

## Fast Electron Temperature Diagnostics on EAST Using $W^{45+}$ Spectral Line Ratios and a Convolutional Neural Network

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### Abstract

Tungsten (W) spectral line emission from highly charged ions provides an important diagnostic for electron temperature in high-temperature fusion plasmas. In particular,  $W^{45+}$  spectral line intensity ratios exhibit strong sensitivity to electron temperature. However, conventional spectroscopic methods for electron temperature diagnostics typically rely on iterative spectral fitting or collisional-radiative modeling, which can be computationally expensive and limit their applicability for fast analysis. In this work, a new fast electron temperature diagnostic scheme is developed based on  $W^{45+}$  spectral line intensity ratios measured by the X-ray crystal spectrometer (XCS) on the Experimental Advanced Superconducting Tokamak (EAST). The temperature dependence of the selected line ratios is validated using Flexible Atomic Code (FAC) and FLYCHK calculations, confirming their suitability for temperature diagnostics. A convolutional neural network (CNN) is employed to establish a direct mapping from spectral features to electron temperature, enabling rapid inference without iterative modeling. The method is validated against electron cyclotron emission (ECE) measurements, showing good agreement in both temporal evolution and spatial profiles. Compared with conventional approaches, the proposed method significantly reduces computational cost while maintaining high accuracy. These results demonstrate that  $W^{45+}$  spectral line ratios provide an effective and efficient observable for electron temperature diagnostics, with strong potential for real-time applications in fusion plasmas.

## Full Text

### Preamble

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### Abstract

Tungsten (W) spectral line emission from highly charged ions provides an important diagnostic for electron temperature in high-temperature fusion plasmas. In particular, W45+ spectral line intensity ratios exhibit strong sensitivity to electron temperature. However, conventional spectroscopic methods for electron temperature diagnostics typically rely on iterative spectral fitting or collisional-radiative modeling, which can be computationally expensive and limit their applicability for fast analysis.

In this work, a new fast electron temperature diagnostic scheme is developed based on W45+ spectral line intensity ratios measured by the X-ray crystal spectrometer (XCS) on the Experimental Advanced Superconducting Tokamak (EAST). The temperature dependence of the selected line ratios is validated using Flexible Atomic Code (FAC) and FLYCHK calculations, confirming their suitability for temperature diagnostics. A convolutional neural network (CNN) is employed to establish a direct mapping from spectral features to electron temperature, enabling rapid inference without iterative modeling. The method is validated against electron cyclotron emission (ECE) measurements, showing good agreement in both temporal evolution and spatial profiles. Compared with conventional approaches, the proposed method significantly reduces computational cost while maintaining high accuracy. These results demonstrate that W45+ spectral line ratios provide an effective and efficient observable for electron temperature diagnostics, with strong potential for real-time applications in

fusion plasmas.

### Keywords

Tungsten spectroscopy, Electron temperature diagnostics, Spectral line intensity ratios, Convolutional neural network

## 1. Introduction

Tungsten (W) is widely adopted as a plasma-facing material in magnetic confinement fusion devices, owing to its high melting point, low sputtering yield, and favorable thermal properties[1-3]. Tungsten impurities eroded from the divertor can

penetrate into the core plasma, where they become highly ionized and emit characteristic spectral lines[4,5]. These emissions provide insight into impurity transport and also contain valuable diagnostic information on key plasma parameters[6-9]. In particular, spectral emissions from highly charged tungsten ions are well suited for diagnosing electron temperature in high-temperature plasmas, owing to their strong temperature sensitivity and their relevance to core plasma conditions[10-12]. The X-ray crystal spectrometer (XCS) has been widely employed in fusion devices for measuring ion temperature and toroidal rotation profiles based on Doppler broadening and Doppler shift of impurity spectral lines, particularly from He-like and H-like argon ions, such as in the Alcator C-Mod tokamak[13], the Joint European Torus (JET)[14], the W Environment in Steady-state Tokamak(WEST)[15], the Large Helical Device (LHD)[16], and the EAST tokamak[17,18]. As plasma temperature increases, emission from highly charged tungsten ions (e.g.,  $W^{43+}$ - $W^{45+}$ ) becomes prominent in the core region, making these lines suitable for spectroscopic diagnostics in high-temperature plasmas[19-21].

