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Absolute Sensitivity Calibration of Visible Spectroscopic Diagnostic and Temporal Evolution of First Window Transmittance at the COMPASS Tokamak

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Abstract. An absolute calibration of spectroscopic systems is required to measure many important plasma parameters in tokamak discharges like impurity inflow, recycling and the effective ion charge. The procedure of the absolute calibration is described and technical issues and experimental limitations connected with the tokamak operation are discussed here. Namely, an influence of the first window transmittance and its evolution over experimental campaigns on the validity of the absolute calibration is investigated.

Introduction

The COMPASS tokamak (R = 0.56 m, a = 0.23 × 0.38 m, currently with $I_p \leq 220$ kA, $B_T < 1.2$ T and pulse length up to 0.35 s), a divertor device with an ITER-relevant plasma geometry, was re-installed at IPP Prague [*Pánek et al.,* 2006]. Aim of spectroscopic measurements in COMPASS is studying the visible radiation of excited neutral atoms and ions from the plasma periphery — like hydrogen or the most intensive impurity lines. Also, an MHD activity can be studied using such observations. Finally, 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. The effective ionic charge Z_{eff} will be evaluated from the line free region slightly above 520 nm comparing to pure hydrogen plasma Bremsstrahlung using known plasma density and temperature profiles [*Meister et al.,* 2004].

The visible light diagnostic on the COMPASS tokamak currently consists of 2 minispectrometers [*Naydenkova et al.,* 2012] for visible and near UV ranges, which allow to study spectrally resolved data with spectral resolution of about 0.15 nm and temporal resolution of about 10ms, and several photomultiplier (PMT) based systems for studying of fast plasma events in microsecond range with poor spectral resolution limited by interference filter transmittance with typical FWHM of order of 10 nm [*Naydenkova et al.,* 2009]. The absolute sensitivity calibration for visible spectroscopy was performed first time in history of COMPASS tokamak operation. As a result we are able to derive plasma parameters mentioned above, which depend on absolute values of irradiance measured by the spectroscopic systems.

The most typical method of absolute sensitivity spectroscopic calibration at tokamaks is branching ratio method [*Lawson et al.*, 2009]. Using of calibration lamps for absolute sensitivity calibration of spectroscopic systems at tokamaks is not typical but quite attractive alternative. By means of this method it is possible to get the values of calibration constants for the whole range of interest with good precision. The results of calibration do not depend on radiation and composition of plasma. In situ calibration is not necessary in this case. The aim of this article is to streamline the method.

Experimental setup

Absolute calibration was done by means of the ORIEL calibrated source, which consists of the 45 W calibrated lamp of known spectral irradiance (http://www.newport.com/Calibrated-Sources-and-Services/378236/1033/info.aspx) as provided by NIST calibration standard and a radiometric power supply. This standard does not require any auxiliary optics to be used. Under normal use, the lamp is simply placed at a 50 cm distance from the input aperture of our optical system, on which the calibrated irradiance is projected. If a different distance was selected (to adjust signal levels or because of physical constrains of the set up), an inverse-square law was used to approximately calculate the spectral irradiance, using a 50 cm calibration data provided with a lamp. To improve the accuracy of the calculation the distance from the filament was carefully determined. Accurate placement is important; since a 2.5 mm position error results in a 1 % error in calibration. The calibration data are valid for surface 1 cm^2, which means that for optical system with aperture larger than 1 cm^2, a correction needs to be made for the area difference between a plane and a spherical surface. Producer guarantees that inaccuracy of the data caused by the lamp stabilization is maximum 2 %. Output of this lamp can also be slightly (up to 5 %) polarized. Our calibrated 45 W lamp is supposed to be used in the range 250–2400 nm. So as we use the 45 W QTH (quartz tungsten halogen) lamp, our measurements have low precision in the range less than ≈ 330 nm. Using a lamp that produces too high or too low radiation puts higher demands on the linearity of our detection system. So as a calibrated lamp has only 50 hours guaranteed lifetime and calibration dramatically varies with a lamp usage, we use one more originally non-calibrated lamp for recalibration on the base of calibrated lamp, and this recalibrated lamp we use for our calibration procedures. We check periodically a validity of our recalibration because of evolution of lamp emission during its lifetime.

