Synthetic emission evaluation and line-ratio fast diagnostic for the thermal helium beam RFX-mod system on NSTX-U

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A new time-dependent helium collisional radiative model (CRM) with state-of-the-art atomic data is used to produce synthetic line emission to evaluate the application of the thermal helium beam (THB) diagnostic system on NSTX-U. This diagnostic is currently in operation on RFX-mod, and that is proposed to be installed on NSTX-U. The THB RFX-mod system is based on the 667.8, 706.5, and 728.1 nm helium line-ratios to determine electron temperature and density radial profiles. The purpose of this synthetic analysis is to evaluate the applications of this diagnostic to determining fast electron temperature and density radial profiles on the edge of NSTX-U, and that are needed in turbulence studies. This diagnostic is limited by the detection of the 728.1 nm line, which is the weakest one of the three. This synthetic study will also aid in future evaluations of a similar 2-D diagnostic systems on the divertor.

I. INTRODUCTION

Helium line-ratio diagnostic for determining electron temperatures and densities is a standard and important technique applied in measurements of plasma edge, scrape-off layer (SOL), and divertor regions on several fusion experiments such as TEXTOR,[1,2] RFX-mod,[3] PISCES-B,[4] JET,[5] and JT-60U.[6] It has also been used for edge turbulence measurements on NSTX by gas puff imaging,[7] validation of plasma transport models on MAST,[8] and on edge turbulence characterization on RFX-mod.[9,10]

Until recently, this powerful diagnostic technique was limited by the quality of atomic data available, and the time-evolution of the long relaxation times of the triplet spin system of the metastable state of helium.[8,11] A new Hibrid-Time-Dependent/Independent (HTD/I) helium line-ratio model that employs state-of-the-art R-Matrix,[12] R-Matrix With Pseudostates (RMPS),[13] and Convergent Close Coupling (CCC)[14,15] electron-impact excitation and ionization data, and that takes into account the transient relaxation times of all the atomic states has been developed.[11] This new HTD/I model has more than double the radial range of electron temperature and density measurements, as well as improved agreement between them and Multi-Point Thomson Scattering (MPTS) measurements,[2,11] in comparison to the widely used helium atomic model developed for TEXTOR.[1]

In this work, the new HTD/I helium line-ratio model is fisrt used to analyze emission data and to obtain electron temperature and density radial profiles from the THB system on RFX-mod.[10] The obtained profiles are then compared to those predicted from the old TEXTOR atomic model,[1] that is typically employed on RFX-mod.

In the second part, the same state-of-the-art atomic data set used by the HTD/I is employed in a time-dependent collisional radiative model to predict line emission of a thermal helium gas-puff as it propagates along the radial direction of NSTX. In this analysis, the synthetic model predicts emission from the 587.6, 667.8, 706.5, and 728.1 nm lines. The 587.6 nm emission intensity is compared to previous simulations from 3-D DEGAS 2 on NSTX,[16] that employed the old atomic data sets from TEXTOR.[1] This comparison helps to evaluate the impact of the new helium atomic data set[11] on line intensity predictions.

Finally, predicted gas-puff emission for the 667.8, 706.5, and 728.1 nm lines is used to evaluate the sensitivity of the THB system in order to assess diagnostic applications on NSTX-U. To support this assessment, synthetic electron temperature and density radial profiles for NSTX-U are produced using the HTD/I line-ratio model,[11] and compared to actual profiles.

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II. TIME-DEPENDENT COLLISIONAL RADIATIVE MODEL

To successfully model spectral emission, it is necessary to account for the main populating/depopulating mechanisms in a collisional radiative model. Our application of collisional radiative theory to the calculation of excited populations is similar to the concept of the ADAS[21] suite of codes for population and emission modeling. Any ion/atom can be modeled by a set of nl-terms (LS-coupling) with radiative and collisional couplings. On the edge plasma region, the processes that play the main role in populating the various nl-terms include:

- Spontaneous decay: $(A_{j\to i}/A_{i\to j})$.
- Electron-impact excitation/ de-excitation: $(q^e_{j\to i}/q^e_{i\to j})$.
- Radiative recombination: $[\alpha_i^{(r)}]$.
- Dielectronic recombination: $[\alpha_i^{(d)}]$.
- Three-body recombination: $[\alpha_i^{(3)}]$.