Accurate determination of electron temperature ( $T_e$ ) is essential for understanding plasma confinement and energy transport[22,23]. Electron temperature in fusion plasmas is conventionally measured using electron cyclotron emission (ECE) and Thomson

scattering

(TS),

which

provide

reliable

well-established

diagnostics[24-26]. However, spectroscopic approaches based on highly charged impurity emissions offer additional advantages. In high-temperature plasmas,

emissions from high-Z ions are typically localized in the core region and exhibit strong sensitivity to electron temperature through electron-impact excitation processes[9,27]. In particular, line intensity ratios provide robust diagnostic observables with reduced dependence on absolute calibration[28,29]. Moreover, spectroscopic diagnostics can remain effective under conditions where conventional diagnostics may be limited, such as reduced optical access or high radiation environments[30]. Despite these advantages, conventional spectroscopic

methods for electron temperature diagnostics often rely on iterative spectral fitting or

collisional-radiative modeling, which can be computationally expensive and limit their applicability for fast analysis. Therefore, developing a fast and reliable spectroscopic diagnostic method is of considerable importance. In this context, fast electron temperature inference based on W45+ spectra measured by XCS provides a promising approach for plasma diagnostics and transport studies in future fusion devices.

In this work, the temperature dependence of selected W45+ spectral line intensity ratios is first validated using FAC calculations and FLYCHK collisional-radiative modeling, establishing the physical basis for spectroscopic electron temperature diagnostics[31,32]. Based on this, a fast diagnostic method is developed using W<sup>45+</sup> spectra measured by the XCS system on EAST. A convolutional neural network (CNN) is employed to map spectral features to electron temperature, enabling rapid inference without iterative modeling. The remainder of this paper is organized as follows. Section II describes the XCS system and spectral analysis. Section III presents the diagnostic model. Section IV discusses the results, and Section V summarizes the conclusions.

## 2. Materials and methods

2.1. The XCS system on EAST. The XCS diagnostic system on EAST consists of two complementary configurations: the tangential XCS (TXCS) and the poloidal XCS (PXCS), both of

which have undergone systematic upgrades to improve diagnostic stability, spectral resolution, and measurement reliability[33,34]. These two viewing geometries provide different sensitivities to plasma parameters, with the TXCS configuration offering enhanced sensitivity to toroidal rotation and core plasma emission due to its tangential line of sight. In this study, particular emphasis is placed on the TXCS system, which has been widely applied in high-temperature plasma experiments on EAST. In this study, the focus is placed on the TXCS system, which has been successfully applied to the observation of spectral emissions from highly charged

tungsten ions, including W43+-W45+, under high-temperature plasma conditions[20].

As illustrated in Figure 1 [Figure 1: see original paper], the TXCS system adopts a spherically bent quartz crystal (011,  $2d = 4.913 \text{ \AA}$ ) as the dispersive element, enabling high-resolution wavelength discrimination through Bragg diffraction. The diffracted X-ray spectra are recorded by a two-dimensional PILATUS 900K detector, which is mounted on a motorized linear rail system. This configuration allows precise positional adjustments of the detector, thereby enabling flexible coverage of different wavelength ranges and optimization of spectral acquisition for various impurity species. The PILATUS 900K detector consists of nine

modules, each comprising  $487 \times 195$  pixels with an individual pixel size of  $172 \times 172 \mu\text{m}^2$ , providing both high spatial and spectral resolution. Owing to its large detection area, the system is capable of simultaneously recording spatially resolved spectra along the vertical direction, covering a range of approximately  $Z = -40 \text{ cm}$  to  $40 \text{ cm}$  across the plasma cross-section. The corresponding spatial resolution can reach approximately  $0.5 \text{ mm}$  under optimal conditions, allowing detailed characterization of core plasma emission structures. In addition, the TXCS system features a high temporal resolution, with a minimum acquisition time on the order of  $10 \text{ ms}$ , enabling time-resolved measurements of plasma dynamics during transient events[35].

