

# High-resolution spectroscopy diagnostics for measuring impurity ion temperature and velocity on the COMPASS tokamak

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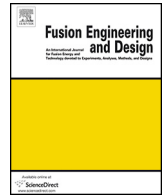
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## High-resolution spectroscopy diagnostics for measuring impurity ion temperature and velocity on the COMPASS tokamak



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### HIGHLIGHTS

- We built a new diagnostic of poloidal plasma rotation on the COMPASS tokamak.
- Improvements in throughput via toroidal integration and fiber optimizations shown.
- Poloidal rotation and ion temperature measured in L- and H-mode and during RMP.
- Design and parameters of a new CXRS diagnostic for COMPASS are introduced.

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### ABSTRACT

High-resolution spectroscopy is a powerful tool for the measurement of plasma rotation as well as ion temperature using the Doppler shift of the emitted spectral lines and their Doppler broadening, respectively. Both passive and active diagnostic variants for the COMPASS tokamak are introduced. The passive diagnostic focused on the C III lines at about 465 nm is utilized for the observation of the poloidal plasma rotation. The current set-up of the measuring system is described, including the intended high-throughput optics upgrade. Different options to increase the fiber collection area are mentioned, including a flower-like fiber bundle, and the use of micro-lenses or tapered fibers. Recent measurements of poloidal plasma rotation of the order of 0–6 km/s are shown. The design of the new active diagnostic using a deuterium heating beam and based on charge exchange recombination spectroscopy (C VI line at 529 nm) is introduced. The tool will provide both space (0.5–5 cm) and time (10 ms) resolved toroidal plasma rotation and ion temperature profiles. The results of the Simulation of Spectra code used to examine the feasibility of charge exchange measurements on COMPASS are shown and connected with a selection of the spectrometer coupled with the CCD camera.

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### 1. Introduction

High-resolution spectroscopy is a powerful tool for the measurement of plasma rotation as well as ion temperature using the Doppler shift of the emitted spectral lines and their Doppler broadening, respectively [1]. Eq. (1), using SI units, describes a shift of the

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rest wavelength of the emission line  $\lambda_0$  with respect to the observed wavelength  $\lambda_D$ , which is caused by motion of the ion with velocity  $v$  at angle  $\alpha$  between the observer and ion motion:

$$v = \frac{c}{\cos(\alpha)} \frac{\lambda_D - \lambda_0}{\lambda_0} \quad (1)$$

where  $c$  is the speed of light. Assuming Gaussian line profiles, ion temperature  $T_i$  can be derived from the observed line's full-width at half of maximum  $\Delta\lambda_{FWHM}$  using Eq. (2) with quantities given in SI units:

$$T_i = \frac{m_i c^2}{8 \ln 2 \cdot k_B} \frac{(\Delta\lambda_{FWHM})^2 - (\Delta\lambda_{FWHM, instr})^2}{\lambda_0^2} \quad (2)$$

where  $m_i$  is the ion mass, and  $\Delta\lambda_{FWHM, instr}$  is the instrumental broadening at the measured wavelength,  $k_B$  is Boltzmann constant.

Passive diagnostics monitor spectral lines emitted as a result of spontaneous decay of excited atoms or ions in the plasma. Active diagnostics use the neutral beam to induce processes of charge exchange, and therefore, observations are well localized but limited by the attenuation of the beam. Both passive and active variants of this diagnostic for the COMPASS tokamak [2], a device of the ITER-like divertor plasma geometry (major radius 0.56 m, minor radius 0.23 m, toroidal magnetic field 1.15 T, plasma current up to 330 kA, electron temperature about 1 keV, discharge duration about 300 ms, auxiliary heating 2 × NBI 300 kW, linear size ratio to ITER plasma 1:10), are introduced in the next sections.

