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An ultraviolet-visible-near infrared overview spectroscopy for divertor plasma diagnosis on Wendelstein 7-X

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A new ultraviolet-visible-near infrared (UV-VIS-NIR) overview spectroscopy has been developed for routinely monitoring divertor recycling, intrinsic and extrinsic impurity fluxes on Wendelstein 7-X (W7-X). The overview spectroscopy is part of a large integrated system which allows several diagnostic systems to share the same field of view through an endoscope. During the first divertor operation phase on W7-X, a temporary view port was setup for the overview spectroscopy in order to investigate the divertor plasmas and provide reference data for the commissioning of the whole integrated endoscope system. The overview spectroscopy uses a 5-channel spectrometer to cover the wavelength range 300-1100 nm. The reciprocal linear dispersion of the spectrometer are in the range of 0.04-0.19 nm/pixel. The spatial coverage of the system is 10 cm in the vertical direction and 20 cm in the toroidal direction. The first full spectral survey identified H, He, C, O, Fe, Ne, N and Ar lines. The temporal evolutions of hydrogen and impurity radiation with maximum 10 ms resolution were obtained. Spectra fall in the range of filter transmission curves have been investigated for the filter camera systems which will be commissioned along with the endoscope in the next operation phase. https://doi.org/10.1063/1.5033371

I. INTRODUCTION

Wendelstein 7-X (W7-X) has been designed to use the island divertor concept for the power and particle exhaust. This island divertor concept, which utilizes large magnetic islands intrinsically formed in the magnetic topology induced by external coils even without taking into account the plasma effect, was successfully applied for the first time on W7-AS stellarator.[1] The W7-X program aims to further test the feasibility of the island divertor concept under steady-state operation with fusion relevant plasma parameters.[2] Three major island chains with rotational transform (ι) values of 5/6, 5/5 and 5/4 have been chosen, and ι=5/5 is defined as the standard case.[3] An endoscope system has been developed to better understand the island divertor performance.[4–6] The endoscope has a single in-vessel tube to guide the light from the inside of the plasma to the outside of the vacuum chamber. Then the light is split into 11 branches to be used by several diagnostic systems, including 5 narrow band filter cameras, 1 infrared camera and 5 light-to-fiber interfaces for spectroscopy systems. The overview spectroscopy plays a key role in this integrated system for its wide wavelength coverage from 300 nm to 1100 nm (UV-VIS-NIR), while other systems are more specified on much narrower

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wavelength ranges. A divertor gas inlet system installed under the horizontal divertor is also inside the endoscope's view, which can be used for fueling, impurity seeding and active spectroscopy diagnostics.[7–9]

After the initial limiter operation phase, ten test divertor units (TDU) with passive cooling[10] were installed on W7-X. The first divertor operation campaign, operation phase 1.2a (OP 1.2a), was carried out in the second half of 2017. During OP 1.2a, full spectral survey was performed by overview spectroscopy. Spectral lines of fueling gas (H, He), intrinsic impurities (C, O, Fe), and seeded impurities (Ne, N, Ar) were identified. Temporal evolutions of fuel and impurity line emissions were routinely monitored. Background emissions in the interested ranges of filter cameras were also checked using the overview spectroscopy. This manuscript describes the setup of the new overview spectroscopy system and gives first experimental results.

II. OVERVIEW SPECTROSCOPY SYSTEM AND INITIAL SETUP ON W7-X

The overview spectroscopy system is designed to observe the same divertor plasma as several other diagnostic systems via an endoscope system. Figure 1 shows the schematic view of the endoscope and the overview spectroscopy system. The endoscope system views the divertor region from the outboard side (AEJ51 port) of W7-X, and the field of view (FOV) is 70 × 70 mm. A rotatable first mirror allows the system to vertically scan the FOV through the divertor region. The light from the divertor plasma is reflected by 6 aluminum coated mirrors (M1-M6) to the outside of the vacuum chamber. Then at the exit pupil the light is divided into fractions of 50% intensity by two perpendicular oriented mirrors installed on a prism shape workpiece. Each fraction is further split into UV branch (below 550 nm), VIS branch (550-950 nm) and IR branch (above 950 nm) by dichroic beam splitters (S1-S4). The transmission is expected approximately 38% taking into account 6 mirrors (90% each), 2 CaF_2 windows (95% each) and 1 beam splitter (80%).[5] The intensity beam splitters (S5-S8) are added in the UV and VIS branch to further divide the light paths. In total, there are 4 UV, 4 VIS and 2 IR branches available. As for overview spectroscopy system, a full spectrum branch is created in a special way by drilling 19 holes with 1 mm diameter on the prism tip, and maximum 19 fibers