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

$$P_{res} = \text{const} \cdot P_{tok} ,$$

where const is calibration constant in W/(m^2nm·lvl) or W/(m^2nm·V) and P_{tok} is measured value of plasma radiation of tokamak in levels , or Volts respectively. Calibration constant is the ratio of tabulated spectral irradiance of calibrated source P_{tab} in W/(m^2nm) and measured values of calibrated source radiation in levels, or volts respectively:

$$\text{const} = P_{tab} / P_{lab} .$$

The whole system consists of vacuum window, which represents an interface between vacuum and spectroscopic system, the lens, which is located inside the diagnostic port just behind the window and collects plasma radiation to optical fibre. Then, this 20 m long optical fibre transfers signal to the diagnostic room in order to protect the detection part of the system from X-rays radiation of the tokamak (see Figure 1).

In the case of PMT based system there is additional lens, which spreads the light to the wide photosensitive surface of PMT detector. Depending on the aim of experiment there can be used an interference filter. The transmittance and sensitivity of the system is limited mainly by filter transmittance and PMT photosensitivity.

The two portable spectrometers HR 2000+ manufactured by Ocean Optics are used for spectral measurements in our experiments in the detection ranges of 247–473 nm and 460–663 nm. Their principal parameters are: spectral resolution 0.17 and 0.15 nm, signal-to-noise ratio 250:1, integration time 1 ms to 65 s, and sensitivity 41 and 75 photons/count.

The calibration source described above was set to the entrance of the described system at the conditions for a calibration recommended by producer. Instead of the 1 cm^2 hole, the entrance of the well-defined area was used for the calibration. In the case of PMT measurements, distance between source and entrance to the system was increased from 50 cm to 6.7 m because of high sensitivity of PMT for high voltages.

Results

Calibration constant for spectrometer has meaning of spectral transmittance and photosensitivity of the spectroscopic system and it depends on wavelength. It is possible to see in Figure 2 that the calibration constant strongly increases at the edges of operational range, because of reduced sensitivity of the spectrometer there.

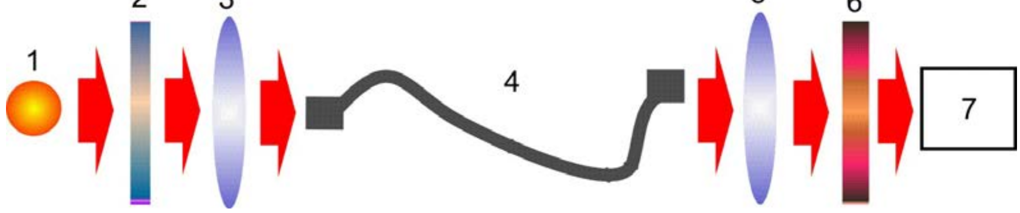

Figure 1. Scheme of absolute calibration. 1. calibration source, 2 vacuum window, 3 and 5 lenses, 4 optical fibre, 6 interference filter, 7 photomultiplier tube or minispectrometer.

Also, signal to noise ratio (SNR) is the most important at the edge, where it strongly decreases. Therefore, low intensity spectral lines can be missed here because of a low SNR. This fact should be taken into account during data interpretation and correct and accurate noise filters must be used not to lose any spectral lines. Moreover, a longer temporal integration should be used to measure reasonably high values of signal, which are not hidden in the noise.

The calibration constant of PMT based system also includes an amplification of photomultiplier. The dependence of the calibration constant on the voltage applied to the photomultiplier is shown in Figure 3.

The whole voltage range recommended by producer for operational regime of PMT was tested during the calibration. This procedure was done to be able to change freely input voltage of the system during tokamak operation, if decreasing or increasing of system amplification is required.