## 2. Plasma rotation measurements on COMPASS

### 2.1. Poloidal rotation diagnostic

The passive diagnostic focused on the carbon triplet, i.e. C III lines at 464.742 nm, 465.025 nm and 465.147 nm [3], is used to measure the poloidal rotation of the edge plasma on COMPASS. The setup consists of: (1) an objective, (2) a fiber bundle, (3) focusing optics for coupling the fiber to the spectrometer, (4) a high-dispersion two-grating spectrometer [4] (2700 grooves per mm,  $f = 0.5$  m,  $f/\# \sim 10$ ) and (5) a scientific CCD camera, see Fig. 1.

The objective, mounted on a vertical tokamak port, is composed of two spherical lenses and focuses plasma radiation onto the optical fiber bundle, with a demagnification of 4, which corresponds to a coverage of up to 50 mm on the plasma (typically from 10 mm outside up to 40 mm inside the separatrix).

The fiber bundle (see Fig. 2) consists, on the tokamak side, of 7 flower-like arrangements of 7 optical fibers each, with a total of 49 fibers. On the spectrometer side, the 49 fibers are arranged as a one-dimensional array, with a size of  $3080 \mu\text{m} \times 50 \mu\text{m}$ . The specifications of each fiber are: fused silica, core diameter of  $50 \mu\text{m}$ , cladding diameter of  $62.5 \mu\text{m}$  and numerical aperture of 0.22. The purpose of such an arrangement of fibers is to increase the amount of collected light, by reshaping hexagonal groups of 7 fibers into a linear array, which has a shape of the entrance slit of the spectrometer.

The light from the fiber is coupled into the spectrometer by an optical setup, consisting of 2 spherical lenses, with a total magnification of 5. This setup is necessary because the fiber and spectrometer numerical apertures are quite different (0.22 and 0.06, respectively). With this setup, the image of the end face of the fiber bundle appears magnified by a factor of 5 ( $15 \text{ mm} \times 250 \mu\text{m}$ ) at the entrance slit of the spectrometer, but with a numerical aperture of 0.07 (measured), which is appropriate for coupling into the spectrometer. If necessary, the amount of gathered light can be increased, by way of increasing the width of the slit up to  $250 \mu\text{m}$  (the height of the slit is 20 mm and the width is variable from 0 to  $400 \mu\text{m}$ ) at the expense of wavelength resolution. This was not the case though, as a slit width of  $100 \mu\text{m}$  (which was the width used

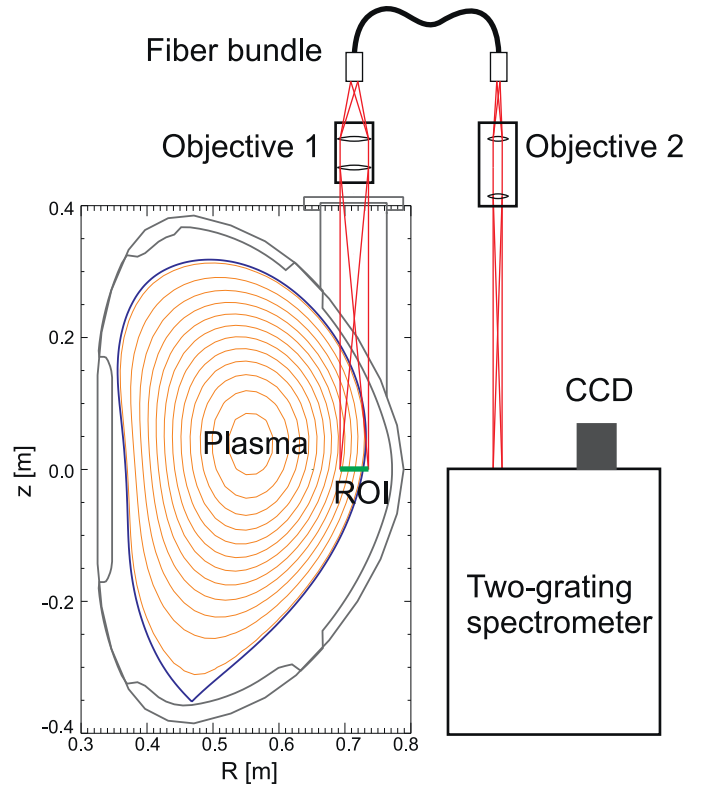


Fig. 1. Scheme of the experimental set-up of poloidal rotation measurements on COMPASS. Region of interest (ROI) is indicated in the poloidal cut of the vessel with the plasma. Objective 1 focuses plasma radiation onto the fiber bundle, from which it is projected by Objective 2 onto the entrance slit of the two-grating spectrometer equipped with a camera.