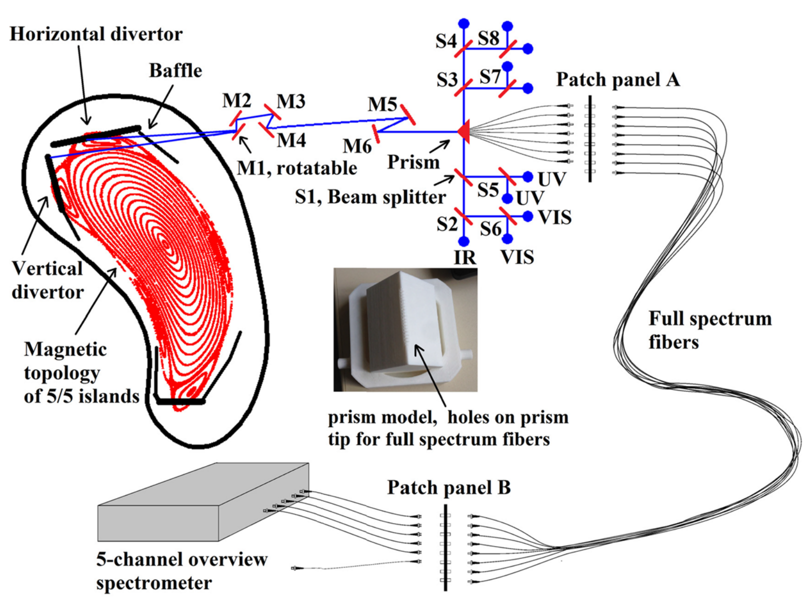

FIG. 1. Schematic view of the AEJ port endoscope and overview spectroscopy system. The endoscope uses a rotatable first mirror to vertically scan the FOV through the divertor region. Six mirrors (M1-M6) guide the light to the outside of vacuum chamber. A prism and eight beam splitters (S1-S8) divide the light into 11 branches. On the tip of the prism, 19 holes are drilled for the installation of full spectrum fibers, which carries the light to the 5-channel overview spectrometer. The plotted magnetic topology corresponds to the standard 5/5 island divertor configuration.

with full spectra can be installed. The WF fiber type by the manufacturer CeramOptec with 800 µm core diameter is used as full spectrum fiber for its good transmission in the used UV, VIS and NIR spectral range. Between the endoscope and the spectrometer, the fibers are divided into three sections by two patch panels. The patch panels are employed to simplify the installation and management of the large number of fibers applied in the divertor spectroscopy (full spectrum fibers, UV fibers, VIS fibers and NIR fibers). One patch panel is located in the W7-X torus hall near the endoscope (patch panel A), and the other one is located in the spectrometer room (patch panel B). Connecting the fibers in different ways at the patch panels significantly increases the flexibility of the whole divertor spectroscopy systems and adapts it to the experimental requirements. For the overview spectroscopy system, Section I is 5 meter long fibers from the prism to patch panel A. Section II is ~80 meter long fibers from patch panel A to patch panel B. Sector III is 12 meter long fibers from patch panel B to the spectrometer.

