

Use of a High-Resolution Overview Spectrometer for the Visible Range in the TEXTOR Boundary Plasma

Sebastijan BREZINSEK, Albrecht POSPIESZCZYK, Gennadij SERGIENKO,
Philippe MERTENS and Ulrich SAMM

*Institut für Energieforschung-Plasmaphysik, Forschungszentrum Jülich GmbH
EURATOM-Association, Trilateral Euregio Cluster, D-52425 Jülich, Germany*

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Passive spectroscopy is a standard diagnostic to observe the boundary layer of fusion plasmas. This method of visible spectroscopy is focused on the measurement of deuterium recycling flux and on the monitoring of impurity fluxes of O, He, etc., or W, C, etc., which result from erosion of plasma-facing components. In addition, ro-vibrational analysis of molecular transitions provides information about the molecular break-up in the plasma. Spectrometers used for studying the plasma boundary have to fulfill high demands with respect to the spectral, spatial, and time resolutions, the observable wavelength range, to the sensitivity and dynamic range of the detector in order to simultaneously observe and analyze the emission of both, atomic and molecular species present in the observed region. We present an overview spectrometer system that is able (a) to simultaneously measure strong atomic lines (e.g. D_α) and weak molecular bands (e.g. C_2 Swan band), (b) to resolve narrow molecular lines (e.g. D_2 Fulcher- α band) and allow their ro-vibrational analysis, and (c) to provide information about the spatial distribution in the plasma boundary. A full characterization of the custom-made system in a cross-dispersion arrangement with respect to resolving power, simultaneous wavelength coverage, sensitivity, etc., is presented. Examples of spectra (“footprints”) taken from an injection of C_3H_4 into TEXTOR are presented.

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1. Introduction

Present-day fusion devices use graphite and/or tungsten as a plasma-facing material (PFM) at the locations of highest particle flux, such as the divertor target plates. Complex processes such as physical and, in the case of graphite, chemical sputtering occur at the surface. Material erosion and subsequent deposition leads to formation of surface layers, which can—in the presence of two or more PFMs—contain complex mixed materials. A limited number of *in situ* diagnostics is currently available to identify and monitor the different species that are released from these PFMs under particle bombardment.

Passive spectroscopy in the visible range is a standard diagnostic to monitor the fluxes of carbon-containing species (C, CD, etc.), which are released from the surface or built during the molecular break-up [1], other fusion-plasma related impurities (W, O, etc.), as well as the fluxes of recycled fuel particles (D, D_2 , etc.). To simultaneously observe and analyze the emission of these species from a given observation volume, a spectrometer system has to fulfill high demands with respect to the spectral, spatial, and time resolutions, to the observable wavelength range, and the sensitivity and dynamic range of the detector. An optimized system should be able (a) to simul-

aneously measure both strong atomic lines (e.g. D_α) and weak molecular bands (e.g. C_2 Swan band), (b) to resolve narrow molecular lines (e.g. D_2 Fulcher- α band) and allow their ro-vibrational analysis, and (c) to provide information about the spatial distribution. We present and characterize a spectrometer in cross-dispersion arrangement, which can be applied as a good compromise and which fulfills most of the needs apart from the spatial distribution from a single measurement. Experiments with injection of C_3H_4 were performed in TEXTOR, and the spectra of the break-up products such as CH and C_2 were recorded simultaneously to demonstrate the potential of the device. In addition, the D_2 Fulcher- α was observed during local D_2 injection and was analyzed ro-vibrationally.