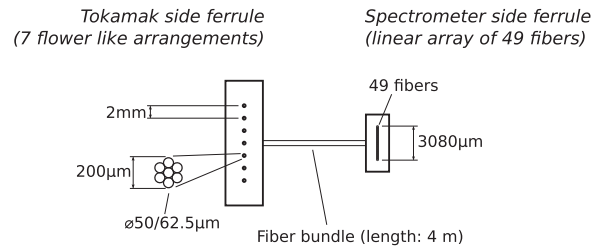


Fig. 2. Depiction of the arrangement of fibers in the fiber bundle.

for most acquisitions) was enough to obtain acceptable signal to noise ratio, and a further degradation of the wavelength resolution was not necessary.

The scientific CCD camera (model ANDOR iXon DU-897) is attached at the output of the spectrometer. Its main characteristics are: thermoelectrically cooled to  $-50^\circ\text{C}$ , back illuminated EMCCD,  $512 \times 512$  pixels, pixel size of  $16 \mu\text{m} \times 16 \mu\text{m}$ , frame transfer and quantum efficiency of 80% in the region of interest.

Typically, shots are acquired using an exposure time of 20 ms at a rate of 40 frames per second, with a vertical binning of 32 pixels and using the frame transfer capability of the camera. This last feature enables the readout of the frame without any smearing. The main constraint limiting the acquisition frame rate is low light intensity.

Usually, the throughput of the system is limited by non-optimized fiber coupling on the tokamak side caused by the use of sets of circular lenses only. Consequently, there is the same magnification factor in both the radial and toroidal directions. While radial resolution is the requested parameter, the toroidal direction can be strongly integrated with respect to highly toroidally

symmetric plasmas in tokamaks. We propose the optical solution based on a combination of standard circular lenses and a set of cylindrical lenses, which allows having different magnification in radial and toroidal directions. A conventional (off-the-shelf) objective based on circular lenses (focal distance of 50 mm), which defines radial zoom ( $8\times$  for the plasma-objective distance of 450 mm) and in which the iris will be adjusted to meet the numerical aperture of used fibers, will be connected to the custom-made anamorphic conversion lens, which improves the toroidal magnification two times. The conversion lens is a compound of a doublet of cylindrical lenses made of poly-methyl-methacrylate material and manufactured by the Single Point Diamond Turning technique. The throughput of system is increased accordingly to an increase of toroidal magnification, i.e. about two times by this improvement.

