EUROfusion

EUROFUSION WPS1-PR(16) 15686

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Preprint of Paper to be submitted for publication in 21st Topical Conference on High Temperature Plasma Diagnostics 2016

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Feasibility of line-ratio spectroscopy on helium and neon as edge diagnostic tool for Wendelstein 7-X[a)]

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A beam emission spectroscopy system on thermal helium (He) and neon (Ne) has been set up at Wendelstein 7-X to measure edge electron temperature and density profiles utilizing the line-ratio (LR) technique or alternatively absolute line emission intensities. The status of the setup for the limiter startup phase (OP1.1) is reported as long as first measured profiles using the He beam. This first campaign is a test bed for further developing the technique for the future high density, low temperature detached island divertor regime.

I. INTRODUCTION

Helium line-ratio technique is widely used in fusion devices as a diagnostic to measure electron temperature and density profiles in the scrape-off-layer and the plasma edge. It is based on the density and temperature dependence of the ratio of selected emission lines of neutral He.
In the low temperature (<< 10eV) and high density (> 10^{20} m^{-3}) conditions expected in the W7-X island divertor He lines are weak (or not detectable for T_e < 5 eV) and the T_e/n_e estimate suffers from great inaccuracy. In order to overcome this limitation LR spectroscopy extended by analysis of absolute line intensities can be performed on Ne instead of He, or in a mixture Ne+He. [1] Ne has lower excitation energy and can provide stronger emission lines at low temperatures. [1]
The startup campaign of Wendelstein 7-X, in which the divertor is not yet installed and five graphite limiters define the plasma boundary, has been used to commission the injection and observation systems with both He and Ne. We derived first time and space resolved profiles of electron temperature and density in the scrape-off layer from this diagnostic applying the LR spectroscopy on thermal He. Initial measurements of suitable Ne I lines from pure Ne and mixed Ne/He gas injections were performed as a basis to develop a suited collisional-radiative model (CRM) for Ne and the combined He/Ne situation.

II. EXPERIMENTAL SETUP

The gas injection system provides two in-vacuo plug-ins (one for the upper and one for the lower plasma edge) consisting of gas and water lines as well as a gas box. In the gas box five piezo valves (opening time of few ms) allow independent gas injection at different poloidal positions. Two valves at the upper injection system are equipped with thin capillary nozzles with inner diameter of 0.6 mm and length of 1.5 cm are used for smaller beam divergency. The gas boxes are mounted at a position directly behind divertor plates (to be installed after OP1.1) in two divertor modules which are connected by the same island flux tube in the m/n=5/5 standard magnetic field configuration of W7-X. The vacuum plug-ins are water cooled, capable of steady-state plasma operations. This system allows puffing different gases (He, Ar, Ne and N_2 during OP1.1, after OP1.1 to be extended by some explosive gases like H_2 or CH_4) at pressures from few mbar up to 60 bar (mostly interesting for plasma fuelling). For the purpose of LR spectroscopy the pressure is set to tens of mbar: high enough to detect the light from line emissions but low enough not to affect the global and local plasma parameters. The thermal beam has a mean velocity of ~ 1.5 km s^{-1} and a divergence of ~ 40°.

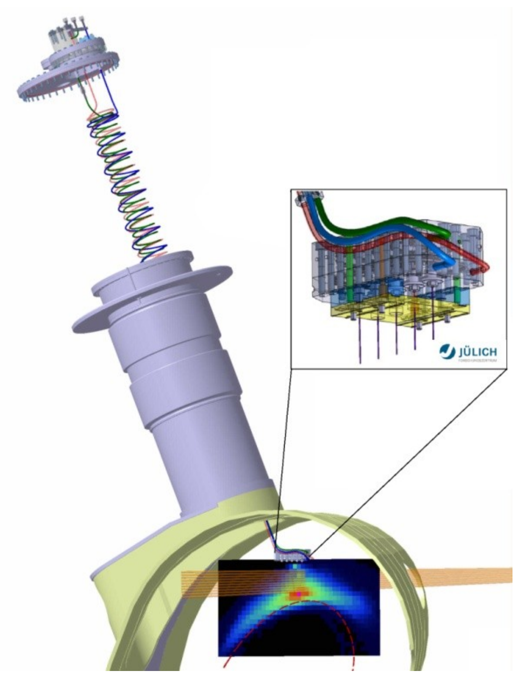


FIG. 1. Overview of the gas injection system at the upper plasma edge. In the zoomed picture the gas box is shown with all 5

