WDS'14 Proceedings of Contributed Papers — Physics, 215–220, 2014. ISBN 978-80-7378-276-4 © MATFYZPRESS

The Absolute Sensitivity Measurements of Spectra in Near IR Range at the COMPASS Tokamak

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Abstract. The new impurity survey spectrometer HR 2000+ is used for registration of the most intense spectral lines in the 654–1085 nm near IR range with spectral resolution 0.23 nm and temporal resolution from 4 ms to discharge duration at the COMPASS tokamak. The procedure of the absolute calibration of the spectrometer is described and technical issues and experimental limitations connected with its operation are discussed here. The measured spectra are interpreted and results are discussed.

Introduction

The COMPASS tokamak ($R = 0.56$ m, $a = 0.23$ m, currently with $Ip \leq 400$ kA, $B_T < 2.1$ T and pulse length up to 0.5 s), a divertor device with ITER-relevant plasma geometry, was re-installed at IPP Prague [*Pánek et al., 2006*]. Aim of spectroscopic measurements in COMPASS is studying the radiation of excited neutral atoms and ions from the plasma periphery like hydrogen or the most intensive impurity lines in as wide spectral range as it is possible. Information on neutral atoms density, impurity inflow [*Weinzettl et al.,* 2012], recycling processes [*Kamiya et al.,* 2004] and rough estimation of particle confinement can be derived from received data.

The spectroscopic diagnostic on the COMPASS tokamak had been composed of three minispectrometers of the HR2000+ type from Ocean Optics. The most of parameters of the devices are preset by producer,[1] but customer can choose some of them. The most important chosen parameters are spectral resolution and operational range. The resolution was chosen for the visible (460–663 nm), near UV (247–473 nm) and red (630–680 nm) spectral ranges, as 0.15 nm, 0.17 nm and 0.04 nm, respectively [*Naydenkova et al.,* 2012]. Temporal resolution of all used spectrometers depends on the aim of experiments and can be set from 4 ms to 65 s. The signal-to-noise ratio is 250:1. The f-number is f/4. The sensitivity is in the range of 41–75 photons/count depending on the wavelength. The spectrometers use the linear silicon CCD array Sony ILX511 as a detector. This set was recently spread by one more minispectrometer for measurements in the near IR range (659–1084 nm) with spectral resolution 0.23 nm. Given resolution does not allow studying spectral lines net areas in our plasma conditions. In result the set of our spectrometers covers region roughly from 250 nm (so called near UV) to 1085 nm (the limit of silicon detectors sensitivity approximately).

The absolute sensitivity calibration for all used spectrometers was performed to be able to derive plasma parameters mentioned above, which are directly connected to absolute values of irradiance measured by the spectroscopic systems. The calibration lamps of known emission[2] are used for the absolute calibration in the spectral range of 330–1084 nm at the COMPASS tokamak [*Naydenkova et al.,* 2013].

Experimental setup

The spectroscopic system for plasma radiation measurements on COMPASS tokamak consists of thick quartz vacuum window, which represents an interface between the vacuum and spectroscopic systems. Depending on the aim of experiment there can be used either the plano-convex spherical lens, which is located inside the diagnostic port just behind the window and collects plasma radiation from infinity to the lens focus, where entrance to optical fibre is located, or fibre alone. 20 m long

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[1] http://oceanoptics.com/product/hr2000-custom/

[2] http://www.newport.com/Calibrated-Sources-and-Services/378236/1033/info.aspx

optical fibre (fused silica core of diameter of 200 μm, cladding with thickness ≈ 20 μm and numerical aperture NA = 0.22) transfers the signal to the diagnostic room in order to protect the detection part of the system from X-rays and neutron radiation of the tokamak.

During the first tests of the new near IR spectrometer the typical system configuration for other spectrometers including use of UV/VIS high OH[3] optical fibre was used. New VIS/NIR low OH optical fibre, with better transmittance in the range of interests, will be used in our further measurements with the near IR spectrometer.

The collecting volume observed by the spectroscopic diagnostics in the case of circular and D-shaped plasma configurations for measurements using collection lens and without it is shown in Figure 1.

Absolute sensitivity calibration is supposed to be done for completion of the spectroscopic system.

The absolute calibration arrangement, shown in Figure 2, was done by means of the ORIEL calibrated source, which consists of the 200 W calibrated lamp of known spectral radiance[4] as provided by NIST calibration standard, and of the radiometric power supply. The procedure was described in details by *Naydenkova et al.* [2013].

