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Optimization of the Collective Thomson Scattering Diagnostic for Future Operation

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Abstract: Collective Thomson scattering (CTS) is a microwave diagnostic allowing measurements of a number of plasma parameters such as the bulk ion temperature, the plasma composition, drift velocities and fast ion velocity distribution function. A CTS system has been successfully installed and commissioned on the Wendelstein 7-X (W7-X) stellarator. The measured spectra are analyzed by the means of the CTS forward model eCTS and the Minerva scientific framework enabling the use of Bayesian inference of relevant plasma parameters. Here we discuss the options for further optimization of the CTS diagnostic and focus on two topics of importance for the inference of bulk ion temperature values from CTS spectra: influence of impurities on the CTS spectra and the width of the notch filters that are employed to protect the receiver from high-power radiation. In addition to that we discuss the possibility of effective charge measurements by CTS. We explore the existence of an optimal notch filter width.

Keywords: nuclear instruments and methods for hot plasma diagnostics, analysis and statistical methods

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Contents

1 Introduction

The Wendelstein 7-X, the world's largest optimized stellarator, has completed two operational periods OP 1.1 (in 2015-2016) and OP 1.2 (in 2017-2018). Collective Thomson scattering (CTS) is a microwave diagnostic capable of measuring a number of plasma parameters [?]. CTS has recently been installed and commissioned on Wendelstein 7-X (W7-X) during OP 1.2, and first measurements of bulk ion temperature, T_i, by CTS were obtained [?]. CTS and deuterium-based charge-exchange recombination spectroscopy measure the deuterium temperature [?], whereas the more common impurity-based charge-exchange recombination spectroscopy diagnostics measure the impurity temperatures [?]. CTS diagnostics are in operation at the LHD device [? ?] and ASDEX Upgrade [?] and will be an important diagnostic at ITER [?]. The measured spectra at W7-X were extensively compared with numerical simulations made by the forward model eCTS [? ?] whose input parameters were inferred by the Bayesian Maximum-A-Posterior method in the Minerva framework [?]. The obtained value of T_i is in agreement with the result obtained by the X-ray imaging spectroscopy [?], and agreement was obtained between synthetic and measured spectra, yet a few discrepancies in spectral shape and width were noted [?]. In this paper we will discuss a possible cause of these discrepancies, namely, the plasma impurity content and its effect on synthetic CTS spectra (Section 2). Impurity ions, being heavier than the hydrogen ions, give rise to contributions to the scattering spectrum close to the central wavelength, thereby distorting the spectrum of the scattering on pure hydrogen.

Additionally we will elaborate on an important consideration for future operation of CTS on W7-X: the influence of the notch filter width on the temperature inference quality. The CTS system on W7-X features two notches at 137 GHz and 140 GHz which are 1000 MHz and 500 MHz wide, respectively. They protect the sensitive heterodyne receiver from high-power radiation. In addition we also have a built-in interlock into the pin-switch which closes automatically if too strong a signal is detected behind the notch filters. The notch filters can be tuned to block a more narrow frequency band which may be beneficial for the bulk ion temperature inference quality. However, as the risk of damaging the CTS receiver increases with the decrease in the notch filter width, it is worthwhile to investigate if an optimal width exists (Section 3).

2 Impurity Content and Temperature Inference

In W7-X plasmas impurity concentrations have been measured by charge exchange recombination spectroscopy and passive spectroscopy. The impurities with the largest concentrations in OP1.2 were carbon, oxygen and argon. In particular the effect of carbon was clearly visible in CTS measurements [?] and needed to be accounted for in the inference of bulk ion temperature, T_i, from the measured spectra. The spectral width, from which T_i is inferred [**? ?**], is sensitive also to the impurity content. To further explore the implications of this for ion temperature measurements by CTS, it is of interest to answer two questions:

1. How large is the error one makes if the plasma is assumed to be pure?
2. How many impurity species should be accounted for in the analysis?

To answer these questions we investigated how the spectra change if the concentration and the number of impurities are varied. We calculated synthetic spectra at $T_i = 3$ keV for different concentrations of the two main impurities: carbon and oxygen. The carbon concentration was varied from 1% to 5% in a hydrogen plasma. The result is depicted in Figure **??** on the left. The oxygen concentration was varied from 0.6% to 1% in a hydrogen plasma[1]. The result is depicted in Figure **??** on the right. In both figures the borders of the rectangular notch region are indicated.