## 2.2. Tungsten Spectral Analysis

showing emission lines from highly charged tungsten ions (W43+-W45+) as well as  $\text{Ar}16^+$ . The spectra were recorded under combined lower hybrid current drive (LHCD) and electron cyclotron resonance heating (ECRH) conditions, with a peak electron temperature reaching approximately  $10 \text{ keV}$ [20]. The W45+ spectral features in the wavelength range of  $3.90\text{-}3.98 \text{ \AA}$  are summarized in Table 1, including the experimental wavelengths and the corresponding atomic parameters calculated using the FAC code, such as transition configurations, radiative transition energies ( $\Delta E$ , defined as the energy difference between the upper and lower levels) and Einstein A coefficients. The experimental and calculated wavelengths show good agreement, indicating reliable line identification. The reported radiative transition probabilities span several orders of magnitude, with the strongest lines exhibiting transition rates on the order of  $5.67 \times 10^{13} \text{ s}^{-1}$ .

electron temperature of  $T_e = 10 \text{ keV}$ .

$\lambda_{\text{ex}}(\text{\AA})$

$\lambda_{\text{cal}}(\text{\AA})$

Transition

$\Delta E \text{ (eV)}$

$A \text{ (s}^{-1}\text{)}$

$3d104s \ 2S1/2 \rightarrow 3d94s(5/2,1/2)4 \ 6f7/2(7/2,3)J$

$5.67 \times 10^{13}$

$3d104s \ 2S1/2 \rightarrow 3d94s(5/2,1/2)4 \ 6f7/2(7/2,1)J$

$2.94 \times 10^{13}$

$3d104p \ 2P3/2 \rightarrow 3d94s \ 4d \ 2DJ$

$9.03 \times 10^9$

$3d104p \ 2P1/2 \rightarrow 3p53d104s5f \ 2FJ$

$4.59 \times 10^{12}$

The spectral feature near 3.9330 Å arises from two closely spaced transitions, which appear as a blended structure due to instrumental and Doppler broadening. To quantitatively separate these overlapping components, the measured spectrum was fitted using a linear background and two Gaussian functions. A common linewidth was imposed for both components, as they originate from the same ionization stage and are subject to identical broadening mechanisms. In addition, the central wavelengths were constrained around their theoretically calculated values to ensure physical consistency and fitting stability. This fitting procedure enables a reliable decomposition of the blended feature and provides the individual line intensities required for subsequent ratio analysis.

The line emissivity of a transition  $u \rightarrow l$  from W45+ can be written as:

$\epsilon_{ul} = n_e n_q q_{ul}(\text{Te}) B_{ul}$  where  $n_e$  is the electron density,  $n_q$  is the density of W45+ ions, and

$B_{ul}$  is the

Maxwellian-averaged excitation rate coefficient, and:

$B_{ul} =$

$\frac{A_{lk}}{A_{lk} + A_{ul}}$

$B_{ul}$  is the branching ratio determined by the radiative decay probabilities. Under the approximation that radiative decay dominates over collisional de-excitation, the excited-state populations are primarily determined by electron-impact excitation. For two spectral lines originating from the same ionization stage, the intensity ratio becomes:

$B_{ul} =$

$\frac{A_{l1} q_1(\text{Te})}{A_{l2} q_2(\text{Te})} \frac{B_{l1}}{B_{l2}}$

The temperature dependence is therefore controlled by the excitation rate coefficients.