On the base of measured system transmittance — limited mainly by interference filter transmittance — it was performed a spectral integration of calibration constant to exclude dependence on wavelength, which is not interesting in this case. The filters should be selected carefully because they can be transparent for several different spectral lines belonging to different plasma components.

To convert measured spectral irradiance (minispectrometers) and irradiance (PMT based systems) into values of power, surface of radiation shell of each element (given by radiation shell position) must be known.

The glow discharge cleaning [*Zhi-wen et al.*, 2002] and boronization [*Tabarés et al.*, 1995] techniques are commonly exploited in tokamaks in order to get suitable vacuum conditions for operational discharges. Glow discharges are used for adhesion of atmospheric gases absorbed on the

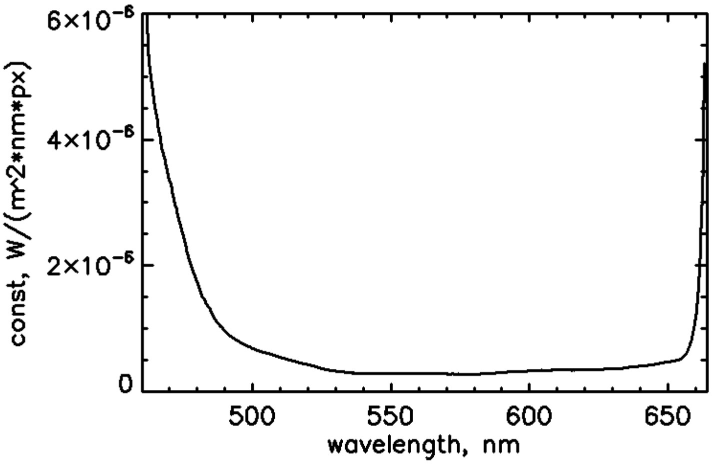

Figure 2. Spectral dependence of calibration constant of minispectrometer HR2000+ with operational range 460–663 nm.

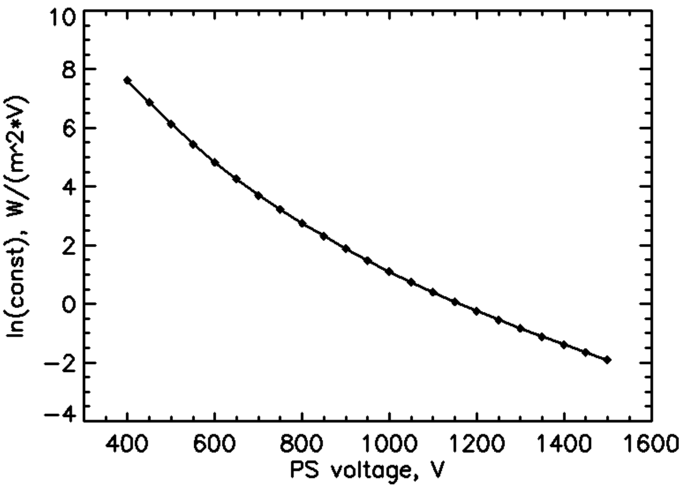

Figure 3. Voltage dependence of calibration constant for PMT based system.

surface of vacuum chamber. The boronization is applied to decrease influx of high Z wall material and carbon sublimated from vacuum walls during operational discharge. It is reached by covering of vacuum surfaces by layer of low Z boron.

If the spectroscopic system uses fibre optics, it is very essential to place the optical fibre properly with respect to the first collecting lens. Laboratory tests show that an exact positioning of the fibre usually increases light collection several times.

We also found that due to small fibre dimensions it is necessary to use equipment allowing fine spatial setting of port plug and calibration lamp for repeatable alignment. Low precision alignment can give a significant error of results of calibration and it is crucial for such measurements.

We also concluded that the 200 W lamp should be used for calibration of the systems which is supposed to operate down to 330 nm, for example for the calibration of spectrometer operating in UV range (up to 247 nm) to increase precision of this calibration by increasing signal to noise ratio.