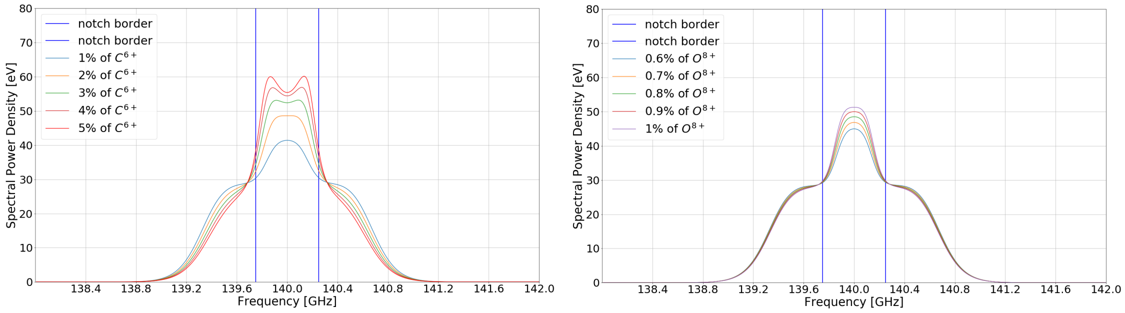

Figure 1: Left: synthetic CTS spectra calculated for different carbon concentrations at bulk ion temperature $T_i = 3$ keV. The larger the amount of carbon, the more narrow the spectrum. Right: synthetic CTS spectral calculated for different oxygen concentrations at bulk ion temperature $T_i = 3$ keV. The effect of oxygen on the wings of the spectrum is small. A larger effect is in the central region which is not visible in measured spectra as it falls within the notch.

In Figure **??** the electron density is a fixed parameter thus the hydrogen ion density decreases with the increase of impurity ions. The change in ion density has a scaling effect on CTS spectra [**?**]. Temperatures of all ion species are assumed to be equal and set to 3 keV. As can be seen in Figure **??**, the spectra consist of two parts: the narrow impurity feature (absent for pure hydrogen plasma) and the broad feature (containing information about both the impurity ions and the bulk ions). It follows from theory that the heavier the impurity is, the more narrow the impurity feature is, at a given ion temperature. This means that often the impurity feature is completely within the notch region which in practice is wider than indicated in Figure **??**. Effective widening of the notch in measurements is due to the non-ideal characteristics of notch filters causing a poor signal-to-noise ratio in a wider spectral range. However, even if the impurity feature is within the notch, the impurities affect the broad spectral feature outside the notch. The increase in impurity concentration, at a given ion temperature, leads to an overall narrowing of the spectral width. Therefore, not accounting

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[1] The oxygen concentration range was chosen based on preliminary measurements obtained by charge exchange recombination spectroscopy during OP1.2.

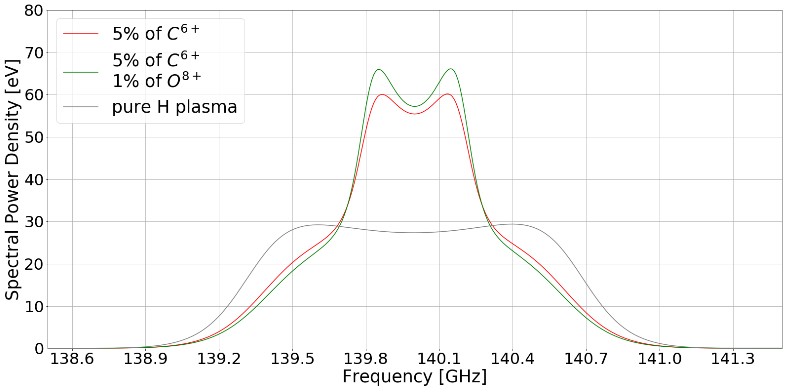

Figure 2: Comparison of a hydrogen plasma with carbon impurity and a hydrogen plasma with a mixture of carbon and oxygen impurities.

for the impurity content will lead to underestimations of the inferred bulk ion temperature. To quantify the underestimation we inferred the ion temperature assuming a pure hydrogen plasma, from the spectrum calculated for a hydrogen plasma containing 5% of carbon. The result of the inference yielded a value of $T_i = 2.3$ keV (instead of the correct value of $T_i = 3$ keV). The number of different impurities to be accounted for was investigated by comparing spectra calculated with several impurity species to spectra calculated with one main impurity - carbon in our case. It was found that the spectral width, and thus the inference of T_i, is dominantly affected by impurity with the largest concentration. This can be seen in Figure **??** where we compare a spectrum with 5% of C^{6+} ions to a spectrum with the same carbon concentration but with added 1% of O^{8+} ions. The change in width caused by the addition of 1% of O^{8+} ions is within the expected error bars and thus the inclusion of oxygen in the analysis will not improve the accuracy of the T_i measurement significantly. However, the discrepancy visible in Figure **??** can be understood in terms of the sensitivity of the spectra to the effective charge:

$$Z_{eff} = \frac{\sum_i Z_i^2 n_i}{n_e} \tag{2.1}$$

where the summation goes over the ion species, Z_i and n_i are the charge and density of the corresponding ion i, n_e is the electron density. The sensitivity to changes in Z_{eff} can be used for improvement of T_i inference[2] provided information on impurities obtained from other diagnostics is incorporated into the CTS analysis.

