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Fast Analysis of Collective Thomson Scattering Spectra on Wendelstein 7-X

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Two methods for fast analysis of Collective Thomson Scattering (CTS) spectra are presented: Function Parametrization (FP) and feedforward Artificial Neural Networks (ANNs). At this time, a CTS diagnostic is being commissioned at the Wendelstein 7-X stellarator, with ion temperature measurements in the plasma core as its primary goal. A mapping was made from a database of simulated CTS spectra to the corresponding ion and electron temperatures (T_i and T_e). The mean absolute mapping errors are 4.2% and 9.9% relative to the corresponding T_i , for the ANN and FP, respectively, for spectra with Gaussian noise equivalent to 10% of the average of the spectral maxima in the database at spectral density 650 GHz^{-1} and within a limited parameter space. Although FP provides some insight in the information contents of the CTS spectra, ANNs provide a higher accuracy and noise robustness, are easier to implement and more adaptable to a larger parameter space. These properties make ANN mappings a promising all-round method for fast CTS data analysis. Addition of impurity concentrations to the current parameter space will enable fast bulk ion temperature measurements in the plasma core region of W7-X.

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I. INTRODUCTION

In the quest for energy generation by controlled nuclear fusion, experiments are conducted in devices that confine hot (hundred million C) plasma of hydrogen isotopes in a toroidal geometry by means of a strong magnetic field. The two leading magnetic confinement concepts are the tokamak and the stellarator. Both feature a helical magnetic field in a toroidal geometry, but where the tokamak is characterized by a strong electric current inside the plasma, the field in the stellarator is entirely generated by external coils. While this comes at the cost of a more complex design, the potential advantages are that the stellarator is intrinsically steady state and has more resilience against plasma instabilities. The most recent large stellarator experiment is the Wendelstein 7-X (W7-X) device in Greifswald (Germany), which saw its first successful campaign in 2016¹. It aims at demonstrating the reactor potential of the so-called optimized stellarator configuration.

In order to gain information on the plasma properties in fusion reactors, a variety of diagnostic techniques are employed.

This paper focuses on Collective Thomson Scattering (CTS), a diagnostic that measures the scattered waves from a narrow, collimated beam of high power mm-waves that is launched into the plasma. The collected spectra contain information on the ions in the plasma, and can in principle be used to obtain ion-related plasma parameters, such as the bulk ion temperature, ion velocity distribution and plasma composition.

To describe the scattering process and compute the scattered spectra, the forward code eCTS is available². For the interpretation of measured spectra, the eCTS code is integrated in the generic Bayesian data analysis framework Minerva, implemented at W7-X³. However, finding the best fit using the eCTS code requires many runs, which takes up to several minutes of computation per spectrum. In this paper we explore the possibility to develop a custom-made inverse mapping, by analysing a data set of simulated spectra that covers the expected operational space of the experiment. We compare the so-called Function Parametrization (FP)^{4?} which defines an inverse mapping based on functions that are used to interpolate between the points in the data base, and the more generic approach of Artificial Neural Networks (ANNs). Both techniques require the construction of a data set of spectra, a form of data reduction such as binning or Fourier analysis, and result in an inverse mapping that can be applied to the data in real time. Moreover, the fast inverse mapping

can be used to do optimization studies, e.g. to tune the diagnostic set up for a particular parameter, or sensitivity analysis, e.g. to investigate the feasibility of the measurement of additional quantities, such as the radial electric field, for given experimental noise. These techniques are generic and have been applied to other diagnostics⁴⁻⁶. We applied them to the specific case of CTS at W7-X, for the given set of parameters. Once the methodology has been set up, creating a mapping for different parameters is a relatively simple action. We first give a short description of the W7-X environment and the CTS diagnostic in section II, then discuss the spectrum information content, dimension reduction and the example database in section III. The principles of the FP and NN techniques and their implementations are recalled in sections IV and V, respectively. Finally, in section VI, we discuss the relative merits of both methods.

II. COLLECTIVE THOMSON SCATTERING ON W7X

Collective Thomson scattering is the scattering of electromagnetic radiation off of fluctuations in the electron density, electric field, magnetic field, and current density. Scattering of the probing radiation is collective provided that the condition $(\lambda_D k^\delta)^{-1} > 1$ is satisfied⁷, where λ_D is the Debye length, and $\mathbf{k}^\delta = \mathbf{k}^s - \mathbf{k}^i$ specifies the direction along which the fluctuations are resolved. The main contribution to the bulk-ion part of the scattered spectrum comes from the electron density fluctuations. It is a powerful mm-wave diagnostic that has successfully been applied on a number of fusion experiments⁸⁻¹². CTS spectra are sensitive to a broad range of parameters, including the electron density, ion species densities, magnetic field and ion velocity distributions¹³. With a broad range of sensitivities comes a broad range of potentially measurable parameters, including the ion temperature, isotope ratio, fast ion velocity distribution, plasma rotation and MHD activity. A CTS system is being commissioned for the upcoming experimental campaign on the stellarator W7X. On W7X the first CTS measurements will be aimed at diagnosing the bulk ions. To this end, one of the 140 GHz electron cyclotron resonance heating gyrotrons, with the output power of approximately 500 kW, will be used as the source of the probing beam. High power of the probing beam is necessary due to the small scattering cross section of CTS. The local scattering process depends on geometric parameters including the direction and polarization

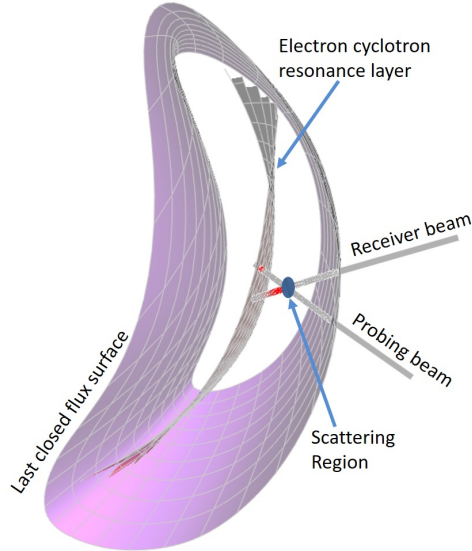


FIG. 1. Schematic of the CTS geometry on Wendelstein 7-X. The scattering angle $\theta = 130^\circ$, the observation angle $\phi = 110^\circ$. The second harmonic electron cyclotron resonance layer for 140 GHz is shown. The probing beam absorption region is in the resonance layer (depicted in red). The red region on the receiver beam path depicts a region of electron cyclotron emission at 140 GHz. The blue ellipsoid shows the location of the scattering volume, where the probing and viewing beams intersect.