For a Maxwellian electron energy distribution:

$q_{ul}(\text{Te}) = \mu$  where

$\mu = \frac{g_{ul}(\text{Te})}{g_{ul}(\text{Te}) + g_{lk}(\text{Te})}$

$\mu = \frac{\int_{\Delta E}^{\infty} \exp(-\epsilon/kT_e) d\epsilon}{\int_0^{\infty} \exp(-\epsilon/kT_e) d\epsilon}$

is the effective collision strength and

$\Delta E$  denotes the excitation

energy from the initial level to the upper level. It should be noted that this excitation energy is distinct from the radiative transition energy listed in Table 1. If the effective collision strengths exhibit a moderate variation with temperature over the range of interest, the ratio of two spectral lines can be approximately expressed as:

$$\propto \Delta E - \Delta E^2 \propto C \times \exp \zeta - 1$$

where  $C$  is a slowly varying coefficient that includes the branching ratios and effective collision strengths. In this approximation, the exponential term represents the dominant temperature dependence of the line ratio. line-specific photon emissivity coefficient (PEC) and the fractional abundance of  $W45+$ , is only weakly dependent on electron density in the range  $n_e = 1 \times 10^{19} - 1 \times 10^{20} \text{ m}^{-3}$ . The PEC for the  $W45+$  transition at  $3.9330 \text{ \AA}$  was calculated using FAC, while the fractional ion populations were obtained from the FLYCHK collisional-radiative model. This transition is taken as a representative line to evaluate the density dependence of the emissivity. As shown in Figure 4 Figure 4: see original paper,  $PEC \times \text{Fraction}$  exhibits a pronounced maximum at  $T_e \approx 2-3 \text{ keV}$ , corresponding to the peak fractional abundance of  $W45+$ . The normalized results in Figure 4(b) indicate that the relative variation remains below 0.1% over the entire density range, demonstrating that the emissivity shows only weak dependence on electron density within the examined parameter range. Since transitions originating from the same charge state exhibit a

similar dependence on the ion fractional abundance, the density sensitivity of the corresponding line ratios can be estimated using a representative transition. The present analysis is therefore intended to evaluate the relative density effect, rather than

to reproduce absolute emissivities.

function of electron temperature for different electron densities. (b) Normalized  $PEC \times \text{Fraction}$  relative to  $n_e = 1 \times 10^{20} \text{ m}^{-3}$ .

The line intensity ratios are calculated based on atomic data obtained from the FAC.

As shown in Figure 5 Figure 5: see original paper, several candidate  $W45+$  line-intensity ratios exhibit a monotonic dependence on electron temperature over the range of 1-12 keV, indicating their potential applicability for temperature diagnostics. The corresponding logarithmic sensitivity, defined as  $d(\ln R)/dT_e$ , is presented in Figure 5(b). Although all candidate ratios maintain finite sensitivity across the considered temperature range, their sensitivity gradually decreases with increasing  $T_e$  reflecting the reduced relative importance of excitation-energy differences at higher electron energies. In addition to

sensitivity, the diagnostic performance of each ratio is further evaluated by considering the associated temperature uncertainty, as shown in Figure 5(c). By jointly examining both sensitivity and uncertainty, it is found that the ratio  $I_{3.9339\text{\AA}}/I_{3.9379\text{\AA}}$  provides a more favorable balance, exhibiting a stable monotonic dependence, sufficient sensitivity, and relatively low uncertainty over the relevant temperature range. This ratio is therefore selected as the primary observable for

subsequent electron temperature inference.

range 1-12 keV. (b) Corresponding logarithmic temperature sensitivity  $d(\ln R)/dT_e$ . (c) The relative temperature uncertainty.

### 2.3. Electron Temperature Inference Using CNN

A convolutional neural network (CNN) is employed to establish a direct relationship between the measured XCS spectra and the electron temperature. As illustrated in Figure 6 [Figure 6: see original paper], the raw spectral signals are first preprocessed through temporal and spatial binning to improve the signal-to-noise ratio, followed by spectral window selection to extract the wavelength range of interest. The resulting input to the model consists of the discretized spectral intensity distribution as a function of wavelength.

Unlike conventional approaches that rely on explicitly defined line intensity ratios, the present method utilizes the full spectral intensity distribution within the selected wavelength range. In this way, the temperature dependence of the spectrum, determined by the relative excitation rates of different transitions, is reflected in the spectral intensity distribution and can be captured by the model. The network

architecture incorporates multiple convolutional layers with residual connections and dilated convolutions, allowing the extraction of both local spectral structures (e.g., individual line intensities and line shapes) and global correlations between different spectral lines. These correlations are closely related to the relative population of excited states and therefore to the electron temperature.