Spectral irradiance by plasma P_{res} in $W/(m^2 \cdot nm)$ is calculated as:

$$P_{res} = \xi(\lambda) * P_{tok}$$

where $\xi(\lambda)$ is the calibration constant in $(W \cdot s)/(m^2 \cdot nm \cdot count)$ and P_{tok} is the numbers of count per second detected by the HR2000+ spectrometer during a plasma discharge. The calibration constant is the ratio of tabulated spectral radiance of the calibrated source P_{tab} in $W/(m^2 \cdot nm)$ and the measured values of calibrated source radiation in counts at the same conditions for the calibration and the measurement:

$$\xi(\lambda) = \frac{P_{tab}}{P_{lab}}$$

The calibration constant for given spectrometer has meaning of reciprocal value of spectral transmittance combined with photosensitivity of the spectroscopic system.

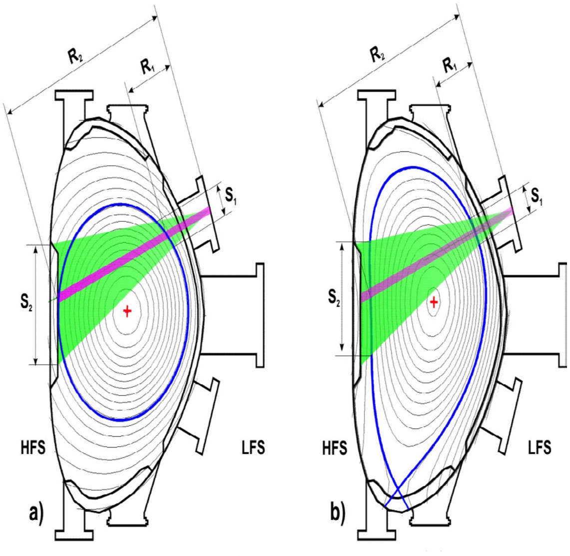

Figure 1. Poloidal cross-section of the COMPASS tokamak at the typical magnetic configurations. (a) circular plasma cross section, (b) divertor configuration. The observation volume of the optical diagnostics equipped with the collecting lens is shown by pink colour (cylindrical), the one without lens is shown by green colour (conical).

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[3] http://oceanoptics.com/product-category/fiber-attenuation/

[4] http://www.newport.com/Calibrated-Sources-and-Services/378236/1033/info.aspx

The calibration results

Precision of the calibration procedure has several constraints, which should be considered to achieve precise results. The alignment, signal to noise ratio and calibration source spectral emission was discussed in [*Naydenkova et al.,* 2013]. One more constraint can be given by improper fibre type choice. fibres produced from different materials have spectral properties suitable for specified usage conditions, so the fibre marking is very important during producing procedure. Widely accepted way to do it is marking by decay of optical transmittance of fibre in a narrow wavelength range [*Saleh and Teich.,* 2007]. Using the fibre in a spectral range of the high attenuation leads to higher detection threshold of spectral lines appearing in the ranges.

The results of absolute sensitivity calibration of this system for the cases of using both UV/VIS high OH and VIS/NIR low OH are shown in Figure 3.

It is possible to see a strong drop of transmittance connected with UV/VIS high OH fibre marking in the 920–970 nm wavelength range. The strong decay of sensitivity above 970 nm is connected with both the optical fibre transmittance decay and with the silicon detector sensitivity decay. Such behavior makes this configuration not suitable for measurements in wavelength range above 920 nm.

Comparison of calibration curves for UV/VIS high OH and VIS/NIR low OH optical fibres shows that sensitivity of two systems is similar for the wavelength range below 920 nm. On the other hand, sensitivity of VIS/NIR low OH fibre is significantly higher above 920 nm. It means the VIS/NIR low OH fibre is more suitable for our case and will be used in our further measurements.

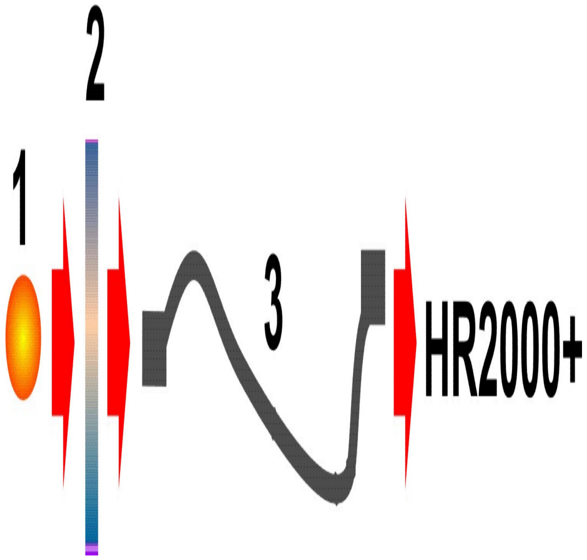

Figure 2. Scheme of absolute calibration. 1. Calibration source, 2. Vacuum window, 3. Optical fibre.

