A new calibration implementation for Doppler Coherence Imaging Spectroscopy

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Abstract

A new widely tunable, continuous-wave laser named C-Wave enables direct calibration at the unshifted, center-of-mass wavelength for most plasma lines in the range between 450 and 650 nm for Doppler Coherence Imaging Spectroscopy. It also provides the ability to scan around each desired wavelength over a small range of ±50 pm, thus enabling an easy way to translate the measured phase difference $\Delta\Phi$ of the diagnostic to the desired Doppler line shift $\Delta\lambda$, that corresponds to the physical parameter of interest, the particle velocity of an observed plasma species.
A first wavelength scan of the C-Wave laser ±50 pm around a single plasma line of interest, C III at 464.881 nm, is presented and compared to a simulated wavelength scan. It demonstrates not only the C-Wave capability as a Doppler CIS calibration source, but also its potential to immensely simplify Doppler CIS analysis for nearly all visible plasma lines of interest.

Keywords: Doppler Coherence Imaging Spectroscopy

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1. Introduction

Doppler Coherence Imaging Spectroscopy (CIS) is a relatively new ([1]) and powerful method to measure particle velocity flows from a radiating body such as a plasma. Due to its ability of producing 2-dimensional images of line-of-sight integrated particle parameters, CIS is increasingly used in high-temperature plasma experiments such as DIII-D ([2]), MAST ([3]), ASDEX Upgrade ([4]) and Wendelstein 7-X ([5]). It measures a single emission line from the plasma, with which a spatial interference pattern is produced by a set of birefringent plates on a camera chip. To analyze the measured plasma line interference pattern, a reference interference pattern is produced with a monochromatic calibration line. Ideally, these calibration lines are at the unshifted, center-of-mass position of the observed plasma line, λ_0. Strong (impurity) plasma lines of interest in the visible part of the light spectrum include e.g. C III, C II, He II and many other lines from higher excitation stages. However, these atomic emission lines usually cannot be generated with conventional spectral calibration lamps. This is why for many observed plasma lines, calibration wavelengths in the vicinity of a few nanometers to λ_0 are used. An example is the C III multiplet at 464.881 nm, for which a Zn I calibration line at 468.014 nm is usually used. In these cases, the analysis of the $\Delta\Phi \rightarrow \Delta\lambda$-relation becomes much more difficult, since additional phase effects, generated by the birefringent plates of the Doppler CIS, have to be considered and accurately determined.

Previous calibration methods rely on spectral lamps and conventional lasers that drastically limit the availability of close, intense calibration lines. Ideally, a good calibration method for the Doppler CIS diagnostic should be tunable to the unshifted spectral line ($\lambda_{\texttt{cali}} = \lambda_0$) and be able of performing wavelength scans of the range of expected Doppler line shifts of the particle species in the edge of a high-temperature plasma experiment[1]. Both features simplify the analysis process, since it will not rely on simulations of phase effects for which a very accurate knowledge of optical and birefringent plate parameters is required. In particular, the small-range scanning capability allows to determine the sign of the $\Delta\Phi \rightarrow \Delta\lambda$-relation without doubt for the applied plate configuration. Moreover, if the tuning process is precise enough, it will be possible to measure the multiple phase offset present for emission lines such as C III.

A newly developed, widely tunable continuous-wave (CW) laser (called ”C-Wave”) based on optical parametric oscillation (OPO) provides monochromatic line emission over nearly the entire visible spectrum (450-525 nm and 540-650 nm) and the near infra-red (900-1300 nm) ([6]). For the Doppler CIS at W7-X, the C-Wave laser was specifically customized to apply precise wavelength selection with an accuracy of < 0.1 pm and wavelength scanning over a range of ±50 pm around a chosen wavelength λ_0. This is possible thanks to a newly developed software tool called ”AbsoluteLambda”, that involves a feedback loop based on constant monitoring of the laser emission by a high-resolution wavemeter. Concerning stability, the laser usually needs a few minutes to settle to a selected wavelength λ_0, but can then reliably keep the selected wavelength with an accuracy of < 0.01 pm for several days if it is not disturbed by major vibrations. Within ±50 pm around the selected λ_0, the wavelength can be varied fast and stably as well, usually requiring only a few seconds to access the desired wavelength variation. This is later demonstrated in Figure 3. With this new calibration source, several problematic issues of conventional calibration sources (with $\lambda_{\texttt{cali}} \neq \lambda_0$) for CIS can be dealt with:

1. All plasma lines in the range of 450-525 nm and 540-

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[1] At 464.8 nm, a Doppler line shift of 50 pm $\approx$ 30 km/s.