of the incident beam, the local direction of the magnetic field, and local plasma properties such as density and temperature. In addition, the incoming and scattered waves propagate through a dispersive plasma in which cut-offs, resonances and refraction may occur. Locally, the CTS scattering geometry is determined by the following two angles: the observation angle $\phi = (\mathbf{B}, \mathbf{k}^\delta)$ and the scattering angle $\theta = (\mathbf{k}^s, \mathbf{k}^i)$. In this work, the geometry $\phi = 110^\circ$ and $\theta = 130^\circ$ in the bean-shaped plasma cross section was used, of which a schematic representation is shown in figure 1.

Inference of parameter values from the measured spectra is typically done using the Bayesian formalism in conjunction with a forward code of the scattering⁸. The developed forward model of CTS (eCTS) calculates the spectral density of the scattered power¹⁴. The shape and width of the CTS spectra are governed by the spectral density function, $S(\mathbf{k}^\delta, \omega)$, which in turn is influenced by a variety of plasma parameters⁸. The spectral density function in the eCTS code is calculated in the electrostatic approximation, where only the scattering

off of fluctuations in the electron density is taken into account². In this model, the spectral density function is given by¹⁵

$$S(\mathbf{k}^\delta, \omega) = S_e(\mathbf{k}^\delta, \omega) + \sum_i S_i(\mathbf{k}^\delta, \omega), \quad (1)$$

with S_e the electron scattering term and S_i the scattering terms due to electrons screening ion species i . The input parameters of eCTS are: the incident radiation mode, scattered radiation mode, incident power P_{in} , probing frequency ν_{in} , overlap volume O_b , electron density n_e , ion species densities n_i , electron temperature T_e , ion temperature T_i , strength of the magnetic field B , observation angle ϕ , and the angle between the probing and scattered waves $\theta = (\mathbf{k}^s, \mathbf{k}^i)$. Eight CTS spectra computed by the eCTS code, at different T_i and fixed scattering geometry, are shown in figure 2.

A. Mapping parameter space

In principle, all eCTS parameters can be included in the mapping, but it was decided to restrict the mapping to the parameter subspace that can be known *a priori* during a measurement, with an exception for the impurity effects, which were not implemented in the eCTS code that was used for this work.

In order to obtain this subspace, the following assumptions were made. Firstly, P_{in} , O_b , the electron density and the attenuation of the collection system are assumed to influence the collected spectral power density uniformly over the whole spectrum and are referred to as scaling factors. These are not known *a priori*. All these scaling factors were taken out of the model by normalizing each spectrum to its mean value before further processing.

During the next operational campaign, T_i is not expected to exceed 4 keV and $T_e \lesssim 8 \text{ keV}$. Both temperatures were taken as free parameters in the range $0.5 \dots 10.0 \text{ keV}$. During measurements, there is an uncertainty in the scattering geometry, mainly due to refraction of the probing and scattered radiation in the plasma. The range of angles that can occur for a fixed measurement set up was estimated to be $\pm 2^\circ$ for both θ and ϕ . The magnetic field as a function of scattering location is known, but due to uncertainty in this location, the magnetic field might slightly vary: $B = 2.2 \pm 0.05 T$.

In this work, Deuterium (ion mass $m_D = 2u$ and charge number $Z_D = 1$) was chosen as

TABLE I. Expected values of the relevant plasma and geometry parameters during measurement and the parameter ranges that were used in the mapping.

parameter	expected value	mapping parameter range
T_i	< 4 keV	0.5 - 10 keV
T_e	$\gtrsim 8$ keV	0.5 - 10 keV
θ	$130 \pm 2^\circ$	125 - 135°
ϕ	$110 \pm 2^\circ$	105 - 115°
B	2.2 ± 0.05 T	2.1 - 2.3 T
n_i/n_e	0.2 - 1	0.2 - 1.0

the main ion species. The impurity concentrations are not known. However, they affect the CTS spectrum in several ways. Firstly, by dilution: $n_e = \sum_i n_i Z_i$. This was simulated in a simplified way: by adding the main ion species density to the mapping parameter space. Since the electron density is considered a scaling parameter, the ratio n_D/n_e was used as input parameter, in the range 0.2...1. In a very clean plasma, the impurity concentrations can be so small that n_i comes close to n_e . To simulate such a clean plasma, another two mappings were made with the density ratio in the range 0.9...1.

Plasma impurities also affect the shape of the CTS spectrum. As stated in equation 1, each ion species has a contribution S_i to the total scattering. These terms do not only depend on general parameters (θ , ϕ , B , ω) and species-specific properties (m_i , Z_i , n_i , T_i), but also on the properties of other plasma species. A quantitative analysis of measured CTS spectra requires a quantitative inclusion of impurities in the data analysis model. The eCTS code used for this work did not include impurity concentrations, but its results do provide a methodological comparison of the two fast analysis methods.

The total mapping parameter space spans six dimensions, plus the sampling frequency ν_s . The expected parameter values are summarized in table I, together with the actual parameter ranges used for the mapping. These ranges were chosen larger than or equal to the expected values.

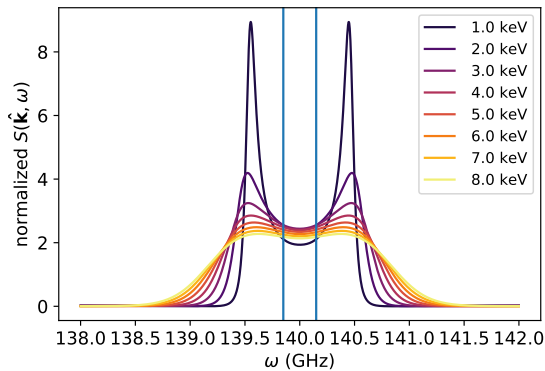


FIG. 2. Collective Thomson scattering spectra as calculated by the electrostatic code eCTS, with different ion temperatures. The other input parameters were $T_e = 5 \text{ keV}$, $\theta = 130^\circ$, $\phi = 110^\circ$, $B = 2.2 T$ and $n_i = n_e$.