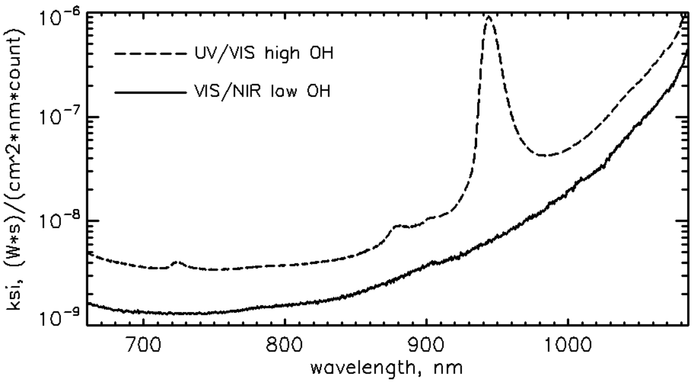

Figure 3. Absolute sensitivity calibration constant for spectroscopic system using near IR minispectrometer with UV/VIS high OH or VIS/NIR low OH optical fibres.

Plasma radiation measurements in near IR range

The first measurements using the spectroscopic system based on the near IR minispectrometer, including UV/VIS high OH optical fibre, were performed recently. The typical D-shaped discharge #6181 is considered as an example and shown below. The integration time for near IR spectrometer was set to 130 ms, because this time will allow us to separate our standard discharge to ramp up, flat-top and ramp down phase. So long integration time will allow us to measure the brightest impurities spectral lines, which will allow making conclusion about plasma composition in different phases of the discharge, but at the same time information about temporal evolution of each spectral line will be lost. The spectrometer is triggered at t = 950 ms.

The temporal evolution of the main plasma parameters of the D-shaped discharge with roughly constant line average plasma density in the flat-top phase is shown in Figure 4. Figure 4a shows the temporal evolution of the integral visible plasma radiation. Plasma current is shown in Figure 4b. The plasma is kept at the predefined equilibrium and position during the discharge (Figure 4c). The temporal evolution of line averaged electron density measured vertically is shown in Figure 4d. Line averaged electron density was corrected to actual plasma geometry and plasma position using EFIT reconstruction [*Havlicek et al.,* 2007]. Puffing of working gas (deuterium) demonstrated in Figure 4e.

The discharge is divided into four phases. The first phase is the plasma current ramp up. The plasma column formation and shaping of originally circular plasma to D-shaped take place during this phase. A strong plasma wall interaction, which is a usual case there, leads to strong impurities influx and, as a result, intensive radiation of low ionized impurities is observed.

The flat-top phase is defined by constant plasma current. The constant plasma position is also achieved during this phase. Electron density is feedbacked and kept almost constant. The wall desorption can also be expected by the fact that the density is kept constant with decreasing gas puff. A low plasma wall interaction has an effect on plasma radiation, which leads to constant minimal value. High plasma temperature spectral lines of different high-ionized impurities are observed in this phase.

The ramp down phase is characterized by ramp down of plasma current. D-shaped plasma returns to circular one. Plasma position changes and often becomes unstable due to strong coherent motes appearing there, especially at the end of discharge. It leads to a strong plasma wall interaction and a recordable impurity influx from the walls. Therefore, high intensity of lines of low ionized impurities is measured in this phase.

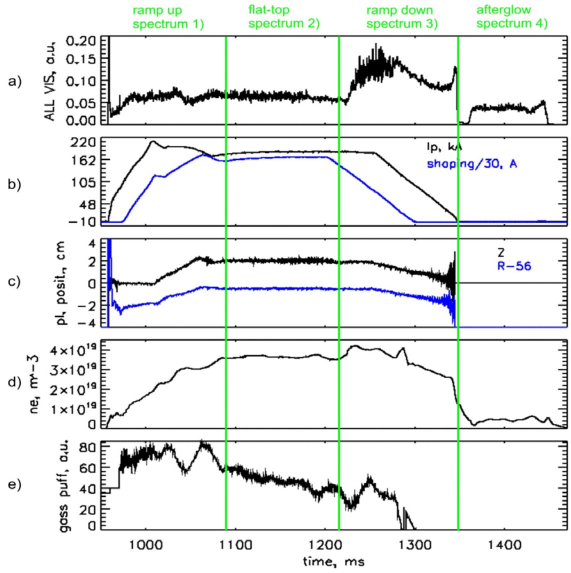

Figure 4. Temporal evolution of (a) integral visible plasma radiation, (b) plasma current, (c) vertical and horizontal plasma position, (d) line averaged electron density, and (e) gas puffing during the discharge #6181 with D-shape plasma. Ramp up, flat-top, ramp down and afterglow parts of the discharge are divided in figure by green lines.