Through the hierarchical feature extraction of the CNN, the complex dependence of electron temperature on the spectral intensity distribution is effectively captured. The final output layer directly provides the inferred electron temperature  $T_e$ . The model

parameters are optimized using the Adam algorithm by minimizing the mean squared error (MSE) between the predicted values and the reference electron temperatures obtained from electron cyclotron emission (ECE) diagnostics. The dataset consists of 140 EAST discharges in the range of #88594-#100331. To ensure a reliable evaluation of the generalization capability, shot #98958 is completely excluded from the training dataset and used as an independent test case. After training, the model enables fast and direct inference of electron temperature from measured spectra, without the need for iterative spectral fitting or repeated collisional-radiative calculations.

In addition, the integrated gradients (IG) method is employed to interpret the trained CNN model, allowing identification of the spectral regions that contribute

most significantly to the temperature prediction[36]. The IG attribution for feature  $i$  is defined as:

$$\frac{\partial F(x_c + a(x - x_c))}{\partial x_i}$$

$I_{Gi}(x) = x_i - x_{ci}$  where

denotes the baseline input and  $F(\cdot)$  represents the network output. In this work, the baseline was chosen as the mean value of the training dataset to provide a physically meaningful reference state for the intensity-ratio inputs. The integral was

approximated numerically using discrete steps along the straight-line path from  $x_{ci}$ . The resulting attributions were normalized to enable comparison among input features.  $I_{Gi}$  to the measured spectral features. The IG distribution is highly non-uniform, with dominant contributions concentrated within specific wavelength regions. As shown in wavelength intervals around 3.9315-3.9353 Å and 3.9373-3.9386 Å. These regions correspond to the characteristic W45+ emission lines involved in the candidate line-intensity ratios identified in Figure 5. The consistency between the IG-derived importance and the physically selected temperature-sensitive line pairs indicates that the CNN model primarily relies on spectral regions associated with strong temperature sensitivity. In particular, both I3.9330Å/I3.9379Å and I3.9339Å/I3.9379Å contribute to the model prediction, while the latter provides improved diagnostic performance based on the combined sensitivity and uncertainty analysis. This agreement between data-driven feature importance and atomic-physics considerations supports the reliability of the proposed method.

### 3. Results and Discussion

After completing the training, the long-pulse discharge #98958 (with a duration of approximately 105 s) is selected as an independent test case to evaluate the model performance. Figure 8 Figure 8: see original paper shows the temporal evolution of the electron temperature for shot #98958, comparing the XCS-predicted results with the reference ECE measurements. Overall, the predicted  $T_e$  follows the evolution of the discharge well, reproducing both the global trend and the main fluctuations. Good agreement between the two diagnostics is observed throughout most of the discharge, covering the initial rise, the high-temperature phase, and the later stage. The enlarged views further show that the model reproduces the detailed temporal variations of  $T_e$ . The residual  $\Delta T_e$  shown in Figure 8(b) remains within a relatively narrow range for most of the discharge, with the maximum deviation not exceeding 1 keV, indicating a generally good consistency between the predicted and measured temperatures. These results suggest that the selected spectral line ratio provides sufficient temperature sensitivity to track the temporal evolution of  $T_e$ .

measurements and CNN predictions. (a) Time evolution of  $T_e$ . (b) Residual  $\Delta T_e$  between CNN-predicted and ECE-measured values.