capillary nozzles as planned for the later divertor operation. Also shown are the lines-of-sight (solid orange lines) perpendicular to the beam and the position of the last closed flux surface (red dotted line). The colored area represents the emission of the He line 706.5 nm simulated by EMC3-EIRENE.[2]

Fig. 1 shows an overview of the injection system at the upper plasma edge along with the lines-of-sight (los) of the observation system. The spectroscopic observation is realized here with an array of 8 optical fibers (core diameter of 1 mm, length 150 m) fitted to a photo lens mounted directly behind a vacuum window at a diagnostic observation port of two meters length. The los are perpendicular to the beam propagation. Their adjustment is based on EMC3-EIRENE simulation of the He line emissions.[2] This optical setup leads to a spatial resolution of 1 cm and an observable radial range of 8 cm in the scrape-off layer. The width of each los at the nozzle position is 1 cm.

The light is guided to a Czerny-Turner spectrometer, with focal length of 19 cm and a dispersive grating of 300 grooves/mm. The spectral resolution is about 0.5 nm. The light is focused at the entrance slit through a lens with objective aperture of f/4. At the spectrometer exit the light is detected by a CCD camera. The detector is a frame transfer CCD sensor with 512×512 pixels (13×13 µm each). When used in a 512×8 binning mode it provides acquisitions with a time resolution of 14 ms.

At the gas injection for the lower plasma edge a single fiber is connected to an Echelle spectrometer with a focal length of 25 cm. It provides extended domain spectra (200-800 nm) with spectral resolution of 50 pm and time resolution of 100 ms. The detector is a frame transfer ICCD with 1024×1024 pixels (24×24 µm each). This setup is used for first feasibility studies of the beam emission spectroscopy on Ne.

Both observation systems have been absolutely calibrated with an integrating (Ulbricht) sphere. For this the photo lenses with connected fibers have been dismantled from the diagnostic port and placed in front of the sphere. The spectra acquired while illuminating with the sphere are compared to the spectral radiance provided by the sphere manufacturing company. In this way a calibration curve is obtained taking into account the transmission of the fibers, the optics and the grating. This curve is then used to compute the absolute value of the measured line intensities.

III. EXPERIMENTAL RESULTS

The measurements presented in this work were obtained during a standard H discharge, with ECRH injected power of 2 MW, central $T_e \sim 8$ keV, line-integrated $n_e \sim 1.5\times10^{19}$ m^{-2}.

Repetitive (4-5) 75 ms-long helium puffs were carried out during the discharge through one nozzle in the upper box with a flux of about 1.5×10^{19} atoms/s at reservoir pressure of ~30 mbar. Spectra were acquired continuously during the discharge with an exposure time of 25 ms.

Fig. 3 shows the spectra taken before, during and after one puff. The measured He I lines are the singlet $\lambda_1 = 667.8$ and $\lambda_2 = 728.1$ nm as well as the triplet $\lambda_3 = 706.5$ nm visible line. Intrinsic lines are those of C II at 678 and 711 nm respectively.