650 nm can be absolutely calibrated at their non-shifted, center-of-mass line position.

2. With the small-range scanning capability of the laser (in a range of ±50 pm), the $\Delta\Phi \rightarrow \Delta\lambda$-relation for CIS can be directly measured for each Doppler CIS plate configuration and does not have to be simulated.

Thanks to these features, not only CIS, but also other spectroscopic systems such as high-wavelength resolution spectrometers can be reliably wavelength calibrated. An alternative method involves tunable diode lasers, who can usually be varied over a range of a few nanometers ([7]). The tunable C-Wave laser is used as a calibration source for the two Doppler CIS systems on Wendelstein 7-X. In this work, a first wavelength scan of the C-Wave laser ±50 pm around a single plasma line of interest, C III at 464.881 nm, is presented and compared to a simulated wavelength scan. This is done to demonstrate the laser capability as a Doppler CIS calibration source, immensely simplifying the complex CIS analysis procedure by:

1. omitting the need to determine an additional phase term arising due to $\lambda_{\texttt{cali}} \neq \lambda_0$
2. omitting the need to calculate the dispersion function $\frac{\Delta\Phi}{\Delta\lambda}$ if the wavelength scan is performed for the used plate configuration.

CIS analysis has been described in many previous works ([12], [8], [9]) and will not further be discussed here.

2. Wavelength scan with the tunable laser

As reported in [5], there are two Doppler CIS systems used in W7-X, that observe the same divertor area from different view ports, enabling better understanding of the line-integrated emission and flow patterns. Those two systems are named after the ports from which they observe the plasma, AEQ21 and AEF30, and they are also characterised by different birefringent plate configurations. The thickness, material and type of plates determine the fringe phase shift for an observed emission line wavelength. The more or thicker plates are used, the smaller wavelength shifts can be resolved. A small-range wavelength scan with the C-Wave was performed with the two W7-X Doppler CIS systems simultaneously to assess the phase dependence on wavelength for both systems. The measurement was performed by using a set of Y-fibres at the output of the C-Wave laser and at the output of a He-Ne laser, that was used as a fixed wavelength reference source. Via the Y-fibres, the calibration spheres of the two systems were connected to each laser at the same time.

The entire wavelength scan lasted for several minutes. Even in the time span of a few minutes, however, ambient temperature changes of and around the birefringent plates can be present. The birefringent plate refractive indices, n_e and n_o, that determine the phase shift of the incident light on the plate, are not only dependent on the wavelength, but also the material temperature. Therefore, ambient temperature changes around the plates can change and distort the measured phase. Since the two Doppler CIS set-ups on W7-X do not involve an active or passive temperature control for the birefringent plates (e.g. via temperature cells or ovens), the He-Ne reference line is necessary to monitor the effects of any temperature variation. The He-Ne laser can be simultaneously used in this context because its line emission at 632.8163 nm is distant enough from the C-Wave wavelength under study to be distinguishable in the Fourier analysis, as firstly reported in ([9], p.68). The distance of two peaks in Fourier space depends on the wavelengths and the fringe size. The tunable laser wavelength was set to the unshifted center-of-mass wavelength of the C III multiplet at 464.8811 nm and varied in a range of ±50 pm around it. In Figure 1, the interferometer signal generated by the two monochromatic laser wavelengths is shown. It consists of two overlapping modulation patterns. For the two W7-X systems, the wavelength peaks of the two lasers (632.8 nm - 464.9 nm = 167.9 nm) proved to be separated enough in Fourier space, as can be seen in Figure 2. The simultaneous measurement of two wavelengths comes at the cost of spatial resolution, since the inverse Fourier transform area becomes smaller.

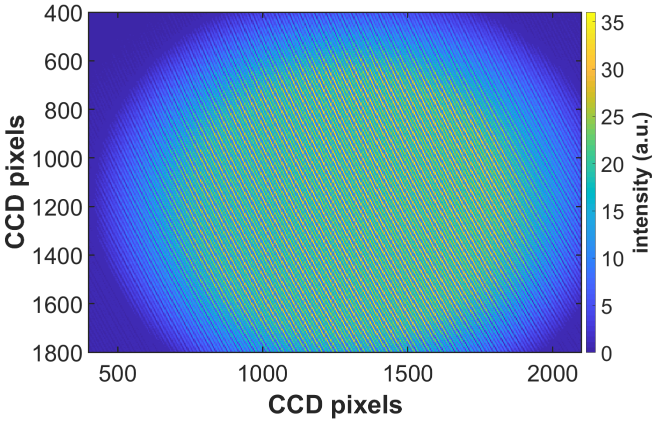

Figure 1: Doppler CIS interferometer signal recorded with the C-Wave laser (started at 464.881 nm) and the HeNe ion laser (632.816 nm), taken from the AEF30 port CIS system.