To further evaluate the accuracy of the model predictions, Figure 9 Figure 9: see original paper shows the regression results of the electron temperature predicted

by the proposed XCS-based model against the reference ECE measurements for the entire testing dataset. The tight clustering of the data points around the identity line demonstrates a strong agreement between the model predictions and the experimentally measured electron temperatures, indicating that the spectral intensity ratio inputs provide sufficient information for accurate  $T_e$  inference. To quantitatively evaluate this agreement, the coefficient of determination  $R^2$  is employed, yielding a value of  $R^2=0.9184$  for the present model. The  $R^2$  value is calculated as:

$$R^2 = \frac{\sum (y - \hat{y})^2}{\sum (y - \bar{y})^2}$$

where

$y$  denotes the reference ECE-measured electron temperature,

$\hat{y}$  the corresponding XCS-predicted value, and

$\bar{y}$  represents

is the mean of the reference data. An

$R^2$  value closer to unity indicates a better consistency between the predicted and measured electron temperatures. The statistical distribution of the prediction errors is analyzed using the Laplace distribution, which is particularly suitable for characterizing non-Gaussian error behaviors commonly observed in plasma diagnostics[37]. The probability density function of the Laplace distribution is given

$$f(x) = \frac{1}{2\zeta} \exp\left(-\frac{|x - \mu|}{\zeta}\right)$$

where

$$\mu$$

is the location parameter, representing the central tendency or systematic

bias of the prediction error, and

$\zeta$  is the scale parameter, characterizing the width of

the distribution and thus the typical magnitude of the absolute prediction error. Figure 9 (b) presents the error distribution of the electron temperature predictions together with the corresponding Laplace fitting. The fitted value of  $\mu$  is 0.009 keV, which is close to zero, indicating that the proposed model exhibits negligible systematic bias with respect to the ECE measurements, while the relatively

value suggests that the

majority of prediction errors remain within a narrow range of 0.25 keV. It is observed that relatively larger prediction errors occur in the low-temperature regime ( $T_e < 3\text{keV}$ ). This behavior can be primarily attributed to the inherently weak emission of W45+ ions at low electron temperatures, where the

spectral line intensities decrease significantly, resulting in a reduced signal-to-noise ratio and enhanced sensitivity to experimental noise and background fluctuations. This effect is further reflected in the statistical error analysis based on the Laplace distribution. In the low-Te regime, the error distribution exhibits a broader spread, corresponding to a larger scale parameter  $b$ , indicating increased uncertainty in the prediction. In contrast, at higher electron temperatures, stronger tungsten spectral emissions lead to more reliable intensity ratios, yielding a narrower error distribution and improved prediction accuracy.

temperature. (b) Prediction error distribution with Laplace fitting.

#98958, comparing the XCS-predicted results with the reference ECE measurements.

The predicted profile follows the overall shape of the measured profile well, including the central peak and the gradual decrease toward larger

. Good agreement between

the two profiles is observed over most of the spatial range. The residual  $\Delta T_e$  shown in indicating that the prediction is generally consistent with the measurements across the profile.

Overall, the temporal, statistical, and spatial results are consistent with each other.

The model follows the time evolution of the electron temperature and reproduces the main features of the discharge, with relatively small deviations from the ECE measurements. The regression and error analysis show good agreement and no obvious systematic bias. The spatial profile comparison further shows that both the shape and magnitude of the temperature distribution are well reproduced. These results suggest that the selected spectral line ratio can be used for electron temperature inference, and that the proposed method is able to describe the electron temperature behavior in both time and space.

measurements and CNN predictions.(a) Radial profile of Te (b)Residual  $\Delta T_e$  between CNN-predicted and ECE-measured values.

## 4. Conclusions

In this work, a new fast electron temperature diagnostic scheme is developed on the XCS system on EAST, based on W45+ spectral line intensity ratios and combined with a CNN modeling. FAC calculations demonstrate that the selected line ratios vary monotonically with electron temperature, establishing a solid physical basis for spectroscopic diagnostics. By establishing a direct mapping between spectral features and electron temperature, the proposed approach avoids iterative spectral fitting and significantly reduces computational cost. The method is validated using EAST discharge #98958, showing good agreement with ECE measurements in both temporal evolution and spatial profiles, with small deviations and negligible systematic bias. The diagnostic per-

formance is particularly robust in the high-temperature regime, where W45+ emission is sufficiently strong to ensure reliable spectral signals. These results demonstrate that W45+ spectral line ratios provide an effective observable for electron temperature inference. The integration of

physics-based spectral analysis with CNN modeling offers a practical pathway toward fast and potentially real-time spectroscopic diagnostics in fusion plasmas.

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