Besides the focusing optics upgrade we also evaluated different options of increasing the fiber collection area being inspired by astronomer's tests in [5]. Since the spectrometer's slit width masters the spectral resolution and the slit height is also limited (by the detector size), tapered fibers could seem to be one of the most interesting choices, also with respect to the economic effect: price divided by effective fiber collection area. But conservation of etendue in combination with typical  $f/\#$  of high-resolution spectrometers suppresses both the advantages of a big collection area and a fiber narrowing. For example, even for NA as low as 0.12, we have the equivalent  $f/\#$  about 4.2. Decreasing the fiber diameter to fit the slit size, the solid angle is even higher and exceeds the grating size. Scaling of the positive effects is the same or weaker than scaling of expected light losses (always with fiber size squared), moreover, an additional attenuation must be taken into account. Also, microlenses (small lenses applied to each fiber individually) are ineffective there, especially in comparison with conventional optics. They cannot reach an equivalent collection area, and must be applied separately to each fiber, which makes them also economically unattractive. Therefore, we focused on a comparison of fiber bundles of different fiber sizes filling the slit height, namely the fibers of NA=0.12 and core/cladding size of 105/125  $\mu\text{m}$ , 200/220  $\mu\text{m}$ , 400/440  $\mu\text{m}$ , 800/880  $\mu\text{m}$ , and similar fibers starting from 50/125  $\mu\text{m}$  for NA=0.22. Calculating throughput of the whole detection system, a decisive parameter depending on the fiber core diameter and the shape of the spectrometer's slit has been derived and called the effective fiber light collection area. We defined it as a product of (1) the total area of the fiber cores, and (2) the ratio of the light passing through the spectrometer's slit and the light transmitted through the fiber bundle. Since the price of the bundle slowly decreases with fiber size, the effective fiber light collection area strongly increases up to the fiber diameter two times bigger than the slit size. Above this limit, an optical improvement is in the range of few per cent only. The effect is scalable, and can be used for any combination of slit width and fiber size. We choose the bundle composed of 34 fibers of 200/220  $\mu\text{m}$  (NA=0.12) due to easy handling and reasonable value (weighted fibers area) for the money. The fibers form a linear array in both the ferrules. On the tokamak side, centers of the fibers are equidistantly spaced by 310  $\mu\text{m}$ . It allows getting the light from 80 mm of the edge plasma by using a new 8 times magnifying objective. On the spectrometer's side, the fibers are placed in touch with each other. Two of them will serve for spectral calibration purposes and are connected to the bundle only on spectrometer's side. Throughput of system is increased nearly by one order by optimizing a number, thickness and numerical aperture of the fibers with respect to the slit of the spectrometer. In the case of bundles composed from thinner fibers, flower-like fiber structures on the tokamak side reorganized into one dimensional array on the spectrometer's side are a good option. Often, they can be directly combined with the spectrometer without the use of both additional optics and the entrance slit. The flower-like set of thin fibers can be also put together into a

thicker fiber, if the decisive parameter is the bundle price. But then the throughput is lower than in the case of equivalent separate fibers.

## 2.2. Calibration and poloidal rotation measurements

The strong zinc spectral calibration lamp, which provides three useful Zn I lines at 468.014 nm, 472.215 nm, and 481.053 nm [3], is used for a coarse alignment of both the gratings in the spectrometer, and also for a raw estimation of the linear dispersion at the detector plane. Since the nearest spectral line is about 3 nm away from the spectral region of interest but CCD covers only about 1.3 nm, the zinc lamp cannot directly provide the final calibration. Instead, a much weaker hollow cathode iron lamp filled by neon is used having many lines there. The final camera alignment is done using an estimated linear dispersion and expecting Fe I lines at 464.743 nm, and overlapping lines at 465.450 nm, 465.461 nm, and 465.463 nm, and Ne I lines at 464.542 nm, 464.990 nm, 465.210 nm, and 465.370 nm [3]. The spectral calibration is performed repeatedly several times a day to eliminate thermal expansion effects, which can also partly influence shifts of spectrum, and therefore the derived plasma rotation. The linear dispersion, as well as the spectral offset, are obtained from a multi-line analytical fit of the calibration spectrum by Gaussian curves. The calculated value of the linear dispersion is 0.162 nm/mm. The instrumental width for 100  $\mu\text{m}$  spectrometer slit width is  $\Delta\lambda_{\text{FWHM, instr}} \sim 0.029$  nm.

The spectrometer is operated routinely during campaigns on COMPASS, in which poloidal rotation measurements (realization of the upgraded configuration is scheduled for 2015) are requested. Measured spectra from high-temperature discharges contains already mentioned CIII triplet, and a bit weaker O II line in between the carbon peaks at 464.914 nm [3], see the typical spectrum in Fig. 3. The poloidal plasma rotation and ion temperature are derived according to Eqs. (1) and (2), and their typical time evolution is plotted in Fig. 4. As an illustration, we show changes of both quantities in three shots representing the diverted, ohmically heated low-confined plasma evolving to ELM-free H-mode with (#7860) and without (#7866 and #7867) application of edge magnetic perturbations (MP). It is clearly seen, how L–H transition changes the edge poloidal plasma rotation from the electron diamagnetic to ion diamagnetic drift direction and how the ion temperature increases there. It also appears that the application of the edge magnetic perturbations decreases this effect.