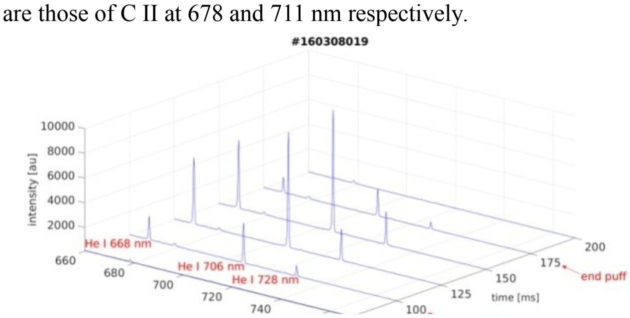
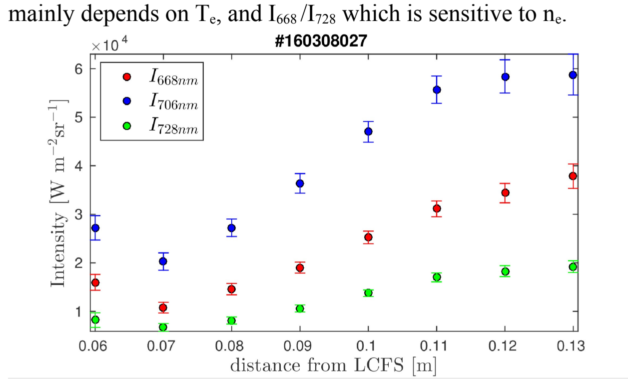


FIG. 2. Spectra acquired before, during and after a He gas puff.

The absolute value of the line intensities is obtained by subtracting the background and multiplying by the calibration factor. A Gaussian curve fitting is then applied to the lines and its integral gives the line intensity. Fig. 4 shows the intensities of the three He lines for the different lines-of-sight. The innermost los is lying 6 cm outside of the last closed flux surface, while the outermost in a distance of 3.3 cm from the nozzle.

FIG. 3. Radial profiles of absolute line intensities of the three He lines.

From the line intensities two ratios are computed: I_{706}/I_{728} which mainly depends on T_e, and I_{668}/I_{728} which is sensitive to n_e.



The derivation of T_e and n_e is done by comparing these experimental ratios with calculated ratios from a collisional-radiative model (CRM). This model simulates the spectral emission of the neutral He taking into account all significant populating and depopulating mechanisms for the considered atomic levels. The successful application of the line-ratio technique depends strongly on the accuracy of the set of atomic data used in the CRM. In this work two different models have been applied. The first is a stationary CRM that was previously routinely used at TEXTOR for the He-beam diagnostic.[3] The second is a new hybrid time dependent/independent CRM with a renewed set of atomic data.[4] This model takes into account the long relaxation time of the triplet spin term which is mainly populated from the triplet metastable state. The time dependent solution is important only at lower densities (< 1-2×10^{18} m^{-3}) at which the relaxation times for the metastable-triplet system (~10 µs) are longer than the time constant of the beam propagation.

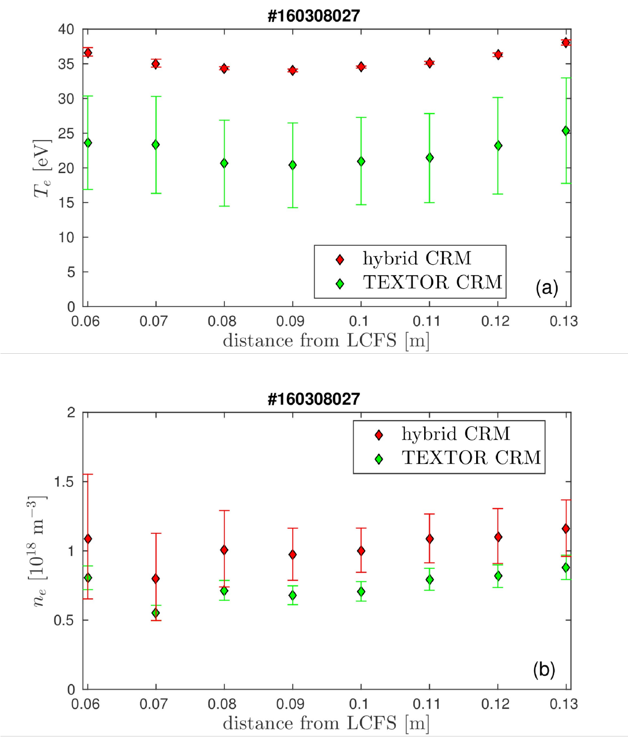


FIG. 4. Edge radial profiles of electron temperature (a) and density (b) from He-beam line-ratio technique.