3 Notch Filter Width and Temperature Inference

The CTS probing radiation on W7-X is supplied by one of the ECRH gyrotrons [**?**] operating at 0.5 – 1 MW output power and 140 GHz probing frequency. The CTS uses a sensitive heterodyne receiver to measure a scattering signal in the frequency band 135 GHz to 145 GHz. The receiver needs to be protected from incident gyrotron and stray radiation. To this end, notch filters are used

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[2] Or inference of Z_{eff} from CTS measurements which is outside the scope of this paper.

to attenuate signals in a frequency band around the probing frequency. For this reason the data points measured within the notch region have to be discarded in the data analysis process. Bayesian inference can be used on what remains of a spectrum after the notch region has been removed. To investigate how the notch width affects the inference of bulk ion temperature, we analysed a spectrum from which regions of increasing width have been removed. The synthetic spectrum and the simulated notch widths are depicted in Figure **??** where the narrowest notch region is 0.2 GHz and the widest is 1.4 GHz.[3] We initially inferred the ion temperature from the full spectrum obtaining convergence after approximately 100 iterations and the result $T_i = 5 \pm 0.01$ keV. Then we inferred the ion temperature from the same spectrum from which notch regions of differing widths were excluded and the number of iterations pre-set to 500. The exercise was repeated with Gaussian noise introduced into the notch region[4]. It was found that the inference for a pre-set number of iterations is improved by the addition of noise. We understand that in a Bayesian fashion in terms of the amount of information in this spectral region. Namely, the removed region is dominated by the impurity contribution which is not very sensitive to the changes in bulk ion temperature[5]. Thus the presence of noise is recognized as an indication of a lack of useful bulk temperature information within the notch. This led us to the conclusion that notches wider than the currently employed can be used without causing loss of accuracy in T_i inference. The constraint on the notch width is given by the lowest expected bulk ion temperature (the wings of the spectrum must remain outside of the notch otherwise no signal can be detected).

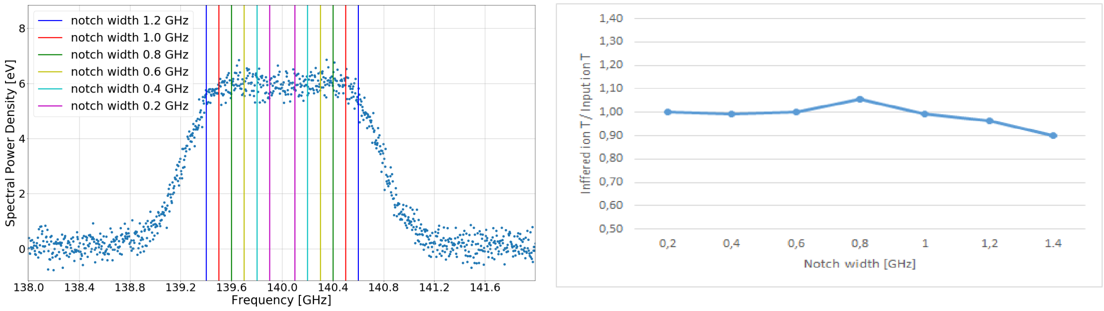

Figure 3: Left: A synthetic spectrum with added noise from which regions of different widths have been omitted and ion temperature inferred. The input temperature is $T_i = 5$ keV. The part of the spectrum within the notch does not carry information about the bulk ion temperature. Right: The ratio T_{output}/T_{input} is given as a function of the omitted notch region widths.

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[3] Note that the negative values of spectral power density in Figure **??** are not physical. Gaussian noise is generated independently from the calculated synthetic spectrum and is then added to it which results in the spectrum shown in Figure **??**.

[4] Introduction of Gaussian noise can be justified by considering that when background is subtracted from a measured CTS signal, and calibration is applied, what remains is thermal noise.

[5] The impurities affect the inference quality through plasma dilution as explained in Section 2.

4 Summary and Conclusion

We looked into two topics important for the data analysis and operation of the CTS diagnostic: impurities and the notch filter width.

Study of the influence of impurities on synthetic CTS spectra led us to conclude that for bulk ion temperature inference it suffices to account for the dominant impurity in the data analysis.

The minimum width of the hardware notch is constrained by the CTS receiver safety in given experimental conditions. On W7-X, the probing gyrotron is one of ten ECRH gyrotrons. This implies that there can be unabsorbed ECRH radiation entering the receiver at frequencies close to the probe frequency. Furthermore, the gyrotron frequency can be unstable and chirps in frequency occur when the source is turned on or off. For these reasons a hardware notch of several hundred MHz is currently necessary (at the moment 500 MHz). However, the notch width study showed that notch regions larger than the currently employed on W7-X are acceptable for bulk ion temperature inference. The maximum width of a hardware notch which could be used depends on the width of the expected spectra defined by the relevant ion temperature range and impurity content. The replacement of data within the notch region by Gaussian noise prior to the Bayesian inference of T_i, will reduce the number of iterations needed for convergence of the fit.

The possible improvement of T_i inference by independent measurement of effective charge should be further investigated.

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