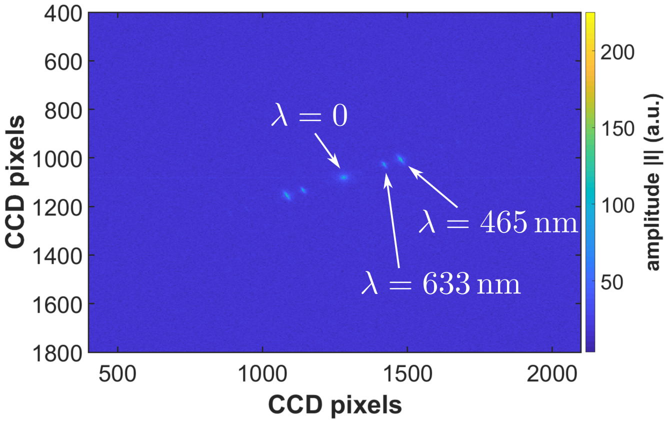

Figure 2: 2D Fourier transform image of the interference pattern in Figure 1.

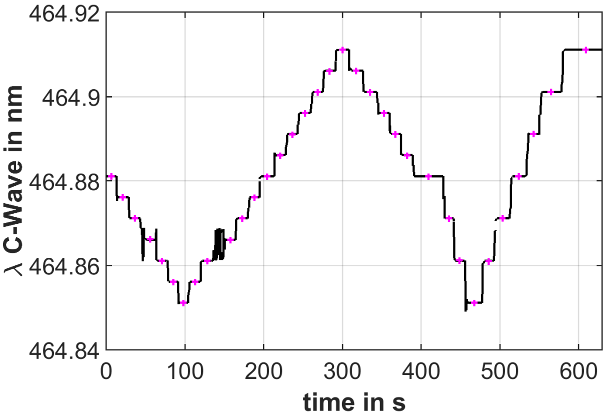

Figure 3: Wavelength of the C-Wave laser during the scan experiment. The magenta markers indicate each scan step that will be analyzed in this work.

The two Doppler CIS systems employ different plate configurations ([5]) in the current plasma campaign OP1.2b[2]. The AEQ21 system consists of a 10 mm α-Barium Borate (α-BBO) displacer plate, the second system in AEF30 applies a 10 mm α-BBO displacer plate and a 6 mm α-BBO delay plate. In Figures 3 and 4, the C-Wave wavelength during the scan, the temporal evolution of the tunable laser phase difference and the He-Ne laser phase difference are shown for both Doppler CIS systems during the scan experiment. The tunable laser wavelength was decreased and increased in 5 pm and 10 pm steps several times around the center-of-mass wavelength of the C III multiplet at 464.881 nm, which was set as reference point ($\Delta\Phi = 0°$). In both figures, the scan data appears interrupted sometimes, which is due to the C-Wave, that mostly needs 1-2s to stabilize after changing the wavelength for these ranges. As expected, the phase variation is stronger for the AEF30 system, which has an additional delay plate. However, in that system, the temperature drift of the phase was slightly higher, corresponding to $\Delta\Phi \approx 3°$ over 10 minutes for the C-Wave and $\Delta\Phi \approx 0.3°$ over 10 minutes for the HeNe laser. At AEQ21, $\Delta\Phi < 1°$ over 10 minutes for both lasers, since one less birefringent plate was used. Furthermore, for the AEQ21 system, the sign of the $\Delta\Phi$-$\Delta\lambda$-relation was opposite to the one in AEF30, since the orientation of the birefringent displacer plate axis was different.

The effect of the temperature-induced phase drift, which differs for different wavelengths, appears to be stronger for light in the blue part of the spectrum than in the red. This effect was already reported in [9], in which a stronger overall phase drift was observed due to a different plate configuration. With the He-Ne laser, the temperature-induced phase drift could be monitored, being relatively linear for both systems and therefore allowing the assumption that the temperature drift for the C-Wave was linear as well. The rate of the temperature-induced phase drift was estimated with all phase data points at $\lambda_0 = 464.8811$ and subtracted from the measured phase to extract a temperature drift corrected $\Delta\Phi \rightarrow \Delta\lambda$-relation for the C-Wave, which can be seen in Figure 5.