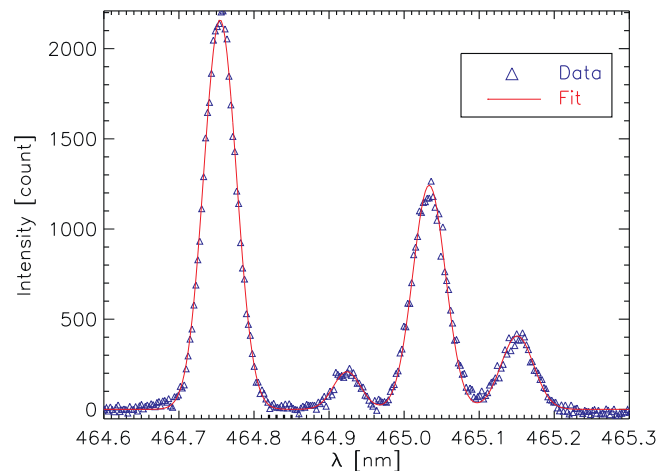
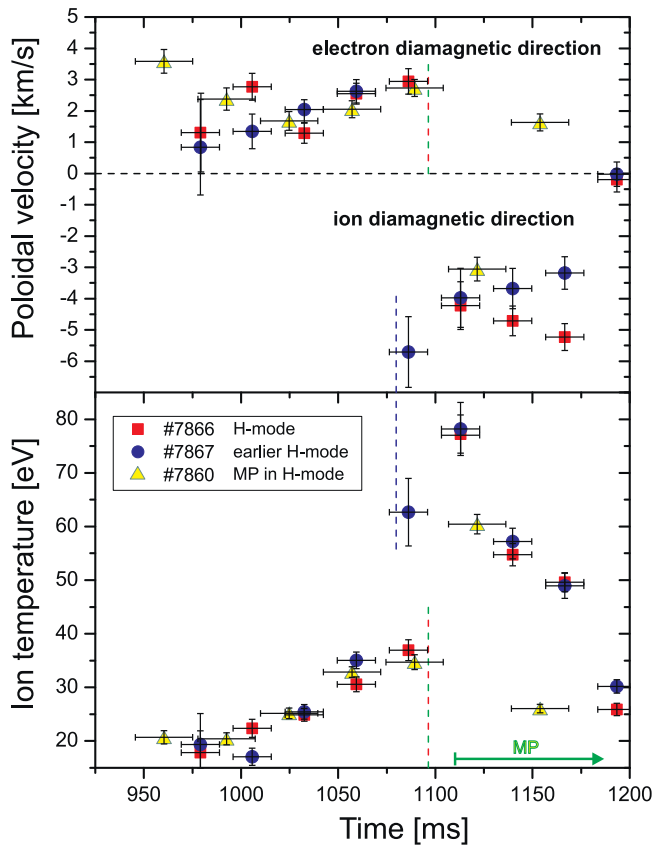


Fig. 3. Measured spectrum near the CIII triplet at  $(1006 \pm 13)$  ms in the diverted ohmically heated low-confinement plasma in the shot #5852 on the COMPASS tokamak. The second peak from the left is O II line at 464.914 nm.



**Fig. 4.** Temporal evolution of poloidal plasma rotation and ion temperature on COMPASS in a diverted ohmically heated plasma in the shots with the transition to ELM-free H-mode (from 1096 ms in #7860 and #7866, from 1080 ms in #7867) and with edge magnetic perturbations (MP) (from 1110 ms in #7860).