We studied the evolution of system transmittance during the experimental campaign on the COMPASS tokamak. We observed that spectral lines in range up to 460 nm disappear after several discharges, i. e., transmittance of the window was strongly reduced, as it is demonstrated in Figure 4.

Decrease of the transmittance is caused by re-deposition of first wall materials, sputtering of carbon plates and boronization on the inner surface of the window.

In addition, the evolution of transmittance of the PMT-based system was studied in a narrow spectral region around 520 nm. This spectral range is used for determination of the effective ion charge, Z_{eff} from measurement of absolute intensity of bremsstrahlung radiation. Comparison of signals during flat-top part of discharges with comparable parameters is shown in Figure 5.

A significant drop of signal after boronization is observed. It is difficult to conclude from existing measurements, if additional re-deposition of carbon and wall material has any influence to next decreasing of signal.

At the end of experimental campaign the system was dismantled out from the tokamak. The window is made of fused silica. The window was properly cleaned by alcohol and HCl. Afterwards, its transmittance reached tabulated values for fused silica.

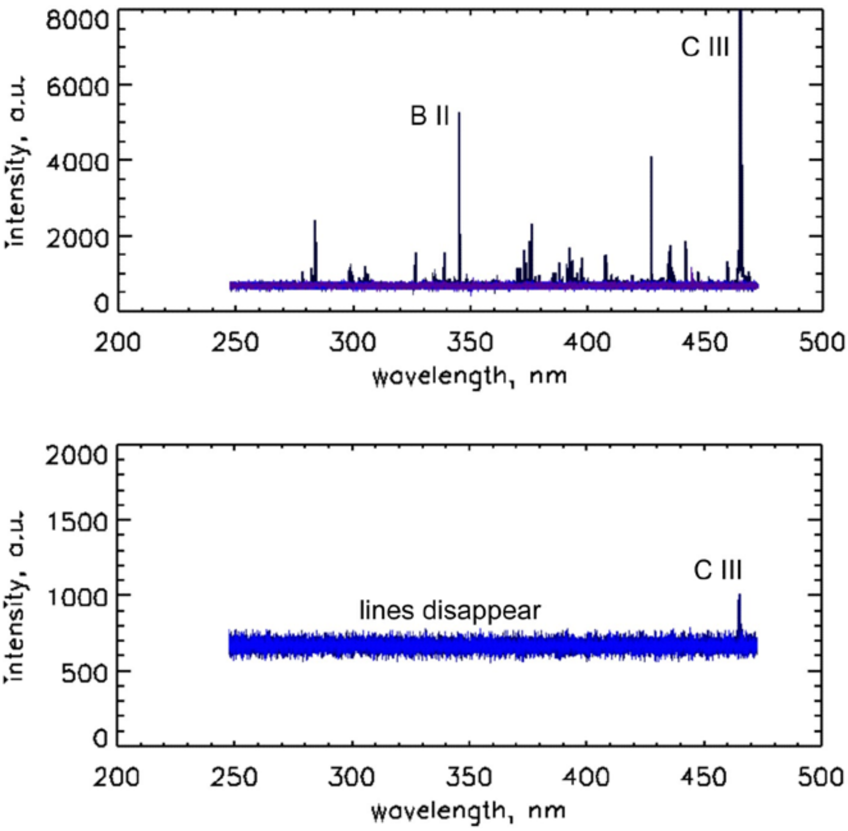

Figure 4. Spectra measured by the minispectrometer in UV range at the beginning (top) and at the end (bottom) of the experimental campaign.