2. The Cross-Dispersion Spectrometer: Principal Function, Set-Up, and Technical Data

Conventional spectrometers, e.g. in Czerny-Turner arrangements, are equipped with only *one* dispersive element: grating or prism. Single dispersion systems are restricted in the simultaneously covered wavelength span to a few nanometers at a typical resolving power $R = \lambda/\Delta\lambda$ of 20,000, which is mandatory for a ro-vibrational analysis

author's e-mail: s.brezinsek@fz-juelich.de

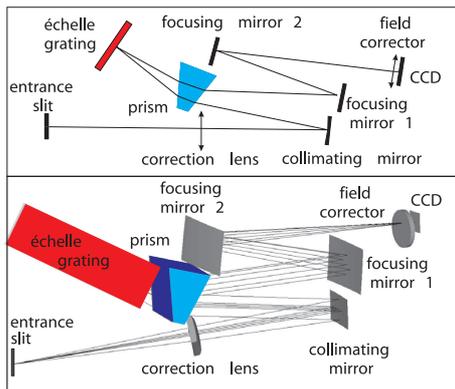


Fig. 1 (a) Schematic view of the spectrometer set-up. (b) Ray tracing calculation showing the optical path in the spectrometer. The optical elements are to scale.

of molecular transitions. The most prominent D_2 transition in fusion boundary plasmas — the Fulcher- α band — is spread over a wide spectral range (600 nm - 645 nm); therefore, several discharges are necessary to record the full spectrum that is needed for spectral analysis.

In contrast, the custom-made spectrometer presented here (MI, model: Mechelle 7500 special; schematic set-up in Fig. 1) consists of *two* dispersive elements: prism and grating. The system covers a spectral range of more than 300 nm without gap at the desired high spectral resolution. The wide span is achieved by the combined use of (i) a highly dispersive échelle grating (ruling: 31.6 grooves/mm, size: 10.0 cm \times 3.0 cm, blaze angle: 63.5°) for wavelength dispersion in the horizontal direction and (ii) an order sorter, i.e., a highly dispersive prism (BAF50 glass, reference angle: 36°), which separates the orders in the vertical direction. The prism is used twice in the optical path (Fig. 1) to ensure complete order separation with compact prism size.

Figure 2a shows the observable spectral orders m projected on the CCD array, starting from $m = 153$ at the bottom (blue spectral range) to $m = 79$ on the top (red spectral range), as well as the used spectral range in each order that is applied for spectrum reconstruction. The centre wavelength in each order, positioned at the blaze angle of the grating, is determined by the order constant $m \times \lambda$ [μm], which amounts to 56.783 for this system. The overlap of different orders is determined by the condition, $\frac{m=x+0.5}{56.783} = \lambda_{\min}^{m=x} = \lambda_{\max}^{m=x+1}$ while five additional pixels on each side are used for averaging. Figure 2b shows the contribution of each order to the *standard range* between 372 nm ($m = 152$) and 680 nm ($m = 84$). The 94th order is marked in red as a guide for the eye in the subsequent figures. The spectrum in each order is spread across several pixels in the vertical direction. Thus, a summation over 5 to 7 pixels is performed to increase the sensitivity of the system, and this provides a so-called spectral channel. In addition, the spectrum reconstruction [2]

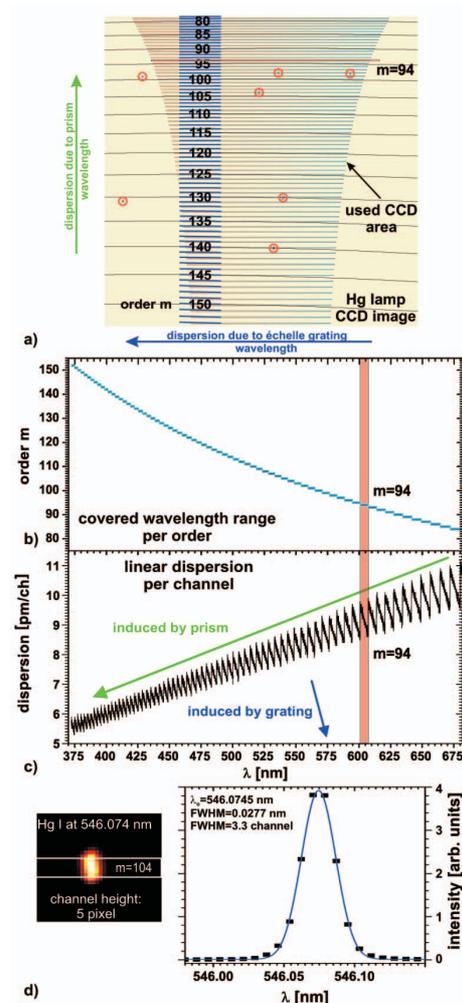


Fig. 2 Spectrum reconstruction: (a) 2D image of a Hg line spectrum. The spectral range per order applied for the complete spectrum reconstruction is represented by the envelope. (b) Distribution of the wavelength coverage per order. (c) Linear dispersion over the full spectral range. (d) A HgI line is used to approximate the apparatus function.

