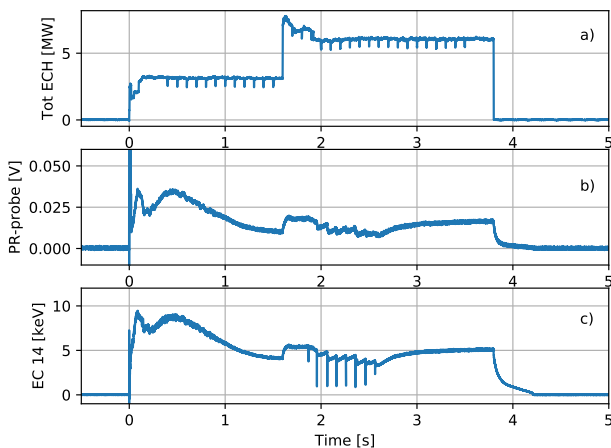


Figure 4: ECE finger-print on Profile Reflectometer stray radiation probe (b) using the data as in Fig. 3. For comparison a central ECE channel is shown (c). After ECH switch-off (@ 3.8 s) the signal from the probe falls off exponentially with the confinement time showing that no large ECH stray radiation power component seemed present.

saturated and is limited to 1 mW in the single mode measured. The Michelson is multi-mode but with the number of modes limited by the  $\approx 10$  modes that the 4 mm section of transmission line in the vacuum window can support (see Sec. 3.1). The total power reaching the Michelson is then expected to be at maximum 10 times larger, i.e. at maximum 10 mW during start-up. Note that this is based

on the *estimates* of modes, and the assumption that the total power is spread equally over these modes. As the power at start-up is expected (and observed) to be far in excess of stray radiation during the plasma phase of the experiment, the notch filter maximum ECH power is set at 10 mW. The ECE losses from vessel to Michelson are 16 dB, or  $\approx$  a factor 40. If one demands the ECH power to be reduced to the overall ECE power at the input of the Michelson one finds a ratio of  $10 \text{ mW} / 1 \mu\text{W} = 40 \text{ dB}$ . Such a ratio is useful as the detector will remain in the same dynamic range during start-up and during the plasma phase.

During the plasma phase the expected ratio ECH to overall ECE for a single mode detector is given in the last column of Table 1. For the Michelson, exposed to 10 modes, the ratio is 10 dB higher. When rounded the ECH power in O2-heated plasma is expected  $\approx 15 \text{ dB}$  more than the overall ECE power. In the experiment, **but X2 mode heating opposed to O2-mode**, the ratio ECH to overall ECE appears to be below unity.

To validate the ECE component a consistency check can be made. Referring to Fig. 4 the ECE power scales to around 20 mV in the ADC. This signal is the ECE response over  $120 \dots 170 \text{ GHz}$  in X-mode (Reflectometer probe) and as such represent a 'spatially averaged' ECE power. From the detector scaling of  $17 \text{ V} / \text{mW}$  it follows that 20 mV measured with the ADC corresponds to  $\approx 1.2 \mu\text{W}$  on the detector. Applying the overall transmission line attenuation of 16 dB between the instrument and the in-vessel antenna, the power at the in-vessel antenna is 16 dB more, or  $48 \mu\text{W}$ . In Table 1 it is estimated to be  $\approx 32 \mu\text{W}$ . From this it is concluded that the expected ( $\approx 30 \mu\text{W}$ ) and measured ECE power ( $\approx 50 \mu\text{W}$ ) are consistent given the margins on such an ECE power measurement.

The probe on the Michelson does not show an ECE signal. But the losses in the Michelson transmission line are higher by  $6 + 4$  (attenuator) = 10 dB. This reduces the  $1.2 \mu\text{W}$  as measured by the Profile Reflectometer probe to  $0.12 \mu\text{W}$ , indeed at the limit of the probe.

## 6 Conclusions and future work

Measurement complemented by modeling suggest that the maximum stray radiation power during ECH start-up, at the input of the Michelson, will not exceed 10 mW in the specific W7-X configuration. A notch at 40 dB brings the signal in the same order of magnitude as the overall expected ECE power. Expected stray radiation levels during the plasma phase in O<sub>2</sub>-heated plasmas are of the order of 15 dB above the ECE levels. A notch filter at 40 dB would cope with this. This margin is comfortable given uncertainties such as i) extrapolation from power measured with a single mode detector to power measured in multi-mode with the Michelson, ii) assumptions on the difference in directivity of a sniffer probe compared to a ECE-horn, and iii) a limited data set in ECH heated plasmas as of yet, and excluding O<sub>2</sub>-heated data. A careful measurement campaign with the Michelson, with the notch filter in place, is required to verify the results.

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