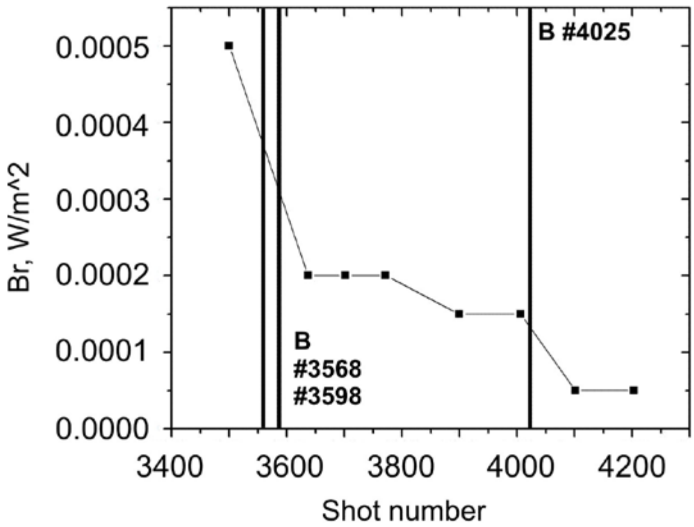

Figure 5. Irradiance of Bremsstrahlung radiation over the experimental campaign plotted for shots with comparable parameters.

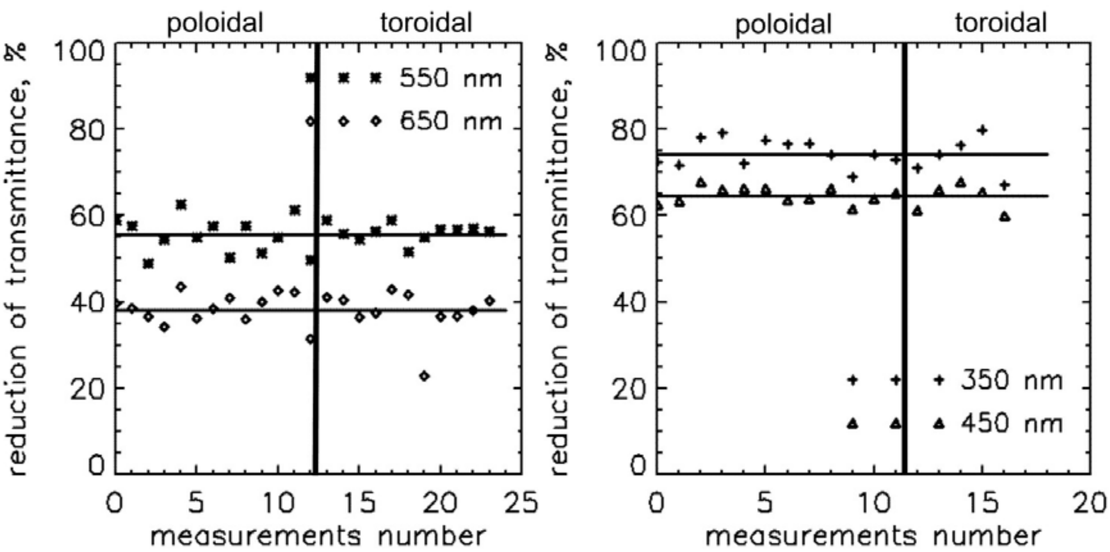

Figure 6. Spatial evolution of the transmittance reduction of first window measured along toroidal and poloidal directions of positioning of the window in accordance with tokamak chamber. Measurement number corresponds to number of step done during movement along the window. Distance between steps is approximately 5 mm.

The transmittance of the deposited layer, its transparent homogeneity and wavelength dependence of transmittance at the range of interest was studied in lab for dirty window before its cleaning. Decrease of transmittance is caused by gradual layering of sputtered first wall material and boronization of tokamak chamber. Composition studies performed in the department of material engineering of IPP; have shown that the film consists mainly from boron and carbon.

The dependence of film transmittance was measured along two axes of tokamak geometry, toroidal and poloidal. Result is shown in Figure 6. Transmittance reduction is

$$R = (T_{clean} - T_{dirty}) / T_{clean},$$

where T_{clean} is transmittance of clean window and T_{dirty} is transmittance of window with deposited layer.

Dependence of film transmittance reduction on the wavelength was plotted in Figure 7.