Any given ion in an arbitrary excited i-term is represented by the following time dependent population equation, with the collisional processes (on the right hand side) included.

$$\frac{dn_i}{dt} = -\Big\{n_e S_i^e + \sum_{j\neq i}\left(A_{i\to j} + n_e q^e_{i\to j}\right)\Big\}n_i + \sum_{j\neq i}\left(A_{j\to i} + n_e q^e_{j\to i}\right)n_j + n^+\left[n_e\alpha_i^{R}\right] , \quad (1)$$

where n_e is the free electron density, n_i is the population of the i^{th} excited term being described, n_j is the j^{th} population of any higher or lower energy term from i, and n^+ is the free He II ion density. The generalized recombination rate coefficient is represented as $\alpha_i^{R} = \alpha_i^{(r)} + \alpha_i^{(d)} + n_e\alpha_i^{(3)}$. Equation (1) may be written in the simpler form

$$v_{bm}\frac{dn_i}{dr} = -C_{i,i}n_i + \sum_{j\neq i} C_{i,j}n_j + n^+\left[n_e\alpha_i^{R}\right] , \quad (2)$$

where $v_{bm} = \sqrt{5k_BT/3m_{He}}$ is the average thermal velocity of the gas-puff, and the diagonal loss, and the non-diagonal gain elements of the collisional radiative matrix are given by

$$C_{i,i} = n_e S_i^e + \sum_{j\neq i}\left(A_{i\to j} + n_e q^e_{i\to j}\right) ,$$
$$C_{i,j} = A_{j\to i} + n_e q^e_{j\to i} . \quad (3)$$

The generalized time-dependent solution as a function of the radial displacement r for the atomic populations is given by[11]

$$n_i(r) = \sum_{k=1}^{N} V_{i,k}\Big\{\sum_{j=1}^{N} V^{-1}_{k,j}\Big[\big(n_j(0) + \frac{R_j}{\lambda_k}\big)e^{\lambda_k r/v_{bm}} - \frac{R_j}{\lambda_k}\Big]\Big\} , \quad (4)$$

where the recombination contribution is given by $R_j = n^+\left[n_e\alpha_j^{R}\right]$, $V_{i,k}$ and $V^{-1}_{k,j}$ are the eigenvector and the inverse eigenvector elements of the collisional radiative matrix, as well as its eigenvalues λ_k. The sums are performed for the total atomic N-terms included in the CRM model, which in this model includes a total off 19 terms in the configurations $1snl$ $(1s < nl < 4f)$.[11] In this specific gas-puff model, the recombination term R_j is ignored due to signal background subtraction,[11] thus simplifying the solution to

$$n_i(r) = \sum_{k=1}^{N} V_{i,k}\sum_{j=1}^{N} V^{-1}_{k,j} n_j(0)e^{\lambda_k r/v_{bm}} . \quad (5)$$

This time-dependent model is used for predicting the line emission of the helium gas-puff. The electron temperature and densities as a function of the time-dependent line-ratios are calculated from the HTD/I line-ratio model.[11]

$$R^{exp}_{T_e}(t) = \frac{I^{(706.7nm)}}{I^{(728.3nm)}}$$
$$R^{exp}_{n_e}(t) = \frac{I^{(667.9nm)}}{I^{(728.3nm)}} \quad (6)$$
$$R^{exp}_{T_e,n_e}(t) = \frac{I^{(706.7nm)}}{I^{(667.9nm)}} .$$

III. THERMAL HELIUM BEAM DIAGNOSTIC ON RFX-MOD

To evaluate the application of the Thermal Helium Beam (THB) diagnostic from RFX-mod on NSTX-U, it is necessary to estimate the expected signal detection level for the three emission lines of helium (667.8, 706.5, and 728.1 nm). The most critical line is the 728.1 nm, since it is the weakest one of the three. In this section a brief description of the THB diagnostic used in RFX-mod is given. A more complete discussion can be found in.[3]

The THB system separates the three different helium emission wavelengths by means of a monochromator. The light collected from the plasma edge at 8 different radial locations is carried to the spectrograph through a bundle of optical fibers. The optics consists of a Czerny-Turner monochromator with a focal length of 300 mm and optical aperture of $f^{\#} = 4$, and a dispersive grating with 1200 $grts/mm$. At the light exit of the spectrograph there are three slits of 1 mm width, that are coupled to three arrays (one for each of the three wavelengths) of 8 optical fibers. The light is then taken to three multi-anode photo-multiplier tubes (PMTs, Hamamatsu R5900U-20 L16) used as detectors for each of the wavelengths. The output signals of the PMTs are amplified and acquired with a sampling frequency of 2 MHz. The system is also equipped with a CCD camera that can acquire a complete spectrum of the collected light at a slower sampling rate. The complete detection system has been absolutely calibrated with an integrating sphere.