### 3. Charge exchange diagnostic on COMPASS

#### 3.1. Introduction to CXRS

Charge exchange recombination spectroscopy (CXRS) is one of the most successful tools for the measurements of impurity rotation and ion temperature profiles [6–9]. This technique has been used since the early 1990s for measurements of both the edge and core ion temperature and rotation of impurity ions, which are among key parameters for better understanding of physics of transport barriers [10]. On COMPASS, CXRS should provide a deeper insight into physics of the observed L–H transitions as well as the effects connected with the application of the edge magnetic perturbations [11] by the measurement of radial profiles of both the toroidal plasma rotation and the ion temperature.

CXRS on COMPASS will use the light emitted during the interaction of impurity ions with neutrals injected by a heating neutral beam; this yields information on local values of both the impurity ion temperature and the rotation using Doppler broadening and the shift of the measured line. Since carbon is the most common impurity in COMPASS, the CXRS diagnostic is proposed for C VI line at 529 nm ( $n=8 \rightarrow 7$ ) there. The deuterium beam, one of two heating neutral beams (NBI) installed on COMPASS, will be used as a source of fast neutrals, which penetrate up to the plasma core. The diagnostic comprises the collection optics coupled with an array of fibers. Light from the plasma will be led to a single spectrometer–CCD camera system.

#### 3.2. Design of CXRS

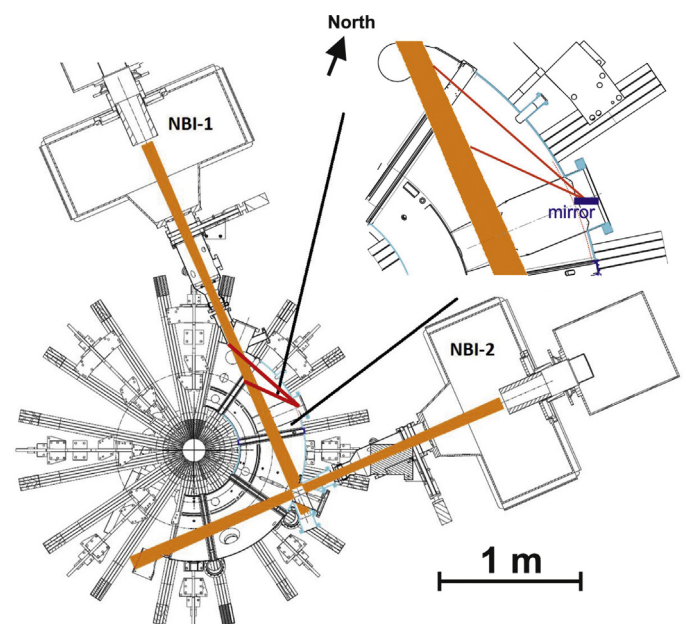
##### 3.2.1. Geometrical arrangement

The geometrical arrangement of the new CXRS diagnostic for the COMPASS tokamak is shown in Fig. 5. The equatorial port, with inner diameter of 150 mm, located in the sector between toroidal field coils 10 and 11 was selected for the installation of the collection optics. COMPASS has two NBIs, operated at beam current up to 10 A and beam energy of 40 keV, and capable of delivering 300 kW heating power in either deuterium or hydrogen atoms. The beams are injected tangentially in the equatorial plane and travel a distance of about 1 m before reaching the beam dump at the vessel wall. The beam diameter at focus is 5.5 cm and the beam divergence is about  $0.7^\circ$ . A better CXRS performance is reached for NBI1, for which the optical design will be introduced.

##### 3.2.2. Collection optics and fibers

The collection optics will be used to image the plasma onto the optical fibers that couple the light to the spectrometer. The first version of the optics design consists of the in-vessel stainless steel mirror and a pair of convex lenses (focal distance of 100 mm,  $f/2.2$ ) located outside the vessel. During glow discharges or other vacuum chamber conditioning processes, the mirror will be rotated to face the optical window and the back of the mirror, protected by a graphite block, will serve as a shutter for the window. The lenses image the carbon charge exchange emission onto 15 fibers of NA = 0.22, and 600/660  $\mu\text{m}$  core/cladding diameter mounted on a plate. However, the port and hence the optical head diameter restrict the magnification that can be achieved through the collection optics. In the mentioned case, the magnification is considered to be about 17. Consequently, the minimum spot size of 10 mm is generated for each line of sight at the intersection with the neutral beam. Using the known spot size, the calculated radial resolution of the CXRS system varies from 5 to 0.5 cm from the plasma core towards the edge as shown in Fig. 6.

