

## Development of neutral-beam-aided diagnostics on the HL-2A tokamak

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### 1. Introduction

Ion temperature is not only an important parameter in tokamak plasma, but also necessary for good understanding of plasma dynamics, especially for the study of the thermal transport of ions [1]. On contrast to those passive techniques, Charge eXchange Recombination Spectroscopy (CXRS) is a powerful active spectroscopy technique since it relies on the interaction between the main impurity ions and Neutral Beam (NB) injected particles, thus allowing for some spatially resolved measurements of ion temperature and bulk plasma rotation. Since the carbon is the dominant intrinsic impurity in HL-2A tokamak plasma, the CVI (529.1nm) line emission from the charge exchange recombination of the full stripped carbon is chosen as the principle measurement wavelength.

### 2. The CXRS system and initial results

A 32/64-channel CXRS system has been developed on the HL-2A tokamak. The CXRS diagnostic routinely measures the C VI impurity line emitted in the visible region ( $n=8-7$ , 529.1 nm). The CXRS system consists of collection optics, a fiber bundle, a spectrometer and a fast-readout charge-coupled device (CCD), as shown in figure 1. A specially designed collection optical system can monitor the half cross-section of the plasma at the low field side. The optics collects the emission from the plasma with charge exchange interactions between carbon impurities and neutral beam atoms and then focuses on the fiber; the fiber leads the emission to the spectrometer in the laboratory. The sizes of the fiber are 0.2 mm and



Figure 1 the CXRS system on HL-2A

0.25 mm of the core and cladding diameters, respectively. A frame transfer CCD detector with Electron Multiplier (EM) and  $512 \times 512$  pixels (Andor Model: DU-897E CSO-BV) is applied for the system and features high time resolution (up to 400 Hz). To achieve a high frame rate by taking the advantage of the pixel binning, the fibers at the spectrometer end are pitch-controlled, which means the space between two adjacent fibers is fixed (controlled) at 0.25 mm, corresponding to the size of 16 pixels of the CCD. High throughput (F/2.8) spectrometer is utilized to guarantee the high temporal resolution. It is a typical Czerny–Turner spectrometer, which consists of two commercial camera lenses with focal length of 400 mm and a grating with 2160 grooves/mm. Two projected images can be obtained by using the double-slit fiber bundles (each with 32 fibers), and a band-pass interference filter is applied to prevent the wavelength overlapping. The full width at half maximum of the filter is around 2.2 nm, and the peak transmission is 58% at 529.45 nm.

As the fiber is pitch controlled, the crosstalk of the system is analyzed. The odd fibers are illuminated by an integrating sphere, whereas the even ones are not. The crosstalk level is defined by the ratio of intensities from an even channel to the average of the adjacent two. The crosstalk is within 2% at the working region, as shown in figure 2.

Due to the aberration of the off-axis rays in the short-focal length spectrometer, the image on the CCD is curved and the shift of wavelength is denoted as  $dx$  in the unit of pixels.

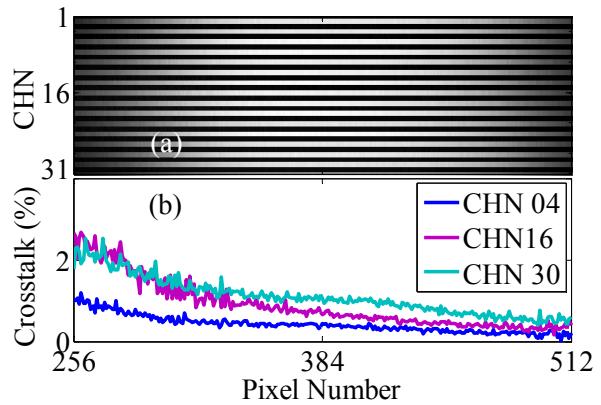


Figure 2 Crosstalk of the system

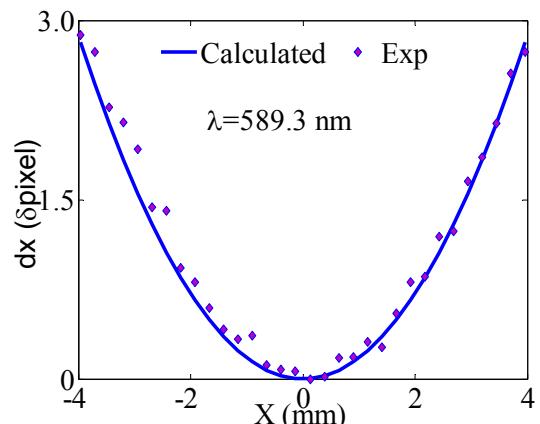


Figure 3 Wavelength shift due to aberration of the short-focal length spectrometer.