To evaluate the feasibility of using the THB system for measuring helium line emission profiles on NSTX-U, the characterization of the sensitivity of the diagnostic is needed. Measuring the minimum measurable emissivity levels is critical, and these values are then compared to the expected intensities obtained from the synthetic emissivities. The minimum signal levels are obtained from measurements of the three emission lines when the gas-puff signal exceeds the background. The background signal is due mainly to the presence of residual helium recycled on the graphite first wall, and in a minor level due to the electronics noise. In standard discharges on RFX-mod, this background corresponds to a measured signal (the signal output of the amplifier), which is lower than 100 mV. It is therefore possible to set the minimum measurable signal level to 100 mV, and the minimum emissivity signal that can be measured is the one corresponding to this signal level.

Figure 1 shows the measured sensitivity curve for the 8 different optical fibers of the THB system. This plot shows the minimum measurable emission for the three different wavelengths, which takes into consideration the minimum voltage signal (100 mV) of the PMTs.

From sensitivity measurements using the actual optics and electronics, it is estimated that the lowest measured value for detecting the 728.1 nm line is between $3.0 - 4.0 \times 10^{14}$ $Ph/Str - cm^2 - Sec$. Figure 2 shows the radial profiles of the measured intensities of the three helium lines for a typical RFX-mod plasma discharge ($I_p = 1.5$ MA, and central electron density around 1.6×10^{13} cm^{-3}). Only six radial points are shown since two optical fibers were located at different radial points of RFX-mod.

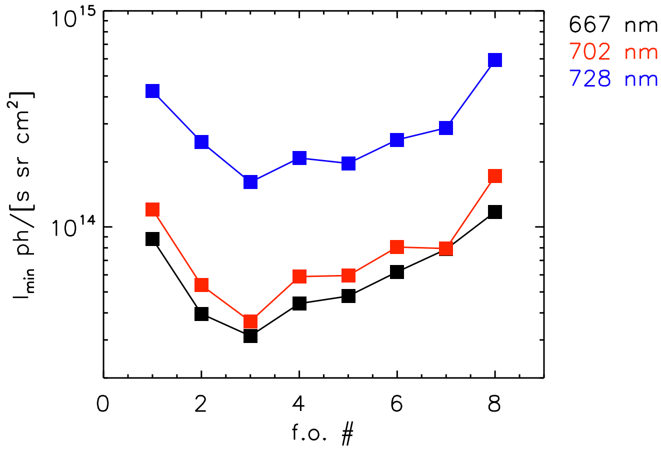

FIG. 1. Measured sensitivity curve of the THB system.

Figure 2 also shows estimations of electron temperature and density profiles determined from the RFX model (old TEXTOR model[1]), and compared to results from the new HTD/I model.[11]

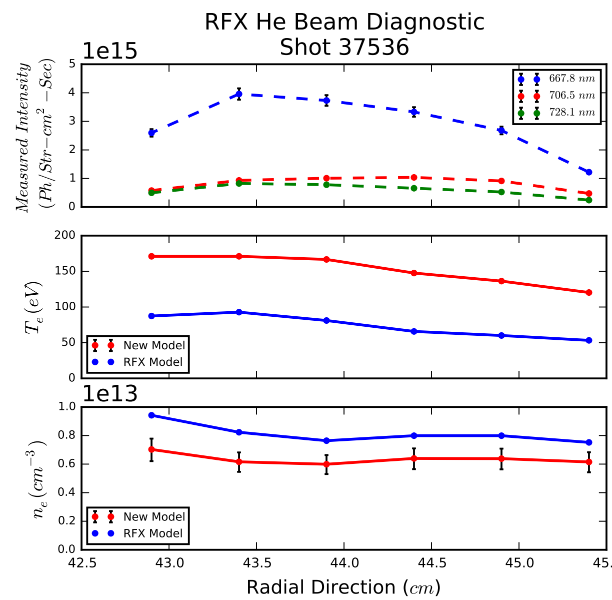

FIG. 2. Electron temperature and density radial profiles from helium line-ratios on RFX-mod.