The focal planes of the endoscope are at the end of the UV, VIS and IR branches, while the prism lies before them. So the light collected by the full spectrum fibers originates from the whole FOV of the endoscope. Based on this, 5 miniature spectrometers are used to simultaneously measure hydrogen and impurity emissions in a large wavelength range (UV-VIS-NIR, 300 nm-1100 nm) while providing moderate spectral resolution. The 5 miniature spectrometers are installed on a desktop mount to share the same power supply and USB2-hub. Each spectrometer will be referred to as a channel of the overview spectroscopy system in the rest of this manuscript. Each overview spectroscopy channel is a miniature Czerny–Turner spectrometer with a fixed grating (Avantes model: AVASPEC-ULS2048L-USB2-RM) to cover 297-459 nm, 452-590 nm, 583-698 nm, 680-889 nm and 789-1121 nm, respectively. Table I lists the grating type, blazed wavelength and resulting wavelength coverage for each channel. The reciprocal linear dispersion of the overview spectroscopy is in the range of 0.04-0.19 nm/pixel, as shown in figure 2(a). The spectral resolution defined as the full width at half maximum (FWHM) of single peak are in the range of 0.19-0.48 nm. The input port for each channel is a standard SMA adaptor with a slit. The slit size is 25 µm in width and 1 mm in height. Each channel has a built-in single array CCD detector with 2048 pixels. The pixel size is 14 µm in width and 200 µm in height. A detector collection lens is used to match the 800 µm fiber size to the detector size. The AVASPEC-ULS2048L spectrometer has high sensitivity as 470000 counts/µW per ms integration time. It was chosen to overcome the difficulty that at the prism, only a small portion of light (0.13%) is extracted and coupled into full spectrum fiber. The absolute intensity calibration was done by put an integrating sphere in front of the vessel end of the fiber. Figure 2(b) shows the sensitivity curve of each channel.

In OP 1.2a, a temporary port AEI51 and a simple optic layout are employed to setup the overview spectroscopy system. The system is required for monitoring the divertor impurity contents and recycling during OP1.2a and providing reference data for the endoscope commissioning in next experiment campaign. The AEI51 port is an inboard view port located in the same poloidal cross-section and coaxial to the AEJ51 port. It views the divertor region from a pump gap between the horizontal divertor and the vertical divertor, as seen in figure 3. To ensure all seven applied fibers (core diameter: 800 µm) at the port AEI51 view the same plasma volume, the fibers are hold closely in a tube of 3 mm inner diameter, then mounted in front the quartz glass vacuum window without lens. The axes of the fibers are parallel and the effective acceptance areas of the fibers are limited by the opening of the pumping slit. The resulting spatial coverage for the overview spectroscopy is 10 cm in the vertical direction and 20 cm in the toroidal direction.

TABLE I. The parameters of 5-channel overview spectrometer.

Channel	Grating (l/mm)	Blazed Wavelength (nm)	Wavelength Range (nm)
Ch01	1800	250	296.3 – 459.6
Ch02	1800	500	451.1 – 590.8
Ch03	1800	500	582.3 – 698.5
Ch04	1200	750	679.8 – 889.5
Ch05	830	800	788.6 – 1121.4