The afterglow phase occurs often after the end of the regular discharge, when the reversing of the loop voltage direction (due to ramping down the primary winding of the transformer) in partly ionized gas can lead to creation of negative plasma current. Usually, the plasma current is just a few of kAmps at this phase. The plasma density is much lower than during the main discharge, and a level of radiation of working gas itself is lower than in regular discharge.

The spectra collected during each phase of the discharge are shown in Figure 5. The measured spectra are interpreted by using NIST Atomic Spectra Database [*Kelleher*, 1999] for the most intensive spectral lines.

The spectrum during the ramp up phase contains all spectral lines of impurities with low ionization energy, as it was expected. Among them are as excited atoms and higher ionized ions, for example carbon ion CIV (772.63 nm) etc.

It is expected that plasma wall interaction reaches minimal value during flat-top phase. It should be reflected in decreasing of spectral lines intensity of low ionized impurities at this phase. It is possible to see this effect on example of BIII spectral lines. The spectrum recorded during the flat-top phase contains the CIV and CIII lines as well, but its intensity is comparable with that during the ramp up phase. It can be explained by so-called "carbon burning," when carbon influxed from the walls goes to fully ionized stage. At the same moment it is possible to see unexpected increase of the most low ionized or excited atoms spectral lines, for example HeI. It can be explained by increase of recycling processes during this phase.

Expected increase of low ionized impurities spectral lines intensity happens during ramp down phase. Lines of He I continue to increase.

All discussed points allow supposing that recycling is dominant process in our scrape of layer and boundary plasma.

During the afterglow phase, the He I lines grow to maximum. Low intensity signal of the B II lines is observed as well. The spectrum allows saying that afterglow phase is the low current, low-density glow mainly in neutral helium.

The glow discharge in helium, which is a part of the cleaning procedure of the vacuum chamber in our tokamak can cause absorption of helium in wall materials. The global behaviour of He lines can be explained by continuous helium gas influx due to its desorption from the first wall during the discharge.

It is also seen that the spectral line of the hydrogen H I (866.502 nm) as well as the most intensive lines of OI appear during the discharge. It might be that a flux of water vapour gets to plasma during discharge, but to make any exact conclusion the additional studying with better temporal resolution is required.

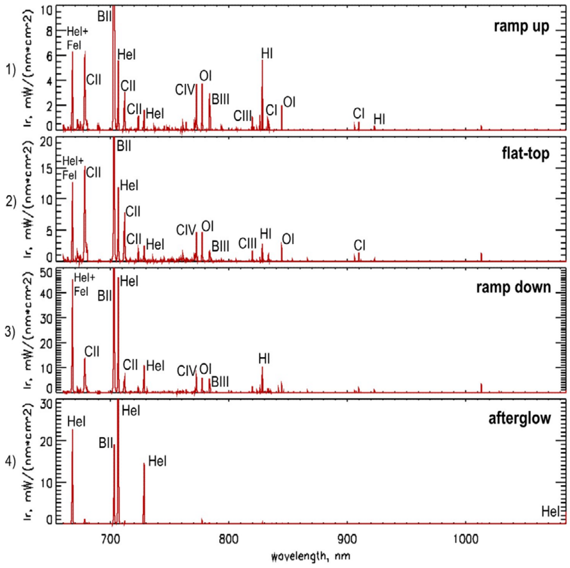

Figure 5. Spectra collected by integration during different phases of discharge #6181 (1) ramp up, (2) flat-top, (3) ramp down, and (4) afterglow.

Conclusion

The new impurity survey spectrometer HR 2000+ was installed to the COMPASS tokamak and routinely used for registration of the most intense spectral lines in the range of wavelengths 654–1085 nm. Measurements are limited by the spectral resolution of the spectrometer, which does not allow distinguishing and studying of many spectral lines in detail.

The spectrometer was absolutely calibrated. The calibration constant for given spectrometer has meaning of reciprocal value of spectral transmittance combined with photosensitivity of the spectroscopic system. The knowledge of system transmittance and sensitivity is principal for correct data interpretation.

The example of plasma spectrum shows almost no spectral lines for wavelengths longer than 930 nm. It is result of low transmittance of the UV/VIS optical fibre in this range. Use of more suitable VIS/NIR fibres will allow getting reasonable spectra also in this region.

Higher sensitivity in comparison with other spectrometers available on COMPASS, allows studying of quite large amount of spectral lines below 930 nm. The brightest ones of them correspond to electron deexcitation processes in atoms and ions.

Acknowledgments. The present work was supported by GACR grant P205/11/2341 and MSMT Project # LM2011021.

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