From figure 2 it is noticed that there are significant differences between the electron temperatures predicted using the new HTD/I model,[11] and those from the old TEXTOR model.[1] It has been experimentally observed that the electron temperatures from the HTD/I model show better agreement to MPTS measurements, while the old TEXTOR model strongly underestimates these temperatures.[2,11] It has also been observed that the new HTD/I model predicts electron densities slightly closer to MPTS measurements[11] as well.

IV. SYNTHETIC EMISSION ON NSTX/NSTX-U

Simulated emission of the 587.6 nm line helium using the Gas-Puff Imaging (GPI) system have been used to validate models of behavior of neutral helium on NSTX.[16] These simulations have been done using the old TEXTOR helium atomic data set[1,17]. The predicted emission profiles were compared to qualitative measurements from the GPI camera.[16] The GPI system consists of a linear manifold with 30 1 mm holes and a fast camera to view the light emission.[18–20]

The analysis in this work makes use of the same injected helium gas ammount, as well as the same electron temperature and density radial profiles employed on the NSTX GPI simulation[16] for two different shots (112811 and 112814).

For the synthetic analysis presented in this work, a nozzle with a single radial and vertical location is considered. A simple gas-puff conical expansion profile with a fixed half-angle ($\theta_{1/2} \backsim 30^o$) (estimated from the NSTX GPI camera observations[16]) is used (figure 3).

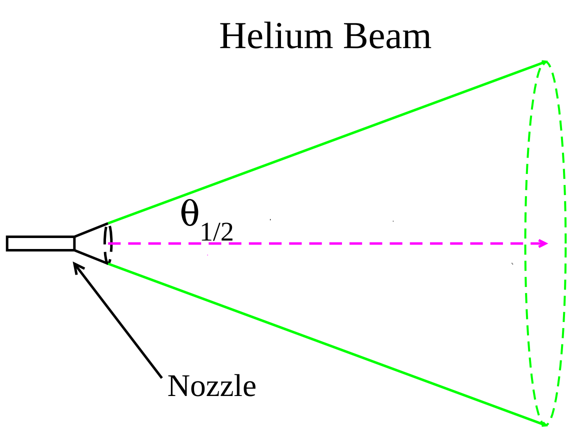

FIG. 3. Conical expansion model employed on the synthetic helium thermal beam gas-puff.

A total of 16 optical fibers are considered. The integration along the line-of-sight is performed between the two intersection points of the spectral view-chord, and the 3-D conical gas-puff expansion by means of Gauss-Legendre quadrature.[22] The 3-D mapping of the radial electron temperature and density profiles is taken into consideration when calculating local emissivities for each Gauss-Legendre line-of-sight integration point.

Figure 4 shows the electron temperature and density radial profiles used to predict the detected synthetic emission for the 587.6 nm helium line.