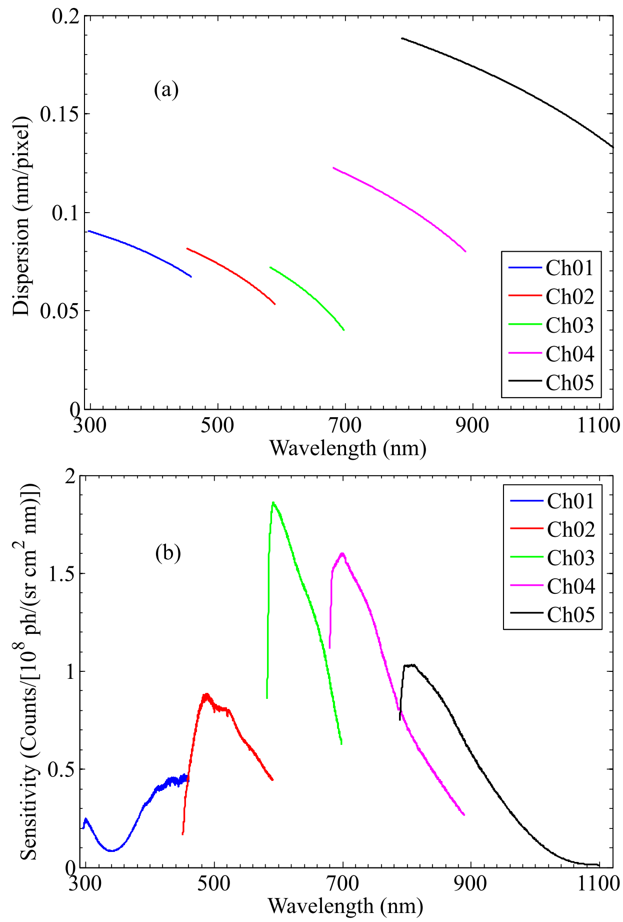

FIG. 2. The reciprocal linear dispersion (a) and the sensitivity curve (b) for the 5-channel overview spectroscopy system.

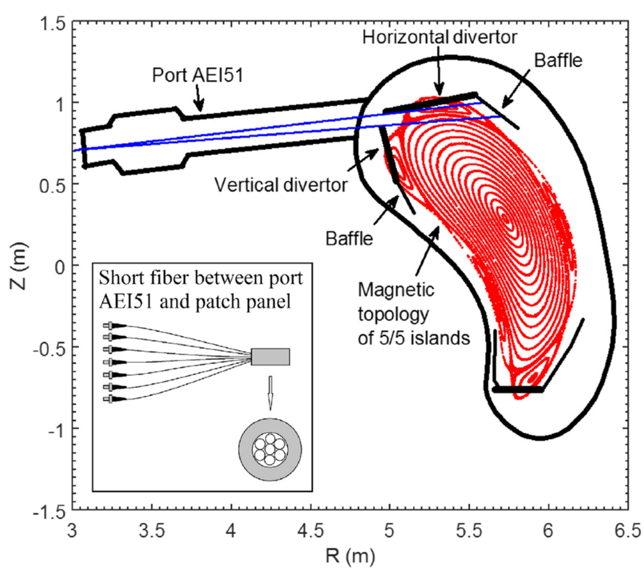

FIG. 3. Layout of the line of sights of the overview spectroscopy during OP 1.2a. A bundle of 7 fibers is placed at a vacuum window at the port AEI51. The effective acceptance areas of the fibers are limited by the pumping gap size between the vertical and horizontal divertor plates, which results in a 10 × 20 cm projected area on the baffle. The plotted magnetic topology corresponds to the standard 5/5 island divertor configuration.

This temporary setup allows the overview spectroscopy system routinely monitoring the divertor plasma during OP1.2a.

III. INITIAL EXPERIMENTAL RESULTS

The spectral survey of the UV-VIS-NIR light (300-1100 nm) emitted from W7-X island divertor region has been routinely performed by using the overview spectroscopy system. In figure 4, typical spectra measured during a standard configuration ($\iota = 5/5$) hydrogen discharge are shown. During this discharge, 2.65 MW heating power is applied by the electron cyclotron resonance heating (ECRH) system. The central electron temperature measured by the electron cyclotron emission (ECE) system is 4.4 keV. The line integrated electron density provided by the interferometry system is 1.75×10^{19} m^{-2}. Neon seeding through the divertor gas inlet starts at 3 s and lasts for 200 ms. The integration times for the overview spectroscopy system are set to 30 ms for channel 2, 10 ms for channel 3 and 120 ms for the remaining channels to optimize the signal to noise ratios. Figure 4(a) shows the spectrum before the neon puff. H, He, C, O and Fe lines are identified and labeled. The helium emission originated from helium gas remaining in the vacuum vessel after helium cleaning discharges applied at previous discharges. In some experimental programs during OP1.2a, helium and hydrogen have been alternately used as working gas, resulting in admixture of helium in hydrogen discharges and vice versa. Carbon, oxygen and iron are the commonly observed intrinsic impurities in the W7-X plasmas. The spectrum in figure 4(b) is measured during the neon puff. Several strong Ne I lines (585.2 nm, 614.3 nm, 640.2 nm, 692.9 nm, 703.2 nm and 837.8 nm) and Ne II lines (333.5 nm, 356.9 nm and 369.4 nm) are identified and labeled.