takes into account the non-equidistant separation of the channels, which are more compressed in the lower orders, as well as their curvature in the higher orders.

Figure 2c depicts the linear dispersion as a function of the wavelength in the standard range. Although the dispersion varies over the full range, the resulting resolving power, which was measured by applying the Rayleigh criterion to pairs of D_2 lines, is almost constant (within 15% of 20,000) when the apparatus function is considered. The latter was estimated by the line width of Hg lines, in particular of HgI at 529 nm, to be below 3.1 channels (FWHM), as shown in the Gaussian fit in Fig. 2d.

Further technical data of the Mechelle are as follows: aperture value $f/7$, focal length $f_L = 190$ mm, entrance slit $25 \mu\text{m} \times 75 \mu\text{m}$, with an SMA905 connector for fiber coupling. The light is coupled to the system by means of a 600- μm quartz fiber. A 16-bit camera (Andor, model:

DV434) with a Peltier-cooled, back-illuminated CCD array, 1024×1024 pixels of $13 \mu\text{m} \times 13 \mu\text{m}$ size, is used as the detector. The CCD has a broadband coating optimized for the visible range and provides a quantum efficiency of more than 90 % at 500 nm and -60°C cooling temperature. The read-out time for the full frame amounts to 1 s at the maximum read-out frequency of 1 MHz.

3. Spectral and Radiometric Calibration

Spectral calibration is performed with the aid of a mercury lamp. The position of seven HgI lines, marked in Fig. 2a, is compared with theoretically calculated positions. The deviation between calculated and measured positions is minimized by a least-square fit procedure. The overall position precision lies within two spectral channels and shows almost no drift under controlled temperature conditions. An Ulbricht sphere is used to radiometrically calibrate the spectrometer system. Figure 3a shows a

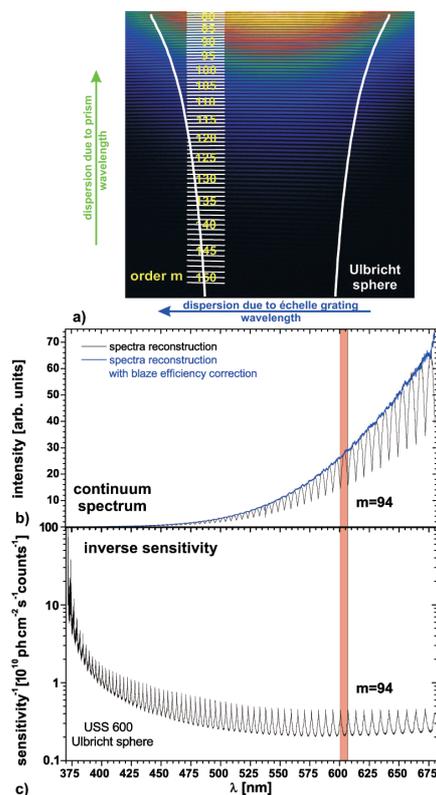


Fig. 3 Radiometric calibration of the cross-dispersion spectrometer. (a) 2D image of the system during exposure by a continuum light source. (b) Complete reconstructed spectrum of the continuum spectrum. Intensity drops caused by the blaze angle dependence of the grating are considered in the calibration by a correction function. (c) Spectral response of the system for the full wavelength span.

false-color 2D image captured from the continuum source; the resulting reconstructed spectrum is depicted in Fig. 3b. The spectrum is a convolution of the light source continuum and the sensitivity response of the detection system. Both image and spectrum show a non-uniformity of the measured radiation within each order. The reduction of the sensitivity of about 40 % between the center and the edges is caused by the blaze angle dependence of the grating. A correction function is introduced to compensate these strong sensitivity drops in the spectrum. The cross-talk between adjacent orders is measured to be below 10^{-3} , and any impact on the calibration can be neglected for the standard range.