Fig. 5 reports the T_e and n_e profiles determined with the two different CRMs. The profiles are averaged on a single puff.

For the TEXTOR CRM we assume the systematic uncertainties of T_e and n_e are 30% and 10% respectively, as found at TEXTOR by comparison the results of the He beam spectroscopy with other edge diagnostics. [3]

For the hybrid CRM no comparisons of n_e and T_e values with other diagnostics have been done so far to validate the set of applied atomic data. We estimate the error bars by propagating the line-ratio uncertainties to the derived electron temperatures and densities. These uncertainties are given by the combination of the experimental uncertainties (at the moment only deviations from the Gaussian fit of the line intensities) and the CRM uncertainties. The latter are not yet rigorously calculated but roughly estimated to be 2.5%.[4] Thus, the error bars of T_e and n_e for this new CRM have to be considered as preliminary. Moreover we note that error bars for T_e are much smaller than for n_e. This is because T_e is more sensitive to line-ratio uncertainties at high values (>~ 100 eV) and less sensitive for lower values. Whereas n_e has an opposite behavior and it is more sensitive to line-ratio uncertainties at low values (ne <~ 5×10^{17} m^{-3}).

The solutions given by the new hybrid model are to be preferred to the ones given by the old TEXTOR model since the hybrid CRM includes a newer and more accurate set of atomic data. This model predicts a good measure of confidence for the electron temperature diagnostic for T_e < 100 eV values and for the electron density diagnostic for $n_e > 5\times10^{17}$ m^{-3}. Our measures lie within this interval, so the model provides reliable estimates for both T_e and n_e.

Comparisons with other edge diagnostics at W7-X are now being conducted, in particular with the Langmuir probes in the limiter and at the Multi-Purpose Fast Manipulator[6] installed during the first operation phase.

First test injections with Ne have been performed in both boxes to collect spectra that are useful for the development of a Ne CRM. This model will be used during the next divertor campaign to estimate T_e and n_e from line emission analysis of neutral Ne.

Ne was injected as a single gas (at reservoir pressure of 15 mbar) and in a mixture with He (15 mbar Ne + 30 mbar He). Fig. 6 shows a Ne spectrum from the observation system at the lower plasma edge. Many Ne lines have been identified and are labeled.

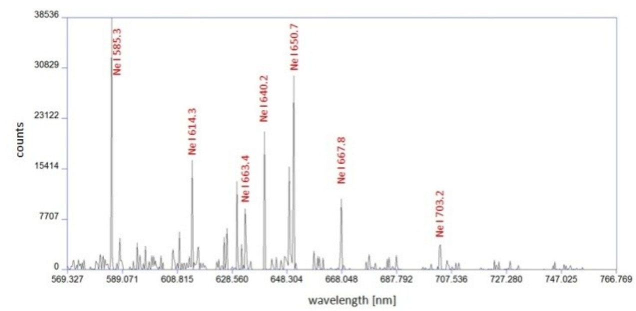


FIG. 5. Overview spectrum of Ne line emissions recorded at the lower plasma edge.

V. CONCLUSIONS

In this paper the thermal He/Ne beam diagnostic for the measurement of T_e and n_e at Wendelstein 7-X is described and its first results are presented.

The gas injection and spectroscopic observation systems have been successfully commissioned during the first plasma operation campaign. Profiles of T_e and n_e have been derived from the line-ratio technique on the He beam. First injections with Ne have been carried out and are being used as a test bed for the development of a Ne collisional-radiative model. This model is required for the envisaged determination of T_e and n_e through Ne line emission analysis during the next divertor campaign.

XII. ACKNOWLEDGMENTS

This work has been funded in part by the Department of Energy under grant DE-SC0014210. The versatile gas injection system has been developed in collaboration between FZ Jülich, IEK-4 and IPP Greifswald. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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