III. DATABASE AND DIMENSION REDUCTION

The goal of this work is to find a fast mapping from the measured spectra \mathbf{q} to the input parameters \mathbf{p} of the eCTS model. The former is presented in figure 2 and the latter in table I. In this work, the spectral density was taken to be $\rho_s = 650 \text{ GHz}^{-1}$ in the range $138 < \nu_s < 142 \text{ GHz}$, which makes for an initial number of parameters $N_{q,0} = 2600$. In order to retain computational tractability of the database building, dimension reduction of \mathbf{q} is necessary. In this process, the sensitivity of the result with regard to \mathbf{p} should be retained while removing the largest possible amount of unnecessary information.

Without noise, only five variables with finite variance in the parameter range are required to determine five independent parameters. However, the measured spectra contain noise which is here assumed to be Gaussian: $\sigma_s = 10\%$ at $\rho_s = 650 \text{ GHz}^{-1}$, defined in relation to the average maximum spectral power density in the input parameter space. Two methods of dimension reduction are considered: binning and the Discrete Fourier Transform (DFT).

For binning, the spectrum is divided in bins, the output of which is given by the average spectral power density in each bin. The noise of the binned spectrum is given by $\sigma_b = \sigma_s / \sqrt{BF}$, with BF the number of values in each bin.

Figure 3 shows the DFTs of several CTS spectra with varying bulk ion temperature. It should be noted that the noise reduction is equal for any combination of the two methods: $N_{q,0} = BF \cdot N_b$ and thus the noise reduction from binning cannot be made once more with

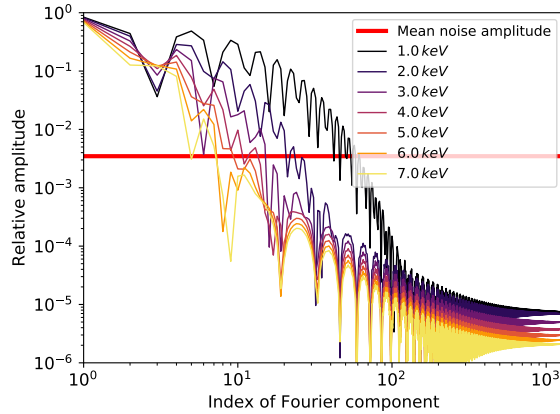


FIG. 3. Discrete Fourier transforms of noiseless spectra at $T_e = 5.0 \text{ keV}$, $\theta = 130^\circ$, $\phi = 110^\circ$, $B = 2.2T$, $n_i = n_e$ and varying T_i . Also shown is the average amplitude of the DFT of the noise $\sigma_s = 10\%$ at $\rho_s = 650 \text{ GHz}^{-1}$. Only components above this level are useful for the approximation.

a subsequent DFT. Thus, in the succession of a DFT over binning, the noise reduction of the first Fourier component is given by $\sigma_{F1} = \sigma_q / \sqrt{N_{q,0}}$.

This balance between the methods was also found in practice. A CTS spectrum with $\rho_s = 650 \text{ GHz}^{-1}$ was binned with several binning factors, followed by a DFT. The normalized amplitudes of these DFT's are shown in figure 4. Firstly, it can be seen that the noise level is equal for all binning factors. Secondly, the differences in the Fourier components above the noise level are negligible for $\rho_s \leq 12.5 \text{ GHz}^{-1}$. Therefore, binning down to 12.5 GHz^{-1} does not significantly reduce the amount of useful amplitude information in the spectrum, given $T_i > 1 \text{ keV}$.

Moreover, for noiseless spectra it was found that the difference between binning and interpolation is insignificant for the resulting DFTs. The computation time required to produce the spectra, however, scales linearly with ρ_s . Thus, a spectral density of 12.5 GHz^{-1} was used for database building (described in section III A). The artificial noise was changed accordingly:

$$\sigma_s = \sqrt{\frac{\rho_s}{\rho_0}} \times \sigma_{s,650}, \quad (2)$$

where $\sigma_{s,650}$ is defined as the equivalent spectral noise at $\rho_s = 650 \text{ GHz}^{-1}$.

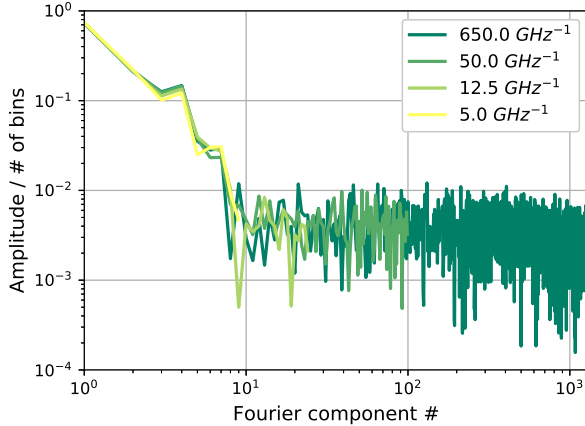


FIG. 4. Discrete Fourier transforms of a CTS spectrum at $T_i = T_e = 5 \text{ keV}$, 2600 bins ($\rho_s = 650 \text{ GHz}^{-1}$) and artificial noise $\sigma_s = 10\%$, that was binned to different spectral densities. Spectral densities $> 12.5 \text{ GHz}^{-1}$ can be used to reduce computation time during database building and application of the FP.

A. Database building

The database was built by doing $N = 25,000$ simulations with the eCTS model, yielding vectors \mathbf{p}^α and \mathbf{q}^α with $(\alpha = 1, \dots, N)$. \mathbf{p}^α were picked from a uniform random distribution covering the expected domain of parameter space (described in table I).