The bare inverse sensitivity curve for the standard range is depicted in Fig. 3c. The spectrometer system, which is optimized for the visible emission range according to the choice of prism, grating, and CCD coating, shows an almost constant spectral response above 450 nm. However, the sensitivity drops significantly between 450 nm and 380 nm; this is largely caused by a reduction in the CCD quantum efficiency by about 50 %, and by a decrease in the glass transmission from 95 % to 55 % due to the prism's 25 mm absorption length.

4. Spectra Examples: Hydrocarbon and Deuterium Molecules

A series of experiments involving the injection of different hydrocarbon species (CH_4 , C_3H_4 , etc.) in similar plasmas has been started in TEXTOR. The aim of the experiments is (a) to check if the injected stable hydrocarbon leaves a “footprint,” e.g. with regard to its appearance, intensity ratio, or the ro-vibrational population of the break-up products C_2 , CH , CH^+ , etc., and (b) to determine the inverse photon efficiencies and branching ratios that relate the photon flux of the break-up products to the particle flux of injected species. An example of a “footprint” spectrum is depicted in Fig. 4a. The spectra of the band heads of the most important transitions, CH Gerö band and C_2 Swan band, are enlarged. A ro-vibrational analysis and comparison with the spectra of other injected species is outside the scope of this contribution, but can be found in detail in [3].

The deuterium spectrum of the Fulcher-band transition ($3p^3\Pi_u \rightarrow 2s^3\Sigma_g^+$) is depicted in Fig. 4b. The main diagonal vibrational transitions ($v = v'$) up to $v = 5$ are indicated. The first main diagonal transition with $v = v' = 0$ is enlarged and the strongest Q lines (Q1 - Q9) are marked. The rotational population of the excited state could be fitted according to a Boltzmann distribution with a rotational population temperature T_{rot} of about 1000 K, which is in line with previous observations [4]. A more detailed analysis of the Fulcher- α band according to the methods described in [4] is the topic of a forthcoming paper, which will deal with the interpretation of the deuterium recycling flux and the molecular break-up [5] at the target plates of the helical divertor (“DED”) in TEXTOR [6].

