Coherence Imaging Spectroscopy systems on Wendelstein 7-X for studies of island divertor plasma behavior

V. Perseo[1], R. König[1], C. Biedermann[1], O. Ford[1], D. Gradic[1], M. Krychowiak[1], G. Kocsis[2], D. Ennis[3], D. Maurer[3], T. S. Pedersen[1] and the W7-X Team[1]

[1] *Max-Planck-Institute for Plasma Physics, Greifswald, Germany*

[2] *Wigner RCP, Budapest, Hungary*

[3] *Auburn University, Auburn, USA*

Introduction

In Wendelstein 7-X (W7-X) the so called “island divertor” concept has been realized, in order to exploit the intrinsic magnetic islands structure in the outer region of the plasma for impurity screening. Predictive EMC3/EIRENE simulations for W7-X, as well as simulations of experimental conditions achieved on W7-AS, show that particle friction can dominate over ion thermal force, pushing the impurities towards the divertor target, and thereby resulting in efficient impurity screening of the core plasma [1]. In order to understand the physics behind these impurity transport mechanisms, flow measurements are required.

Flow measurements are mostly Doppler effect based. The expected velocities, e.g. for carbon, are of order tens of km/s [2], requiring very high spectral resolution instruments to measure the corresponding Doppler shift ($\Delta\lambda$) of just a few tens of pm. Moreover, it would be desirable to use instruments with 3D measurement capability to resolve the complex 3D edge structure in W7-X. These requirements cannot be met by standard spectrometers: only long focal length Echelle ones could provide sufficient wavelength resolution. However, they need to be operated in high order with narrow slits (thus unavoidably low etendue), and they can provide only 1D information [3]. Therefore, Coherence Imaging Spectroscopy (CIS) systems [3, 4] are expected to be a better choice for the W7-X environment.

CIS systems use birefringent crystals sandwiched between two polarisers, manipulating plasma radiation by introducing a phase difference between the two light polarizations: this creates an angle-dependent 2D interferometric phase shift necessary to generate approximately parallel spatial interference fringes on the camera detector. This fringe pattern acts as a spatial heterodyne carrier for Doppler amplitude and phase modulations that can be recovered using numerical Fourier demodulation techniques. Since no slit is used, the CIS system has a high optical throughput, and its velocity and temperature resolution depends just on the crystal set-up. Moreover, it allows 2D measurements, such that 3D information can be gained by using two orthogonal systems.

In the CIS setup described here the light coherence is measured in space and, therefore, its time resolution is determined by the camera (100 frame/s at full frame). This also implies that the recorded picture will have anisotropic spatial resolution: along the fringes, every pixel is carrying information; perpendicular to them, the presence of the fringes themselves are obstructing the spatial information. In this direction, the resolution can be measured in pixels per fringe and depends on the crystal set-up.

Being the first application on a large stellarator, the CIS diagnostic of W7-X has been designed to be as flexible as possible by including some motorized components. Another important feature of the W7-X CIS system is its calibration system based on a tunable laser, that will allow frequent and precise calibration measurements. Here a brief description of the set-up features and of the calibration system will be provided.

Installation at W7-X

The diagnostic is composed of two different systems having almost perpendicular views (fig. 1): one is looking toroidally into the machine, the other is looking vertically onto the divertor. The two views are focused on the same lower divertor region, where also a divertor integrated poloidal row of 5 gas introduction nozzles is located, which allows impurity gas puffs. This enhances local brightness, and thus grants a localization of the measurements. The two systems are placed on two scaffolds in the torus hall, fairly close to W7-X, therefore requiring adequate magnetic shielding of the electrical components. Dedicated magnetic shielding calculations for the two diagnostic locations demonstrated that soft iron boxes with 5 mm wall thickness are sufficient.

Figure 1: Sketch of the two views of the CIS diagnostic on W7-X.

The plasma is observed through vacuum windows. Both ports are shared with other diagnostics: a high resolution spectrometer, a visible camera, and an infrared camera in the port with the vertical view; a fast video camera in the port with the toroidal view. The light is collected by an imaging lens located directly behind the vacuum windows deep inside the about 2 m long ports. The lenses are connected to 4.5 m long imaging fiber bundles, composed of 800x1000 10μm diameter fibers, which transfer the light to the 2 soft iron boxes containing all optical and electrical components of the CIS systems. The described plasma light collecting system allows each fiber to cover 1-2 mm on the divertor.