The input to each simulation consists of the input parameters \mathbf{p}^α and the 50 sampling frequencies in the range $140 \pm 2 \text{ GHz}$. The eCTS code then produces the corresponding spectrum. As stated in section II A, the scaling factor was removed by normalizing each spectrum to its mean value. A final step in the simulation was to apply a notch filter. The notch width is assumed to be 300 MHz , centered at the probing frequency 140 GHz . In principle, the notch can be applied by cutting out the corresponding part of the spectrum. But since this would introduce artefacts in the DFT of the spectra, the notch was applied by replacing the values within the notch by a linear interpolation between the spectral values bordering the notch.

Next to the database built for learning, several test sets were built. These had equal domains, except for the temperatures. Considering that the W7-X plasma will be heated through the electron cyclotron resonance, the temperature subspace in the test sets was limited to temperature pairs that obey $\frac{1}{10} < T_i/T_e < 3$, as shown in figure ??.

B. Principal Component Analysis

As described further in section IV A, 50 variables might still be too much for a stable mapping. On the other hand, the binned or Fourier-transformed spectrum might still contain spectra that is unnecessary for an adequate mapping. The number of dimensions can be further reduced through a Principle Component Analysis (PCA)⁵.

In a PCA, a set of observations of a number of possibly correlated variables is transformed to a different set of values of uncorrelated variables, called the principle components. In this case, the set of observations are the database spectra \mathbf{q}^α . The principle components can be sorted with respect to their variance in the database and thus with respect to their relative importance in the database. Because the principle components are uncorrelated, one can use PCA to reduce the number of variables in the data without discarding the most significant patterns in the database.

The process of a PCA on a database \mathbf{q}^α is as follows: first, the databased is normalized: for each element j in \mathbf{q}^α , $\bar{q}_j^\alpha = (q_j^\alpha - \langle q \rangle_j) / \sigma_j$, with σ_j the standard deviation of variable j and $\langle q \rangle_j$ the mean value of q_j in the database. Then, the covariance matrix $\mathbf{D}^{\bar{\mathbf{q}}}$ of the normalized variables is calculated, the elements of which are given by:

$$D_{ij}^{\bar{\mathbf{q}}} = \frac{1}{N-1} \sum_{\alpha} \bar{q}_i^\alpha \bar{q}_j^\alpha. \quad (3)$$

The matrix $\mathbf{D}^{\bar{\mathbf{q}}}$ contains the cross-correlations between the elements of $\bar{\mathbf{q}}$. The eigenvalues λ_j of $\mathbf{D}^{\bar{\mathbf{q}}}$ are a measure of the regressive significance of the corresponding eigenvectors $\mathbf{D}^{\bar{\mathbf{q}}} \mathbf{e}_j = \lambda_j \mathbf{e}_j$. The principal components of each spectrum are then given by $\tilde{q}_j^\alpha = \mathbf{e}_j \cdot \bar{\mathbf{q}}^\alpha$. If $\lambda_j > (3\sigma_s)^2$, with σ_s the measurement noise, \tilde{q}_j is considered a significant component. The eigenvalues and corresponding eigenvectors are sorted such that $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_{N_s}$ with N_s the number of significant eigenvectors. One can now make a mapping from the significant components in $\tilde{\mathbf{q}}$ to \mathbf{p} .

IV. FUNCTION PARAMETRIZATION

After the dimension reduction is complete, a mapping from the processed variables \mathbf{q}_1 to the eCTS input parameters \mathbf{p} can be made. The first mapping method considered in this work is function parametrization (FP)⁵⁷. In a FP, a regression is performed on a database of examples, in which the error of a certain mapping function $\mathbf{p} = M(\mathbf{q}_1)$ is minimized.

A. Regression function

For the regression in FP, one has to select a function f that can adequately describe the trends in the model. The eCTS model is non-linear, so the regressor must be too if the whole parameter range is to be covered. Multivariate Adaptive Regression Splines (MARS¹⁶) is a regression algorithm that uses non-linear hinge functions as basis for a multivariate model with a multi-dimensional output. The regression consists of a forward pass where basis functions are added to the model and a backward pass where the least useful terms are removed from the model one by one (pruning). An advantage of pruning is that it accommodates automatic variable selection: the inclusion of important variables in the model and the omission of unimportant ones. However, with more complicated patterns or more variables, the number of bias functions that can be added during the forward pass and the number of options during pruning strongly increases. It was found that the computation time and systematic errors of the resulting mapping increase drastically for $N_{\mathbf{q}_1} \gtrsim 10$.

B. Setup for function parametrization

Spectra of length 50 or even their 25 Fourier components are thus too large for a regression with MARS and further dimension reduction is needed. As described in IIIB, this can be achieved with PCA. The function parametrization in this work was thus obtained by performing a MARS regression on the first ten principle components $\tilde{\mathbf{q}}$ of the discrete Fourier transform of the spectra in the database. Gaussian noise was added to the spectra in the database to stabilize the regression described in section IV A. The amplitude of this noise was equal to 0.1% of the mean of the maximum values of each spectrum in the database. All computation for this research was performed on an Intel i5-6300U dual-core CPU along

with 20 GB of RAM.

This FP was applied to test sets with different amounts of noise and $\rho_s = 12.5 \text{ GHz}^{-1}$. The results for $\sigma_{s,650} = 10\%$ are presented in section IV D. The results for tests at different noise levels ($\sigma_{s,650} = 1, 5, 10, 30$ and 100% at $\rho_s = 12.5 \text{ GHz}^{-1}$) are presented in section VI.

C. Error analysis

The simplest error analysis is the comparison of the approximation \mathbf{p}_{inv} with the eCTS input parameters \mathbf{p} . This can be done for each individual example to get a grasp of the approximation error in different parts of the parameter subspace. An error indication can also be obtained for the FP as a whole, defined as follows:

$$\epsilon_i \equiv \frac{1}{N_{\text{test}}} \sum_{\beta} \frac{|p_{i,\text{inv}}^{\beta} - p_i^{\beta}|}{p_i^{\beta}}, \quad (4)$$

with β the number of the test spectrum.