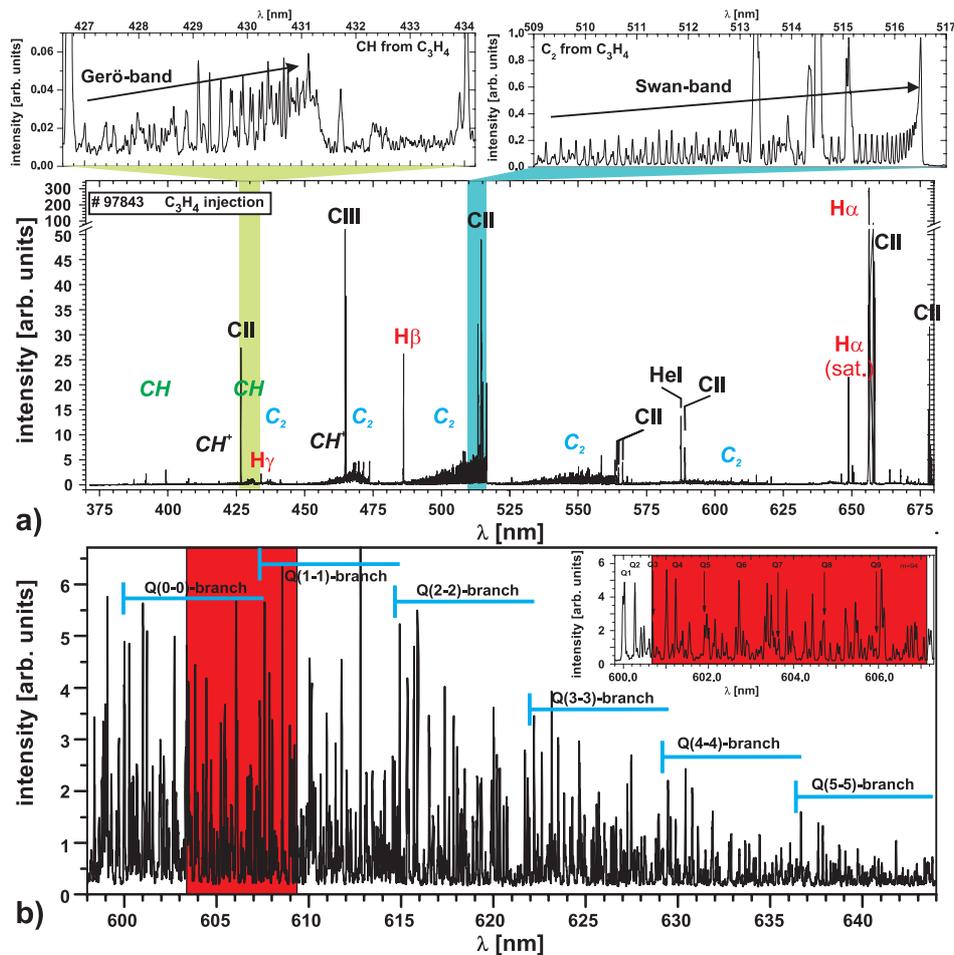


Fig. 4 (a) C_3H_4 injection into the TEXTOR edge plasma through a gas injection module. The emission spectrum in the range between 372 and 680 nm recorded gap-free using the cross-dispersion spectrometer during the break-up of the injected hydrocarbon. The most important observable optical transitions of atomic and molecular break-up products are indicated. The CH Gerö band and the C_2 Swan band are highlighted and enlarged in separate figures on top of the “footprint” spectrum to demonstrate the good spectral resolution of the molecular bands. The integration time of the system was set to 2 s to ensure complete coverage of the C_3H_4 injection pulse. (b) The complete D_2 Fulcher- α band and the Q-lines of the first main diagonal transition. The spectral range in red indicates the coverage of the observation in the 94th order, which is also highlighted in a separate box.

5. Conclusions

The cross-dispersion spectrometer presented here is a good compromise to conduct spectroscopic studies of the plasma boundary of fusion devices in the visible range, i.e., the fuel recycling and the impurity sources. The system covers at once the spectral emission range between 372 and 680 nm and an almost constant resolving power of $R = 20000$ over the full range. The 16-bit dynamic range ensures the possibility of simultaneous observation of atomic and molecular lines. The recommended integration time for the fiber-coupled system depends on the signal strength (extrinsic vs. intrinsic), but lies in the range of 1 s, to ensure an optimized usage of the dynamic range. Synergetic effects can be achieved when — like in TEXTOR — the system is embedded in a set of spectroscopic systems that complement one another [5]. The Mechelle provides high

spectral resolution, large wavelength coverage, and high dynamic range, whereas the other systems with interference filters such as photomultipliers or 2D CCD cameras provide the temporal and spatial resolution.

Experiments at TEXTOR provide “footprints” of the injected hydrocarbons C_3H_4 and information of D_2 molecules in the hot edge plasma. The appearance, destruction path, flux, ratio, and ro-vibrational population of the different species can now be studied in more detail within a single discharge.

Next-generation systems of cross-dispersion spectrometers in the prism/grating arrangement, equipped with prisms made of low absorption material with high dispersion, are currently developed to ensure a larger sensitivity in the spectral region below 450 nm. Such an optimized system will be used for the observation of the new first

wall and boundary layer at JET after installation of the new ITER-like wall with W and Be as plasma-facing materials. The installation of an Echelle cross-dispersion spectrometer system is also planned for observing the boundary layer in W7-X.

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