Investigation of spectra at wavelengths corresponding to the observation with the filter camera systems has also been done. As designed, there are three visible filter cameras and 2 ultraviolet filter cameras mounted on one endoscope.[4] Each camera system has a filter wheel with 6 narrow band interference filters in front of the detector. In total 13 different types of filters for measuring H I lines, He I lines, C I-III lines and CH molecule bands have been prepared for the next W7-X experiment campaign. The full width at half maximum (FWHM) of the filter transmission curves are in the range of 1-3 nm. Investigations of W7-X spectrum inside each filter's transmission range have been carefully done using the overview spectroscopy system. While most wavelength ranges are free of spurious line radiation of other species, the appearance of O II lines inside the H_γ and H_δ filters transmission range has been seen, as shown in figure 5. In the next experiment campaign, reference data will be provided by the overview spectroscopy for the interpretation of the H_γ and H_δ data recorded with the filter cameras.

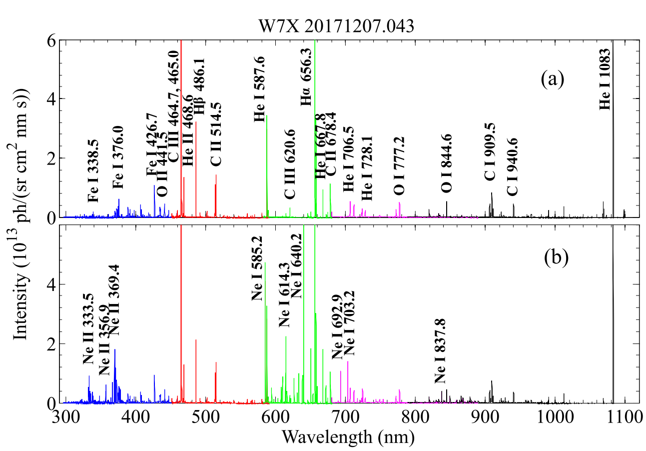

FIG. 4. Example of overview spectra for W7-X hydrogen discharge. (a) Spectrum measured before the neon puff. H, He, C, O, Fe lines are identified and labeled. (b) Spectrum measured during the neon puff. Ne lines are identified and labeled. The upper parts of the strong lines (e.g. H_α) are cut out to get clear demonstration of the weak lines.

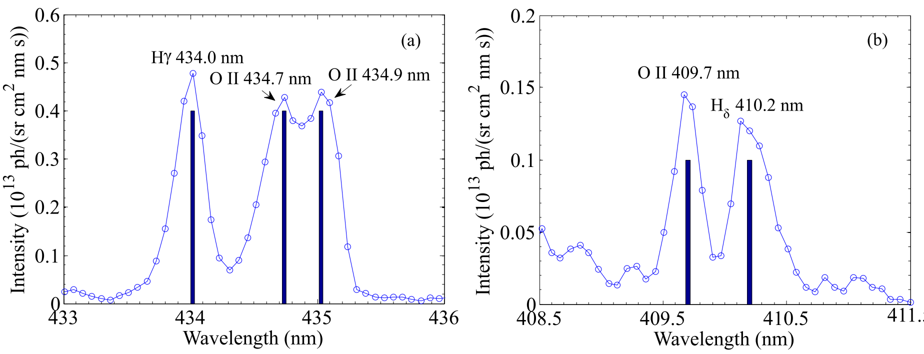

FIG. 5. Investigation of spectrum for the filter camera systems. (a) Overlap of H_γ line and OII lines. (b) Overlap of H_δ line and O II line.