1. Chi-squared analysis

During the campaign, \mathbf{p} will not be available. Reduced chi-squared analysis is proposed as a self-consistent method to provide an indication of the goodness of fit of a spectrum corresponding to the measured \mathbf{p}_{out} , with the observed spectrum. This was implemented as follows:

$$\chi^2 \equiv \sum_{n=1}^N \left(\frac{q_n - S(\omega_n, \mathbf{p}_{\text{out}})}{\sigma_s} \right)^2, \quad (5)$$

where q_n are the normalized spectral power densities measured at frequencies ω_n . S is the corresponding power density as calculated by the forward model, including artificially added noise with magnitude equal to the measurement noise σ_s . \mathbf{p}_{out} contains the measured parameters. Reduced chi-squared is then $\chi_{\text{red}}^2 = \chi^2/K$, with K the number of degrees of freedom. The value of χ_{red}^2 can be interpreted in the following way: The closer χ_{red}^2 is to 1, the better the fit. Values of $\chi_{\text{red}}^2 > 1$ represent an underfit whereas $\chi_{\text{red}}^2 < 1$ represents overfitting. However, as¹⁷ have pointed out, it is not possible to use χ_{red}^2 as a quantitative

measure of the goodness of fit. χ_{red}^2 has an intrinsic probability distribution function, which can only be known for the true model having the true parameter values.

χ_{red}^2 can still provide an indication of self-consistency: under the assumption that the approximation (be it FP or a neural network) follows the true model, χ_{red}^2 of the most accurate measurements should follow the χ_{red}^2 -distribution and thus have a mean value of 1. Moreover, a correlation between ϵ and χ_{red}^2 might provide a rough error estimation for measurements. The results of this analysis are presented in sections IV D 1 and figure ?? in the addendum for the FP and neural networks, respectively.

D. Function parametrization results

The computation time required to make the FP mapping was 71 minutes. The results of the function parametrization for a test set with $\rho_s = 12.5 \text{ GHz}^{-1}$ and $\sigma_{s,650} = 10\%$ are shown in figure 5. The results with other noise levels are presented in section VI. For this mapping with $0.2 < n_D/n_e < 1$ and $\sigma_{s,650} = 10\%$, the mapping error is much lower for the ion temperature ($\epsilon_{T_i} = 9.9\%$) than for the electron temperature ($\epsilon_{T_e} = 49\%$). The FP from the clean plasma approximation ($0.2 < n_D/n_e < 1$), on the other hand, was able to map the spectra to T_e and resulted in an average error $\epsilon_{T_e} = 8.4\%$ for $\sigma_{s,650} = 10\%$. The mapping output of this clean plasma FP are shown in figure ??.

1. Chi-squared analysis results

The χ_{red}^2 values of the FP applied to a test set with $N_{test} = 1000$ for different noise levels are shown in figure 6. With a high noise level, almost no correlation between χ_{red}^2 and ϵ can be recognized and the median χ_{red}^2 -value approaches 1.

At lower noise levels, there is a certain correlation, and probabilities of certain ϵ for given χ_{red}^2 can be provided. For example, in the test set of the $\sigma_{s,650} = 10\%$ in figure 6: $P(\epsilon > 0.1 | \chi_{red}^2 < 10) = 0.21$. In principle, a probability distribution $P(\epsilon | \chi_{red}^2)$ can be obtained in this way. However, since the theoretical uncertainty for a given χ_{red}^2 can only be known for a perfect model and ϵ equal to zero¹⁷, this method cannot be used to provide sound quantitative error estimations.

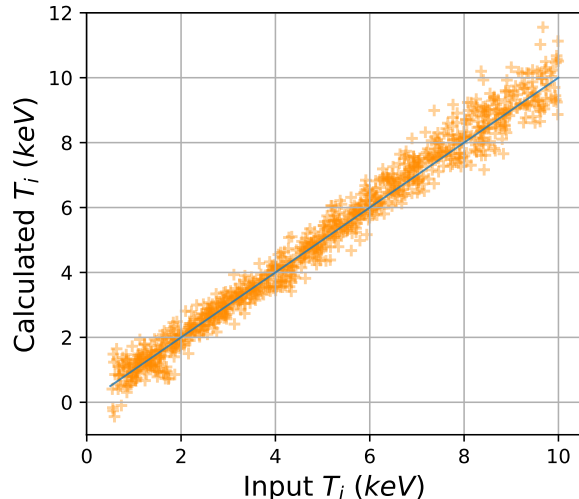


FIG. 5. Input (real) and output (approximated) ion temperature of the application of the FP on a test set with 1000 samples, 1.4 % noise and $\rho_s = 12.5 \text{ GHz}^{-1}$ ($\sigma_{s,650} = 10\%$). The average absolute deviation for T_i is 9.9 % of the input temperatures.

V. ARTIFICIAL NEURAL NETWORKS

An artificial neural network (ANN) is a computing system that consists of a network of artificial neurons: mathematical function that mimic the behaviour of biological neurons. Neurons mutually transmit signals which depend on the signals they receive from other neurons. Although ANNs are much simpler than biological neural networks, they share the ability to learn new patterns through the consideration of examples.

In this research, a specific class of feedforward neural network was used: the multi-layer perceptron (MLP). The perceptron is a class of ANNs that was invented by Rosenblatt¹⁸, initially as a hardware single binary classifier, but later generalised to a computation system consisting of neurons arranged in layers, which can be activated by inputs from all neurons in the preceding layer, and transmit their output o to the succeeding layer. This is summarised in the following recurrent formula:

$$o_i^k = \phi(\text{net}_i^k) = \phi \left(\sum_{l=1}^{N_i} o_{i-1}^l w_{i-1}^{lk} + b_i^k \right), \quad (6)$$

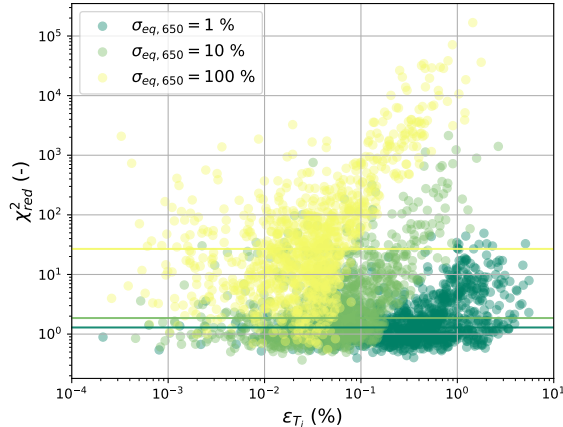


FIG. 6. Scatter plots of χ_{red}^2 versus the estimation error ϵ_{T_i} for a set of $N_{test} = 1000$ tests, at different noise levels. The horizontal lines show the median values of χ_{red}^2 : 26.8, 1.9 and 1.2 for equivalent noise levels of 1%, 10% and 100%, respectively. For measurements with a low error in their category, the values of χ_{red}^2 are distributed around a value slightly larger than one, indicating a good (but not perfect) fit of the FP mapping to the data.