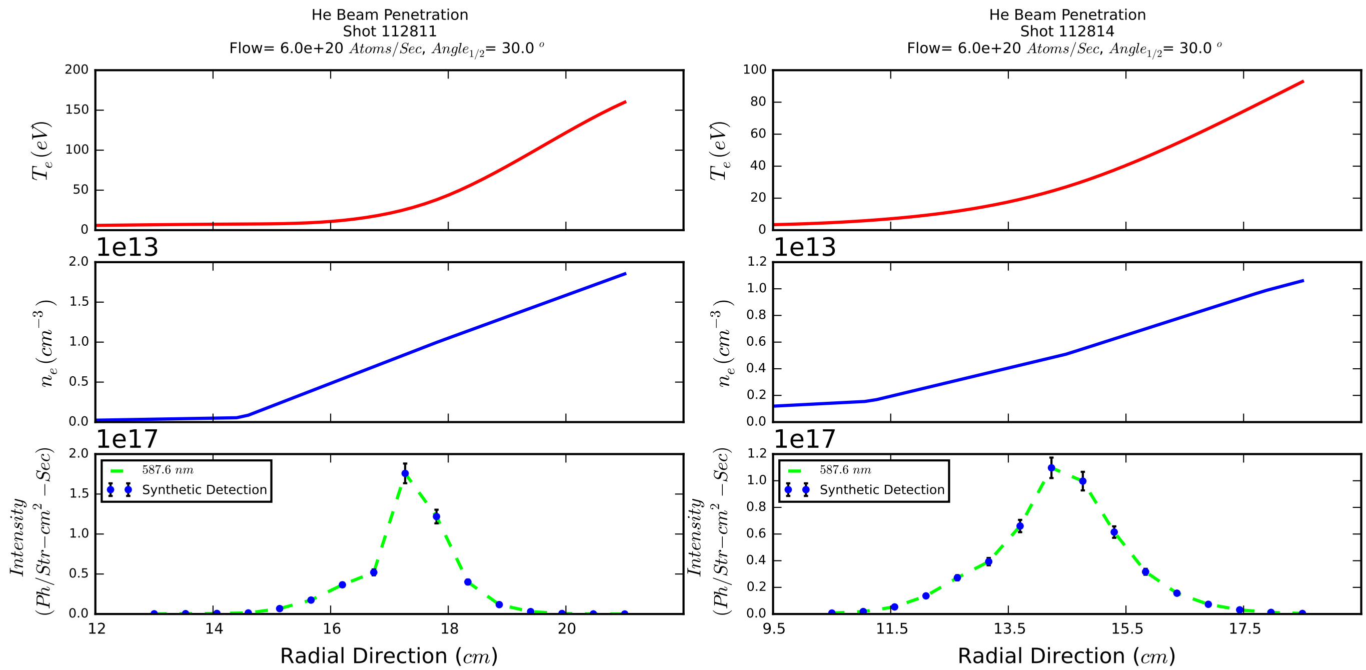

FIG. 4. Synthetic emission for the 587.6 nm helium line on NSTX.

The predicted intensities of the 587.6 nm (Figure 4) using the new atomic data set yield higher emission values than those from the GPI simulations.[16] Due to the high confidence on the new helium atomic data set,[11] it is suspected that the DEGAS 2 simulations may have underestimated the emission.

The same electron temperature and density profiles from the GPI simulation[16] are used to produce synthetic emission for the 667.8, 706.5, and 728.1 nm lines. An uncertainty of $\pm$ 7 % is artificially added to the synthetic intensity “measurements”. Another source of uncertainty is introduced by the 3-D integration along the line-of-sight of the conical expansion of the gas-puff. These synthetic line emission “measurements” are analized using the new HTD/I line-ratio model[11] to obtain radial electron temperature and density profiles. These results are then compared to the actual profiles.

Figure 5 shows the synthetic emission produced by the model, as well as comparisons between actual and predicted electron temperature and density radial profiles from the HTD/I model for two different NSTX shots (112811 and 112814).