No dependence of film transmittance on position on window was found. In this case reduction of transmittance is defined as a ratio of clean and dirty window transmittances. Points at approximately 350 nm are more scattered because of low signal to noise ratio at this wavelengths. The transmittance

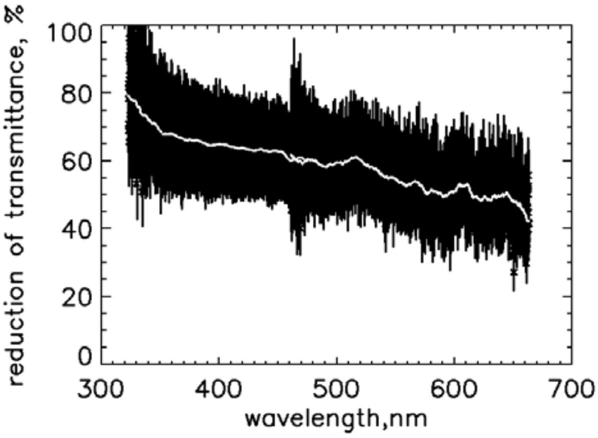

Figure 7. Reduction of vacuum window transmittance in connection with the deposition of wall material and Boron on it during a tokamak operation and boronization procedure measured by two minispectrometers in UV and visible operational range. Inaccuracy of measurements is shown by black curve.

decreases namely at shorter wavelengths. Inaccuracy of the calibration given by non-ideal repeatability of alignment during calibration is approximately 20 %. In the range, where signal to noise ratio is less than 2, it is dramatically increased. Fully non-transparent layer was found in the range bellow 330 nm.

The discrepancy between decrease of bremsstrahlung irradiance measured during experimental campaign (see Figure 5) and decrease of vacuum window transmittance measured after campaign (see Figure 7) at wavelength ≈ 523 nm can be explained by boronization effect, which decrease concentration of impurities in plasma and bremsstrahlung irradiance by itself, correspondingly. The discrepancy between decrease of impurities radiation in the beginning and at the end of experimental campaign (see Figure 4) and decrease of vacuum window transmittance measured after campaign (see Figure 7) can be explained by boronization effect and by probable absorption of light radiated by excited or ionized boron and carbon in deposited layer. Further studying is required to clarify this process.

Because of decreasing window transmittance during the experimental campaign, the correction factors must be taken into account, when calculating plasma parameters derived from absolute spectroscopic measurements. Further studying is required to make some reasonable approximation allowing taking into account these effects. The value of all spectroscopic signals depends on plasma stability, plasma surface interaction, vacuum conditions, plasma position and so on. Any spectroscopic measurements cannot be used as estimation parameter of window transmittance decreasing directly. Discharges with similar plasma parameters will be done before and after each boronization. Comparison of spectroscopic signals from these discharges will allow estimating decrease of vacuum window transmittance. In any case studying of window transmittance in laboratory after the end of campaign is not possible to escape.

Conclusion

Measurements of plasma radiation in UV and visible spectral ranges and fast measurements of selected spectral lines in units of power are routinely used on the COMPASS tokamak. These measurements allow to determine important physical quantities, for example the effective ion charge Z_{eff} and concentration of impurities, if the optical system is absolutely calibrated. Therefore, the off-situ calibration of the spectroscopic system was performed and described here in sufficient details.

It is also demonstrated in this contribution that the absolute calibration is not enough to interpret experimental data correctly, because of several effects connected with tokamak operation. In particular, the transmittance of optical windows significantly decreases, since they are gradually covered by thin layers of material formed during procedure to clean or modify the first wall of the vacuum vessel prior to tokamak discharges. To avoid this problem, shutters will be designed and installed during next opening of the tokamak vessel to protect spectroscopic windows from sputtered material during glow discharges cleaning and boronization.

It is clear, however, that a material re-deposition on the spectroscopic window during tokamak discharges cannot be prevented and has to be taken into account in processing of experimental data. It is also clear that all spectroscopic windows have to be cleaned at any opening of the tokamak vessel to atmospheric pressure.

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