where i and k denote the layer and neuron indices, respectively. net_i^k is the net input of neuron k in layer i , formed by the sum of all N_i neuron outputs of the previous layer, multiplied by the corresponding weights w_{i-1}^{lk} , plus b_i^k , the bias of neuron k . Finally, ϕ describes the "activation" of a neuron based on the information it receives. This so-called activation function should be a strictly increasing and non-linear function between 0 and 1 in the domain $(-\infty, \infty)$. Many activation functions can be used, but for this work, the standard logistic function and its convenient derivative were used:

$$\begin{aligned} \phi(x) &= \frac{e^x}{1 + e^x} \\ \frac{d\phi}{dx} &= \phi(x)(1 - \phi(x)) \end{aligned} \quad (7)$$

A. Training procedure

An MLP can be trained by offering a (possibly pre-processed) simulated spectra \mathbf{q}_1^α to the first neuron layer \mathbf{o}_{in} and adjusting the weights and biases of the network for minimization of

the loss function: $E = \frac{1}{2}|\mathbf{o}_{\text{out}} - \mathbf{p}|^2$. The influence of each weight on the loss function, $\delta_i^k = \frac{\partial E}{\partial w_i^{kl}}$. δ_i^k can be calculated in an algorithm called backpropagation. Following the gradient descent optimization algorithm, the weight adjustments are then given by $\Delta w_i^{kl} = \eta \delta_i^k o_i^k$, with η the learning rate, which can be adapted during training. Also, to avoid ending up in a local minimum of E , momentum can be added through the inertia term α ¹⁹:

$$\Delta w_i^{kl}(t+1) = (1 - \alpha)\eta \delta_i^k o_i^k + \alpha \Delta w_i^{kl}(t). \quad (8)$$

Backpropagation is normally performed on a batch of examples concurrently. The larger the batch, the more general the trends that can be captured. A database can be chopped up in a number of batches, which can be offered one by one to form one epoch of training. In the next epoch, the database can be chopped up again (using a possibly different order of examples) for the next epoch. Depending on the application, the training is continued for one, several or many epochs, or until a certain desired error margin is reached.

During training, the backpropagation is performed on examples from the database. However, similarly to FP, it is better to test the resulting MLP on new test data. The fraction of variance unexplained (FVU) can provide a measure of how well \mathbf{p} is replicated by the model, and is defined as the ratio of the variance in the error over the total variance:

$$FVU_i \equiv \frac{\sum_{k=1}^{N_{test}} (p_{i,pred.}^k - p_{i,true}^k)^2}{\sum_{k=1}^{N_{test}} (p_{i,pred.}^k - p_{i,mean})^2}, \quad (9)$$

with N_{test} the number of examples in the test set, i the index of \mathbf{p} , and the subscripts denoting the true, predicted and mean parameter values, respectively. The FVU can be calculated after each batch, to quantify the training progress. This was done during training for both the training database and the test set. If the FVU of the database keeps decreasing but the FVU of the testset does not, the MLP might be overfitted to the dataset, and not generalisable to new data.

1. MLP training setup

In this work, the MLP regressor class from the SciKit-Learn package²⁰ was used to make the approximation. Three hidden layers were used, containing 150, 100 and 50 neurons respectively. The MLP was trained with the same databases as used for the FP, described

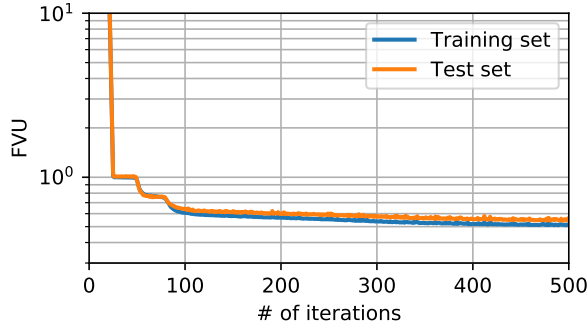


FIG. 7. Neural network training progress for the assumed parameter space described in table I. Each training iteration was performed with a batch of 250 spectra. With a database of 25,000 spectra, an epoch is completed after 100 iterations. FVU is the Fraction of Variance Unexplained, defined in equation 9.

in section III A. The DFT and PCA were omitted: $\mathbf{q}_1 = \mathbf{q}$. The total layout of the MLP is then given by $[N_{q,1}, N_1, N_2, N_3, N_p] = [50, 150, 100, 50, 6]$. Instead of training once on low-noise spectra and applying the resulting model on noisy spectra, the MLP was trained for each desired noise level separately. The MLP regressor was set to use adaptive training and an inertia term $\alpha = 5 \cdot 10^{-5}$ and training was done with batches of size 250.

The training progress for a dataset with $\sigma_{s,650} = 10\%$ is shown in figure 7. The corresponding mapping error $\epsilon_{Ti} = 4.2\%$. The results of the χ_{red}^2 -analysis are similar to those of the FP (section IV) and are shown in figure ?? in the appendix.

B. Error propagation through sensitivity analysis

As described in section IV C, observed measurement errors and χ_{red}^2 cannot provide a quantitative uncertainty of the mapping output during new measurements. A tool that can provide such quantifications, is the sensitivity analysis.

The trained network can be represented as a function MLP : $\mathbf{p}_{inv} = MLP(\mathbf{q}_1)$ with \mathbf{p}_{inv} the retrieved system parameters and \mathbf{q}_1 the preprocessed spectra, or $\mathbf{o}_{out} = MLP(\mathbf{o}_{in})$ with in and out depicting the first and last layer of the MLP. Analogous to the partial derivative $\frac{\partial E}{\partial w_i^{kl}}$ in backpropagation, one can calculate $\left. \frac{\partial o_{out}^i}{\partial \sigma_{in}^j} \right|_{\mathbf{q}}$ for all neuron combinations i and j and a given \mathbf{q}_1 ²¹. Together, the derivatives form the Jacobian matrix \mathbf{J} .