Features of the W7-X CIS systems

As previously stated, the diagnostic core is formed by the birefringent crystals and the polarizers. Other essential components are a narrow band filter (with FWHM of $\sim$2 nm) for selecting just one spectral line from the plasma emission, and a set of camera lenses to collimate the light through the filters, the polarisers, and the crystals.

Since W7-X is a new machine, it is not easy to anticipate which impurity spectral lines will prove to be most suitable for the experimental investigations, and in which direction the highest spatial resolution will be most desirable. Moreover, in W7-X, with its superconducting coil system, the magnetic field will be up all day during the upcoming experimental campaign, allowing no access to the torus hall up to a week. Therefore, some additional components were installed to increase the flexibility of the entire diagnostic.

In order to overcome the spectral line selection problem, two consecutive, motorised filter wheels, each of which could host up to five 2” filters, are being used, allowing to select from 8 filters. In this way, it will be possible to pick the impurity ion to be investigated without accessing the torus hall. This will be especially useful for spectral lines having roughly the same optimized crystal plates configuration. In case the plate configuration is not suitable, a cage system, used to hold the polarisers and the birefringent crystals, will allow changing them in a reliable and rigid way, due to the possibility of unclipping the cages from the segments without any sliding movement. Concerning the spatial resolution, it will be best to align the direction along the fringes, which provides the highest possible spatial resolution, with the steepest gradient expected in the plasma, that is not accurately known in advance. A motorized rotator connected to the cage system will allow the variation of the fringe direction even during an experiment, determining the most interesting gradients.

A special feature of the W7-X CIS system is its novel calibration system. For a diagnostic based on Doppler effect, the calibration process is fundamental in order to get quantitatively valuable measurements. In fact, in order to measure the impurity velocities, it is necessary to obtain a difference between the wavelength emitted by the ion in motion in the plasma (λ_m) and the unshifted wavelength corresponding to the ion at rest (λ_0). In the case of the CIS system, this means measuring two different phases (Φ_m and Φ_0) induced by the crystals. The relation between $\Delta\lambda = \lambda_m - \lambda_0$ and $\Delta\Phi = \Phi_m - \Phi_0$ is non-trivial, since it is linked to the angles of incidence of the plasma light on the birefringent plates [5]. Therefore, the ion velocity is not easy to extrapolate. It is possible to simulate the relation between $\Delta\Phi$ and $\Delta\lambda$, but the simulation gets less and less reliable if all the plate parameters are not precisely known or if the calibration wavelength is not exactly equal to the unshifted wavelength. The latter case is common when the calibration system is based on standard spectral lamps, and it makes the data analysis more complex [6]. At W7-X, the calibration system of the CIS relies on a new continuous wave fully tunable laser, that covers the spectral range 450-525 nm and 540-650 nm. The absolute laser wavelength can be set with an accuracy of 0.1 pm. The laser is coupled with a high finesse wavemeter that feedback controls the wavelength. With the laser, it will be possible to know the correct λ_0 for any plasma line, providing always a reliable reference point for the emission of ions at rest. Furthermore, the system is able to scan the wavelength over $\lambda_0 \pm 50$ pm within 10 minutes, that will directly measure the relation between $\Delta\Phi$ and $\Delta\lambda$, without relying on the optical constants found in literature and used in the theoretical equations of the simulation. Since the laser is controllable via computer and it is placed outside the torus hall (the light will be carried to the systems via two fibers about 100 m long and introduced through a beam splitter or a motorized mirror), the calibration can be performed directly before and after each plasma discharge, so that the temperature effects on the birefringent crystals can be minimized.

Conclusions

The CIS diagnostic, presently being installed on W7-X, will allow detailed 2D investigations of impurity flows in the edge island divertor structures. By using two orthogonal systems, even some 3D information can be gained. The diagnostic will benefit from several new features integrated into such a system for the first time, to reach maximum flexibility on a large fusion device with rather limited personnel diagnostic access. The system will allow remote selection between 8 different impurity lines, using 2 filter wheels, in combination with a novel calibration technique that uses a fully wavelength tunable, wavemeter controlled, continuous wave laser. Furthermore, the system will allow remote scan and adjustment of the highest spatial resolution direction, in order to find the most optimal orientation for every a single discharge. The first results are being expected during the upcoming operation phase, starting in Autumn 2017.

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