Figure 5 shows the measured $\Delta\Phi \rightarrow \Delta\lambda$-relation for both W7-X Doppler CIS systems. The data points represent the time-averaged phase during each scan step (marked in Figures (3) and (4)). In the AEF30 system, a positive phase corresponds to a red shifted line (or flow away from the observer), whereas in the AEQ21 system, it corresponds to a flow towards the observer. For comparison, a simulated $\Delta\Phi \rightarrow \Delta\lambda$-relation has been added to the Figure to quantify theoretical predictions. The simulated phase shift due to a birefringent delay or displacer plate can be calculated according to a formula provided in ([10]). It requires the accurate knowledge of the following parameters:

- the birefringent indices (n_e, n_o) for the material in use (here: α-BBO, provided in [11]).
- the thickness, L, of the birefringent plates
- the orientation of the birefringence axis, θ,
- the angle between the incident light and the plate surface, α,
- and the angle between the projections of the incident light and the optical axis on the plate surface, δ.

The plate parameters, which were applied to the best of the authors knowledge (relying on manufacturer data) need to be known to a high degree of accuracy. Small uncertainties in them as well as inaccurate birefringent index data (n_e,n_o) cause phase offsets that might affect how $\Delta\Phi$ changes for a given Doppler shift $\Delta\lambda$. As can be seen in the Figure, the agreement between the measured and simulated $\Delta\Phi \rightarrow \Delta\lambda$-relation is good, demonstrating the validity of the model. For AEF30, the deviation between the simulated and the measured data is $\delta\Delta\Phi \approx 3°$ for $\Delta\lambda = 30$ pm. For the AEQ21 system, it is $\delta\Delta\Phi \approx 1.5°$ for $\Delta\lambda = 30$ pm. This comparison might also be used to fit the plate parameters for simulations, as has been suggested by [12] (not performed in this work). The data presented in Figure 5 distinctly shows the high velocity resolution of the CIS diagnostic. Therefore, it is clear that the use of conventional calibration sources, for which($\lambda_{\mathtt{cali}} \neq \lambda_0$, a huge (velocity) offset is introduced. For example, in the case of the C III multiplet calibrated with a Zn I spectral line (at 468.1 nm), the offset for the AEF30 system would be $\delta\Delta\Phi \approx 300°$ ($\delta v \approx 70$ km/s) for $\Delta\lambda = 3$ nm. This is also in line with investigations presented in [12]. There are two ways to deal with these large phase offsets/errors: either fit the plate parameters with some effort ([12], [9]) or calibrate at ($\lambda_{\mathtt{cali}} = \lambda_0$) and measure $\Delta\Phi \rightarrow \Delta\lambda$ directly by means of tunable calibration sources.

3. Summary and Conclusion

The main aim of this paper is to inform about the C-Wave as another suitable calibration source for CIS and to prove its

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[2] There have been two plasma campaigns in W7-X so far: OP1.1 with a carbon limiter and OP1.2 with an uncooled carbon divertor, that was split in two parts: OP1.2a and OP1.2b (additional scraper elements in some divertors)