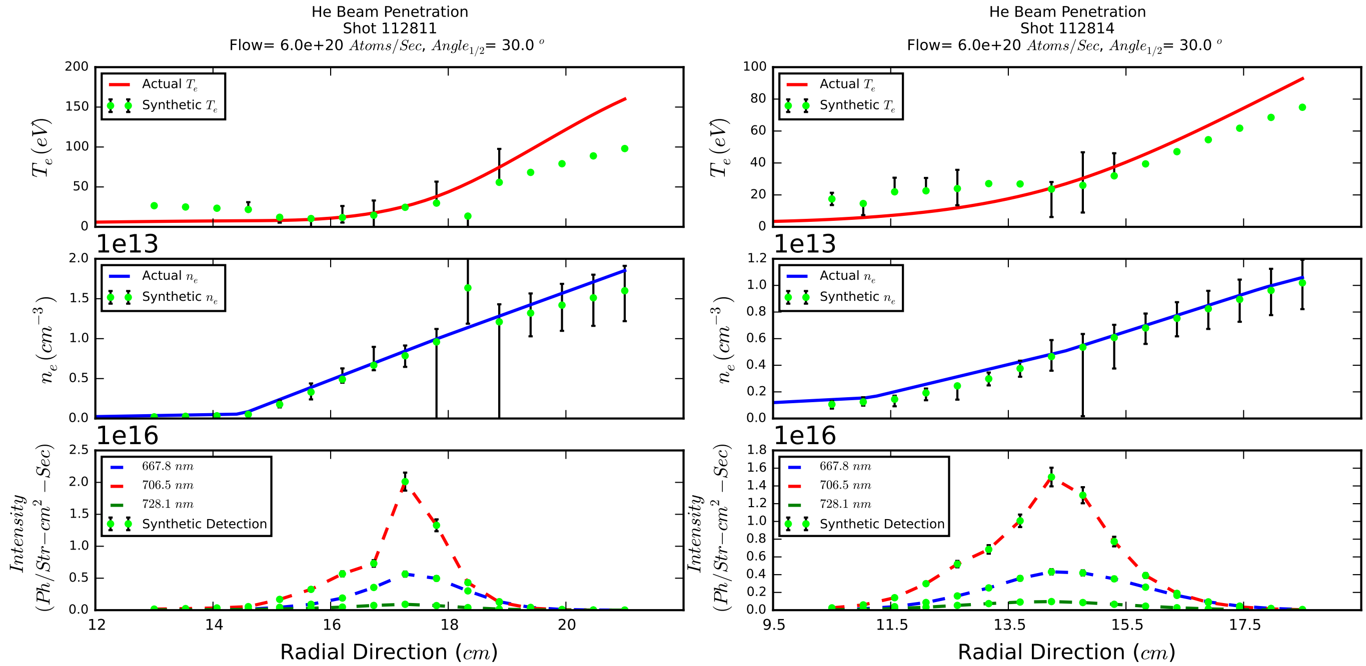

FIG. 5. Synthetic emission for the 667.8, 706.5, and 728.1 *nm* lines of helium, and synthetic electron temperature and density line-ratio diagnostic on NSTX.

For this synthetic diagnostic, a gas-flow of 15.53 $Torr - Litre/Sec$ (6.0×10^{20} $Atoms/Sec$) is assumed.[16] It is noticed from figure 5 that the emission profile of the 728.1 nm line drops close to the signal detection limit ($3.0 - 4.0 \times 10^{14}$ $Ph/Str - cm^2 - Sec$) of the RFX-mod system for some of the radial positions. Still on most of the profile the signal level remains above the detection limit, thus predicting a successful application of the RFX-mod hardware to fast electron temperature and density measurements in the edge region of NSTX-U. Measured electron temperatures and densities in the range of $T_e \backsim 20 \rightarrow 100$ eV and $n_e \backsim 2.0 \times 10^{12} \rightarrow 1.0 \times 10^{13}$ are expected in the edge. The RFX-mod THB can still be improved to reduce the detection limit by optimization of the $f^{\#} = 4$ spectrograph optical aperture, as well as designing a better coupling between optics and plasma. Another way to increase the signal level can be obtained by decreasing the bandwidth of the electronics, since the characteristic frequency of the edge fluctuations in tokamaks is lower then the one of reversed field pinches. The bandwidth of the amplifier can be decreased from 2 MHz to 500 kHz in order to assure signal sensitivity. Finally, increasing the amount of helium in the gas-puff system would directly increase line emission.

By improving the TBH hardware it would allow robust fast measurements ($\backsim 10$ μs) of electron temperature and density profiles on the edge of NSTX-U for turbulence studies. Eventually, if this diagnostic is successful, a similar 2-D system may be used on the divertor region of NSTX-U.

V. CONCLUSIONS

A new HTD/I line-ratio helium model with state-of-the-art atomic data[11] has been used to predict electron temperature and density radial profiles from gas-puff emission on RFX-mod. Results were consistent with those obtained from TEXTOR,[1,11] that showed better agreement to MPTS than those from the old atomic data set[1] typically employed by the TBH system on RFX-mod.

The same new atomic data set was employed on a time-dependent model to predict 3-D helium gas-puff emission and detection profiles for the 587.6, 667.8, 706.5, and 728.1 nm lines on a bundle of 16 optical fibers for two different NSTX shots (112811 and 112814).[16] Emission intensities from the 587.6 nm line were compared to previous GPI DEGAS 2 simulations[16,17] that employed the old helium atomic data set.[1] It was observed that significantly higher emission is predicted when using the new atomic data. It is well known that emission predictions strongly vary with the quality of the atomic data employed in the model.[23] The synthetic "measurements" for the 667.8, 706.5, and 728.1 nm lines were analyzed using the new HTD/I model[11] to predict radial electron temperature and density profiles on NSTX-U.

From this synthetic analysis it is estimated that the expected signal level of the TBH system on NSTX-U should be larger than the detection limit, thus concluding that the application of this diagnostic is a viable option to provide robust fast measurements ($\backsim 10\ \mu s$) of electron temperature and density profiles on the edge of NSTX-U. Applications of a similar 2-D diagnostic system can eventually be expanded to the divertor region of NSTX-U.

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