With the proposed collection optics, the CX emission is expected to be imaged by the lens system onto a linear array of fibers so as to fill the collection optics with f-number of the fibers. Then,



**Fig. 5.** Geometrical arrangement of the new CXRS diagnostic on COMPASS. The edge line-of-sights of the CXRS diagnostic are indicated in the figure.

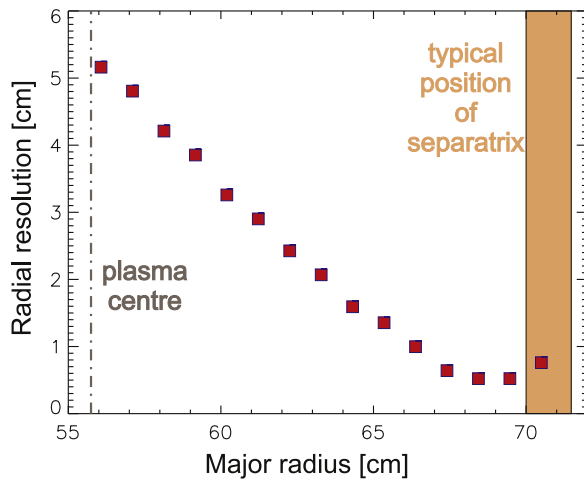


Fig. 6. Radial resolution of CXRS using NBI1.

the light is transferred 20 m away from the tokamak hall to a low radiation area, where the fibers will be coupled to a high resolution Czerny–Turner spectrometer. A prototype of the proposed periscope has already been tested in the optical laboratory for an engineering feasibility study.

### 3.2.3. Spectrometer and CCD system

For the CXRS diagnostic, which will be used for H-mode studies on COMPASS, a high dispersion spectrometer is required for achieving an adequate accuracy of toroidal rotation measurements of about 10 km/s. If it is combined with an observation angle for the edge plasma of  $52^\circ$ , a linear dispersion of the spectrometer should be at least 0.83 nm/mm for the typical pixel size of the camera of 13  $\mu\text{m}$ . At the same time, a lower limit of the spectral region to be covered by the spectrometer–camera system is given by the maximum ion temperature expected in the region of interest. Assuming temperature values of 0.3–1 keV, the C VI line broadening calculated according to Eq. (2) sets this limit to 0.20–0.37 nm. Based on these parameters, the spectrometer and the camera have been chosen.

However, the selection of the camera, the spectrometer, and the fiber optics is not independent since the spectrometer resolution, the covered spectral region, the pixel size of the camera, the number of pixels in both directions of the camera, and the spectrometer slit height are mutually coupled.

For the present CXRS diagnostic, the 0.67 m Czerny–Turner McPherson 207 spectrometer has been purchased equipped with a holographic grating of 1800 grooves/mm optimized for visible wavelength range. The grating size is 120 mm  $\times$  140 mm. The system accepts light up to  $f/4.7$ . The fibers used in the collection optics can be vertically stacked in one column and coupled to the spectrometer system. The spectrometer resolution lies at the above mentioned limit.

The imaging plane of the spectrometer is covered by a charge couple device (CCD) as the detector. We purchased the newest model of ANDOR's EMCCD cameras, iXon Ultra 888. The camera has 1024  $\times$  1024 pixels in the active area, and a pixel size of 13  $\mu\text{m}$ ; thus creating active area of 13.3 mm  $\times$  13.3 mm. The camera has a readout speed of up to 30 MHz, which, in combination with the binning options, allows measurements well below 5 ms. Moreover, it is equipped with a frame-transfer readout. Due to limitations of the exposure time given by a low light intensity, we can also gain from a high quantum efficiency of about 90% for the used spectral region. The system is expected to provide pixel resolution of about 0.011 nm at the mentioned linear dispersion of the spectrometer.