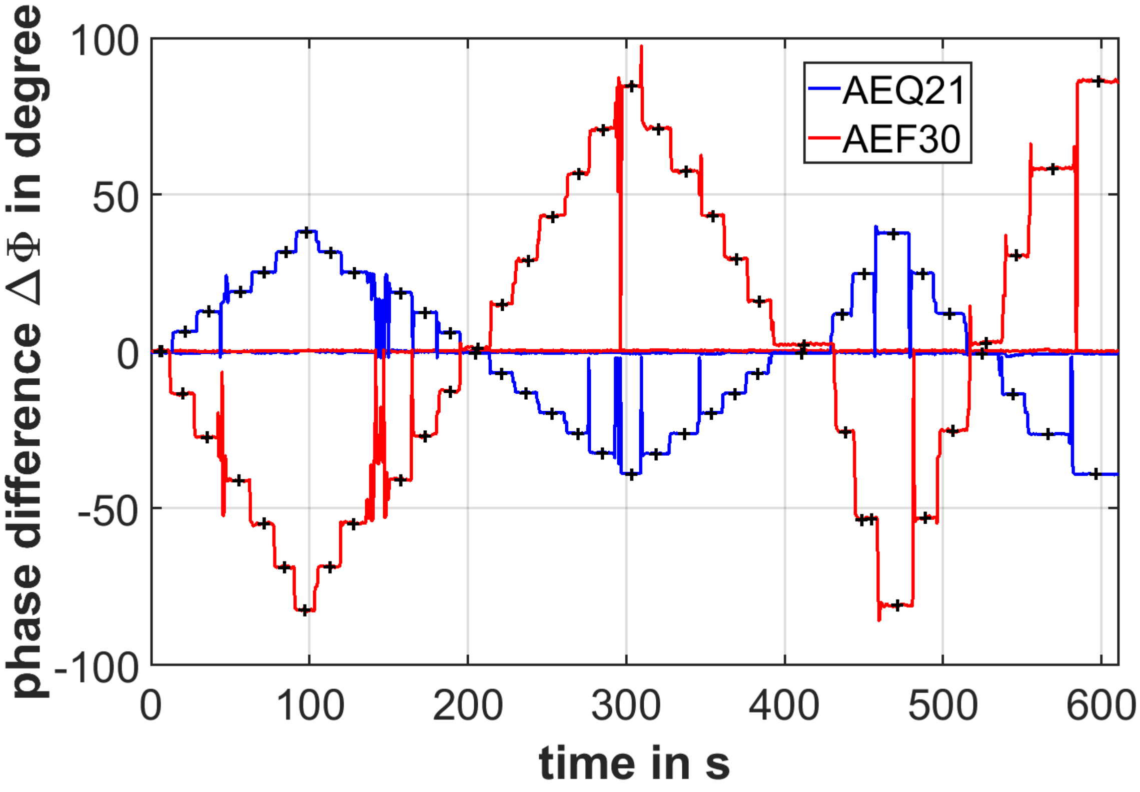

Figure 4: C-Wave wavelength scan performed simultaneously in the two W7-X Doppler CIS systems on the AEQ21 (10 mm displacer) and AEF30 (10 mm displacer + 6 mm delay plates) ports, respectively. Displayed are the averaged measured phase difference of the (fixed) He-Ne laser and the phase difference of the C- Wave. The $\Delta\Phi$ averages were taken in the central 50 pixels in the analyzed Doppler CIS images. As reference phase image, the first measurement image was taken.

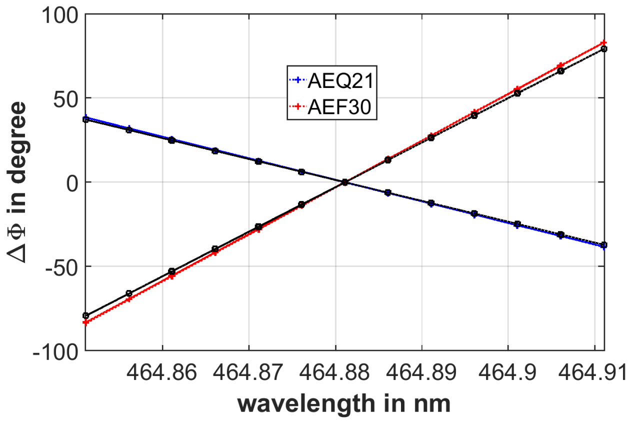

Figure 5: The measured (in color) and simulated (black) $\Delta\Phi \rightarrow \Delta\lambda$-relations for both W7-X CIS sytems in AEF30 and AEQ21.

capability to directly measure the required $\Delta\Phi \rightarrow \Delta\lambda$-relation for analyzing the velocity for CIS. An important assumption for the Doppler CIS analysis with previously applied calibration sources, where $\lambda_{\texttt{cali}} \neq \lambda_0$, is that $\Delta\Phi$ for a certain Doppler shift $\Delta\lambda$ can be accurately predicted. This requires the birefringent indices data n_e, n_o to be precise. Furthermore, diagnostic parameters such as the thickness of the birefringent plates, the orientation of the birefringent plate axes, the precise angle of incidence of the light on the chip, $\alpha = 0°$, and focal length f of the CCD lens need to be known with very high accuracy. Small uncertainties cause phase offsets that can distort the $\Delta\Phi \rightarrow \Delta\lambda$-relation. Under these circumstances, it is not impossible to analyze measured phase data ([12], [4]), however it involves a time-consuming process to identify the precise plate parameters for each new plate configuration or even small changes to the same set-up. With the C-Wave laser as a new calibration source for Doppler CIS, all plasma lines in the range of 450-525 nm and 540-650 nm can be directly calibrated at their center-of-mass position. As has been demonstrated in this work, the $\Delta\Phi \rightarrow \Delta\lambda$-relation can be directly measured with C-Wave, omitting the need for simulating any phases for Doppler CIS in the future, thus making analysis much faster and direct. It is assumed that this is also possible with tunable diode lasers, as comparable wavelength scans were already performed as well ([12],[3],[9]).

4. Acknowledgments

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