One could use these sensitivities as an indication of the relative importance of different spectral regions in the estimation of each p_i . However, it has been demonstrated that such indications are unreliable for dependent input parameters²². Namely, there are many possible networks that describe the same patterns in the data, while having different distributions of the sensitivity.

The sensitivities can also be used for error propagation. In general, an error indication can be obtained from the covariance matrix of the output, $\mathbf{D}^{\mathbf{p}}$. The elements of this matrix are given by:

$$D_{ij}^p = \sum_{k=1}^{N_q} \sum_{l=1}^{N_q} J_{ik} D_{kl}^q J_{jl}, \quad (10)$$

with D^q the covariance matrix of the input. At a fixed point \mathbf{p} in parameter space, the uncertainties in \mathbf{q} can be assumed to be uncorrelated and equal to the spectral noise. In that case, $\mathbf{D}^{\mathbf{q}}$ is a diagonal matrix with constant value σ_s^2 . The synthetic data indeed originate in a single point \mathbf{p} , but due to the finite scattering volume and signal integration time, the collected radiation is given by the integral of scattered power over a small subspace in p-space and time. Although incorporation of the finite scattering volume in the mapping would be overly complicated, its integration in the uncertainty estimation is possible, . For each point at which $\mathbf{D}^{\mathbf{p}}$ is evaluated, one could evaluate $\mathbf{D}^{\mathbf{q}}$ over a set of spectra which was picked from the expected p-subspace.

Using the network trained with spectra at $\rho_s = 12.5 \text{ GHz}^{-1}$ and $\sigma_{s,650} = 11 \%$, $\mathbf{D}^{\mathbf{p}}$ was evaluated on a grid of points in parameter space, at fixed geometry $\theta = 130^\circ$, $\phi = 110^\circ$, $B = 2.2 T$, $n_i = n_e$ and temperatures in the range $0.5 \leq T_i, T_e \leq 8.0 \text{ keV}$.

The obtained uncertainties were compared with the absolute errors of a small test set, the results of which are shown in figure V B. It can be seen in figure 8 that for both temperatures, the majority of tests have $\epsilon_i < \sigma_i(T_i, T_e)$. Also, the average standard deviation of the sensitivity grid corresponds well with the average mapping error of the ANN: $\epsilon_{T_i} = 4.2 \%$. Thus, the sensitivity is a reasonable measure of the mapping accuracy of a specific ANN and can be used to obtain uncertainties of the mapping results for new measurements within the parameter domain covered during training.

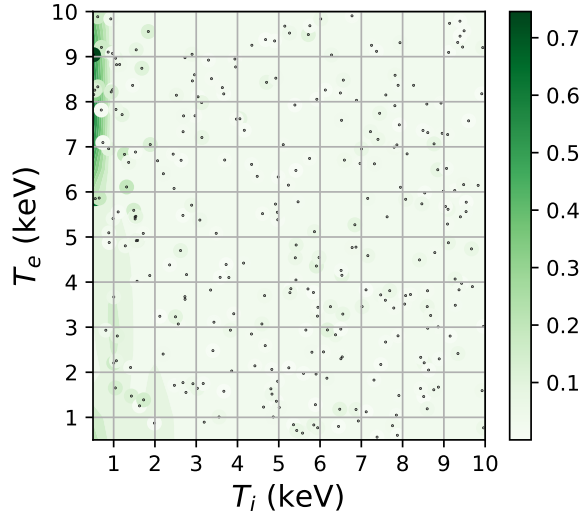


FIG. 8. Contour plot of the normalized standard deviation σ_{T_i}/T_i , as obtained from the covariance matrix D^p . This matrix was evaluated on an equidistant grid with T_i and $T_e = [0.5, 1.0, \dots, 10]$, at fixed geometry $\theta = 130^\circ$ and $\phi = 110^\circ$, $B = 2.2T$, $n_i = n_e$, using an MLP trained with $\rho_s = 12.5 \text{ GHz}^{-1}$, $\sigma_{s,650} = 10\%$ and $2 < n_D/n_e < 1$. The mean standard deviation over the grid is $\sigma_{T_i}/T_i = 4.3\%$. On top of the contour plot is a scatter plot of ion and electron temperatures in a test set with $N_{test} = 500$ spectra. These are depicted by black dots surrounded by a circle, the colour of which represents the normalized deviation on the same colour scale.

VI. COMPARISON AND CONCLUSION

The results of the FP and MLP mappings at different noise levels are shown in figures 9 and 10 for n_D/n_e in the ranges $0.2 - 1$ and $0.9 - 1$, respectively. In figure 9, it can be seen that both FP and ANNs can provide an adequate mapping of the ion temperature, with mean errors $\epsilon_{T_i} = 9.9\%$ and 4.2% , respectively, at the expected noise level $\sigma_{s,650} = 10\%$. However, ANN is much more robust to noise: if the expected estimation error is to be kept below 20% , FP will not be useful for $\sigma_{s,650} \gtrsim 30\%$, whereas $\epsilon_{T_i} = 14.3\%$ for an ANN trained at $\sigma_{s,650} \gtrsim 100\%$. Because the CTS probing beam is also used for heating and there are several other heating gyrotrons operating in the machine at the probing frequency, there will be large amounts of stray radiation in the frequency range of the CTS spectra. Therefore, the mapping method with maximal noise robustness is preferable.