The temporal evolutions of fuel and impurity line emissions were routinely monitored during OP1.2a. Figure 6 shows a hydrogen discharge in standard magnetic configuration (ι = 5/5). The ECRH heating power is 2 MW. The central electron temperature is 4.1 keV. The line integrated

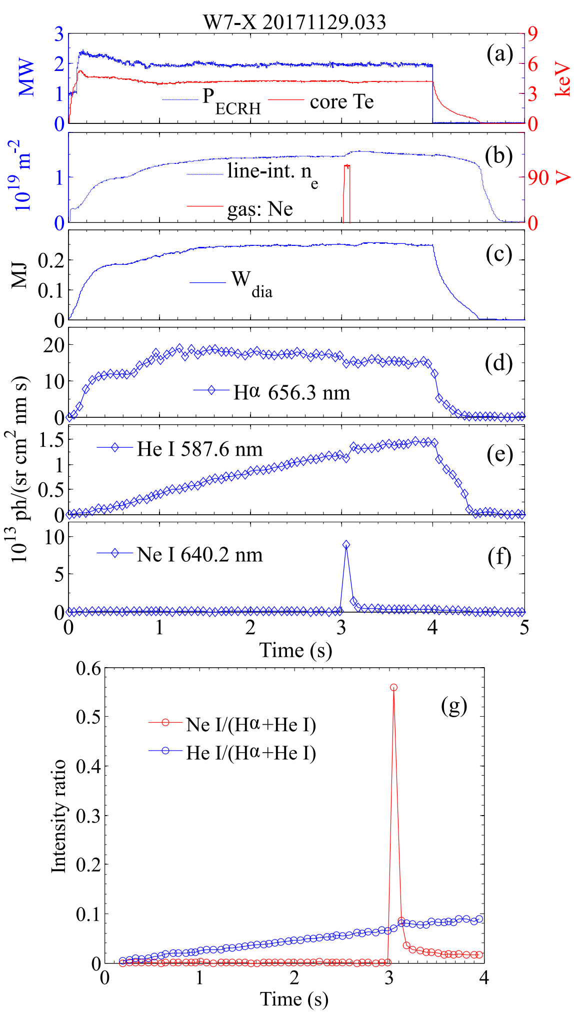

FIG. 6. The time traces of (a) the ECRH heating power and the electron temperature measured by ECE central channel; (b) the line integrated density and piezo valve voltage of the divertor gas inlet system; (c) the diamagnetic energy; (d) the Hα, (e) the He I and (f) the Ne I emissions in divertor region measured by overview spectroscopy; (g) the intensity of He I and Ne I normalized to Hα + He I.

electron density is 1.46×10^{19} m^{-2} before the neon puff, and increased to 1.57×10^{19} m^{-2} after the neon puff. Neon is injected through the divertor gas inlet system at 3 s and the injection lasts for 65 ms. The integration times for the overview spectroscopy system are set to 20 ms for all 5 channels to capture the impurity evolutions. Figure 6(d–f) shows the time trace of the line emissions: H_α (656.3 nm), He I (587.6 nm) and Ne I (640.2 nm). In figure 6(g), the line ratios are shown, using the sum intensity of H_α and He I as denominator. In this discharge, the hydrogen as working gas, comes from pre-fill before the discharge, and gas puff and recycling during the discharge. The helium originates from the numerous helium cleaning discharges prior to the hydrogen discharge. The He I emission increases gradually over time and reaches 10%, indicating outgassing of helium from plasma facing components (PFCs). The neon emission starts to appear at 3 s when the gas inlet is open for the neon seeding. After the injection terminated, the neon emission drops rapidly, and then stays at a low level (2%) until the end of the discharge, indicating its high recycling on the wall.

IV. SUMMARY AND FUTURE PLAN

A new overview spectroscopy system has been successfully commissioned during the experimental campaign OP 1.2a of W7-X and initial results are presented. Spectral survey in island divertor region has been performed. The presence of carbon, oxygen and iron impurities in the W7-X divertor plasma are indicated by their characteristic spectral lines. External impurities seeding through the divertor gas inlet system are well captured by the overview spectroscopy. The temporal evolutions of fuel and impurity emissions are measured with a minimum integration time of 10 ms. Reference data for the filter camera systems has been obtained.

Recently the endoscope at the port AEJ51 has been installed, and the full spectrum fibers will be redirected to the AEJ51 endoscope. Further analysis of overview spectral data will be done to characterize the W7-X divertor plasmas and provide reference data for the next experiment campaign.

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