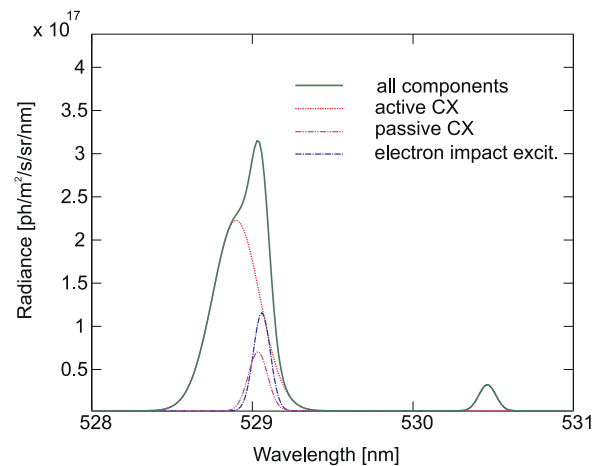


Fig. 7. Simulated spectra generated by the SoS code for COMPASS using plasma parameters from the shot #6133. The left peak is composed from the active charge-exchange (beam dependent), passive charge-exchange and electron excitation components of C VI line at 529 nm. The small peak on the right is C II line at 530.5 nm.

### 3.2.4. Implementation of CXRS diagnostic

Feasibility of the proposed CXRS diagnostic based on measurements of the C VI line at 529 nm ( $n=8 \rightarrow 7$ ), which will be implemented on the COMPASS tokamak, has been numerically examined in different project phases by the Simulation of Spectra (SoS) code, which has been developed for these purposes at the University of Technology, Eindhoven (<http://fusion.phys.tue.nl>). The code takes main plasma and beam parameters, including the real geometry of both the plasma and NBI, the beam attenuation, the instrumentation specifications of the spectrometer and CCD, and plasma emission rates to provide the simulated 'observed' CX spectrum. The code generates both the active and passive CX components of the spectra. Simulated spectra indicate a dominating active charge-exchange signal over a passive one. A realistic simulated case corresponding to the final set-up mentioned above is shown in Fig. 7. The plasma parameters used there were taken from the realized shot on the COMPASS tokamak with the number #6133: central electron temperature was 0.6 keV, line-averaged density  $3.7 \times 10^{19} \text{ m}^{-3}$ , 40 keV neutral (deuterium) beam of current of 10 A with the beam composition of the full, half and one-third energy ratios of 47% (E), 26% ( $E_{1/2}$ ) and 27% ( $E_{1/3}$ ), respectively. The profiles of electron density and temperature were incorporated from the Thomson Scattering diagnostic. Independently of the simulations, a simple set-up based on the low-resolution HR2000+ spectrometer (spectral range of 458–663 nm,  $\Delta\lambda \sim 0.1 \text{ nm}$ ), presently available on COMPASS, was successfully realized to check the presence of both the passive and active components of the investigated CX line at 529 nm.

The spectral calibration of the system is planned to be done by the hollow cathode samarium lamp. The absolute calibration will be performed using the quartz tungsten halogen lamp to allow reconstructions of the carbon ( $\text{C}^{6+}$ ) concentration profile.

## 4. Conclusion

Both passive and active variants of the plasma rotation diagnostic on the COMPASS tokamak have been introduced. For successful implementation, poloidal rotation measurements require a high spectral dispersion of the system as 0.16 nm/mm to resolve typical values of the poloidal rotation of the order of several km/s. Toroidal measurements can be realized with dispersions of only

about 0.8 nm/mm. A passive diagnostic should also be optimized for a high-throughput; otherwise, time measurements are limited by low intensity of the signal. When the beam is available on the device, CXRS can provide well spatially resolved measurements of profiles of plasma rotation, ion temperature, and impurity concentration.

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