The electron temperature mapping accuracy was much smaller for both methods. The

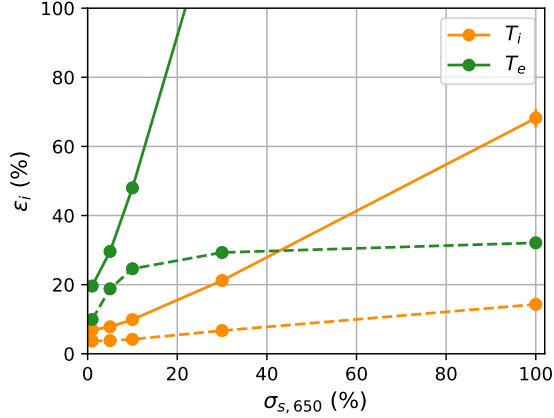


FIG. 9. Mean absolute deviations of T_i and T_e as calculated with function parametrization (full lines) and an artificial neural network (dashed lines) at $\rho_s = 12.5 \text{ GHz}^{-1}$, for different equivalent noise levels and $0.2 < n_D/n_e < 1$.

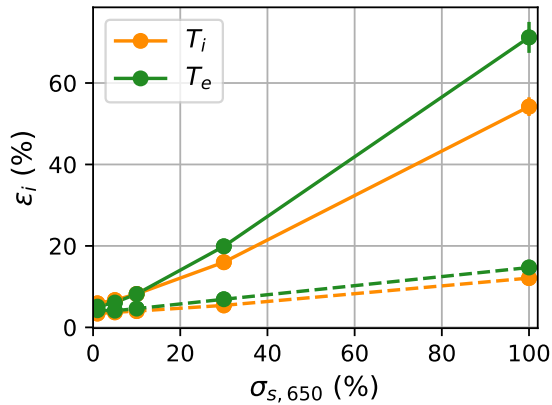


FIG. 10. Mean absolute deviations of T_i and T_e as calculated with function parametrization (full lines) and an artificial neural network (dashed lines) at $\rho_s = 12.5 \text{ GHz}^{-1}$, for different equivalent noise levels and $0.9 < n_D/n_e < 1$.

reason for this is that n_D/n_e and T_e appear very similarly in the CTS equations and thus their influence on the CTS spectra is comparable. It should be noted that with a small range of n_D/n_e in the mapping parameter space, T_e can be estimated just as well as T_i by both the FP and ANN mappings, as shown in figure 10.

In figure 9, the following can be also recognized: for the FP, the error increases linearly with noise, whereas the MLP mapping error levels off just above 30%. This highlights a

fundamental difference between the FP and the MLP. The MARS model does not have parameter space boundaries. It was made to fit best to the examples in the training database, but can be extrapolated for anomalous input spectra and thus map outside of the training parameter space. The MLP, on the other hand, was trained to provide a mapping within the training database only, and will only provide output in that range. This is in the nature of the activation function, which is limited between zero and one for all input values.

As stated in sections IV D 1 and V A 1, chi-squared analysis can be applied to both FP and NN to provide an indication of the goodness of fit of real measurements. A quantitative uncertainty for new measurements can be obtained from a sensitivity analysis. For the MLP, this uncertainty was in good agreement with actual results from predictions on synthetic data. In principal, FP also allows sensitivity analysis. However, in the DFT, the half of the information (the part concerning the location of spectral changes) was discarded, which complicates interpretation of the sensitivity.

An advantage of FP over ANNs is that the terms in the MARS functions form direct links between input and output, thus providing insight in the mapping. The maximum number of inputs to MARS poses the need for a stricter dimension reduction compared to the ANN. This can be achieved by two extra steps: DFT and PCA. In principle, these steps can provide insight into the system complexity and the amount of information that can be distinguished from noise. In the DFT, half of the information is removed: the half concerning the location of spectral changes (corresponding to phase in a DFT of a time-dependent signal). In future expansions of the mapping parameter space, this information might be necessary, further complicating the FP.

The current ANN implementation considers the (binned) spectra as a whole. This method seems more coarse than the dimension reduction in the FP. However, one can also train a new MLP on the transformed variables that were input to MARS, or any other set of variables obtained from the spectra. For example, an MLP can be trained with variable spectral density to emphasize certain spectral regions while reducing the required complexity of the neural network.

In fact, except for the increased computation time required for training, dimension reduction is no principal requirement for the MLP. It has the ability to learn the most relevant patterns by itself. This also makes ANNs more flexible to changes in the parameter space,

i.e. a larger range of scattering geometries or additional dimensions, like the plasma drift or properties of the (fast) ion velocity distribution.

Another important set of additional dimensions are the plasma impurity concentrations, which might have significant influence on the shape of measured spectra in W7-X. As stated in section II A, the parameter space used in this work does not account for impurities. However, once the addition of impurities is implemented in the eCTS code, a new mapping can be made with inclusion of the impurity concentrations.

More in general, the following should be noted: an ANN can only describe the (physics) patterns that were used for training. There are two ramifications of this. The first is that the physics model used to produce the synthetic database is wrong. The eCTS model provides an electrostatic estimation of CTS, which might not cover all processes under observation during measurements. The second aspect is the difference in parameter space between synthetic data and measurements. This includes the omission of impurity concentrations, but also other differences that might or might not be foreseen. For example, due to finite size of the scattering volume, the measured spectra are formed by the addition of different scattering processes and thus span a finite subspace in parameter space, instead of a single point. Also, the synthetic background radiation is uniform white noise, whereas the real background originates in stray radiation from the gyrotron (modulation), ECE from the plasma in the line of sight and any other radiation present in the concerning spectral region.

A. Conclusion

Both FP and ANNs can provide a mapping between synthetic CTS spectra and the bulk ion temperature. Without any additional input, the FP and ANN can estimate T_i with mean absolute errors $\epsilon_{T_i} = 9.9\%$ and 4.3% for spectra with $\rho_s = 12.5 \text{ GHz}^{-1}$ and $\sigma_{s,650} = 10\%$. In a more limited parameter space where n_D/n_e is almost fixed, T_e can also be identified: $\epsilon_{T_e} = 8.4\%$ and 4.6% for the FP and ANN, respectively.

The current mappings can be made into a ready-to-use data analysis method by including relevant impurity concentration ranges in the eCTS code and mapping parameter space. Other notable differences between synthetic and measured spectra might appear as well, for example due different background radiation and scattering physics. These differences might

harm the applicability of both FP and the ANN. But, ANNs have several significant advantages: a much larger noise robustness, ease of implementation and higher adaptability with respect to the parameter space. Thus, artificial neural networks are the method of choice to enable fast CTS ion temperature measurements and possibly other plasma properties in the future.

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