The shift is the average of the spectra of Na  $\sim$  589.0 and 589.6 nm, and the maximum shift can be up to  $\sim$ 2.8 pixels, as shown in figure 3. Besides, the dispersion of the spectrometer is measured by mercury, neon and hydrogen lamps, as shown in figure 4. The reciprocal linear dispersions are around 0.14 and 0.088 Angstrom/pixel at 400nm and 660 nm, respectively. Good consistent between the measured and the simulated results are achieved.

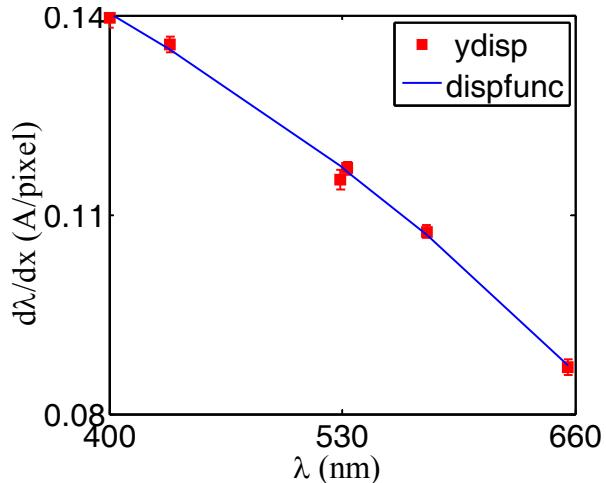


Figure 4 The reciprocal linear dispersion of the spectrometer

In the 2013's experimental campaign, the C VI (529.05 nm,  $n=8-7$ ) charge-exchange recombination line is chosen for the measurement of the ion temperature, bulk plasma rotation and their profiles during the NBI heating. Initial measurements show that the CX signals have enough SNR to obtain the radial profiles of ion temperature and plasma rotation simultaneously. In shot 22535, the frame rate is 125 Hz and the typical spectra are shown in figure 5. During the phase without the NBI, the intensities of CVI line emission are weaker in the core channels (CHN04) than those in the edge (CHN 27), as shown in figure 5(a); and the emissions from the core channels are obviously broader than those from the edge channels, as shown in figure 5(b). The spectra are analyzed by CXSFIT code. The ion temperature and plasma rotation can be obtained routinely, as shown in figure 6. The C III line emission (530.4 nm,  $n=8-6$ ), which is from the plasma edge, is utilized as reference when calculating the toroidal rotation. The spatial resolution is around 1~1.5 cm. As the spectrometer features high temporal-spatial resolution, issues about internal transport barrier (ITB) are under study.

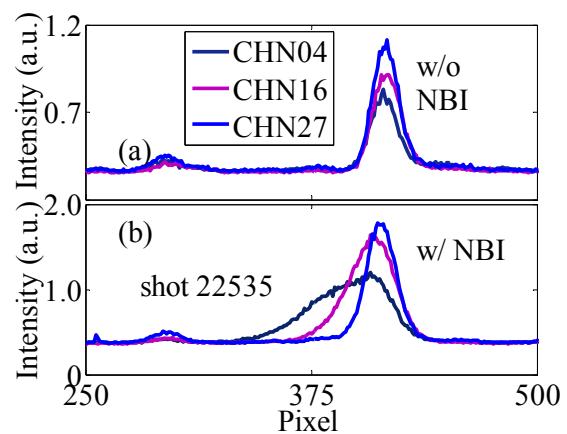


Figure 5 Typical spectra of CXRS

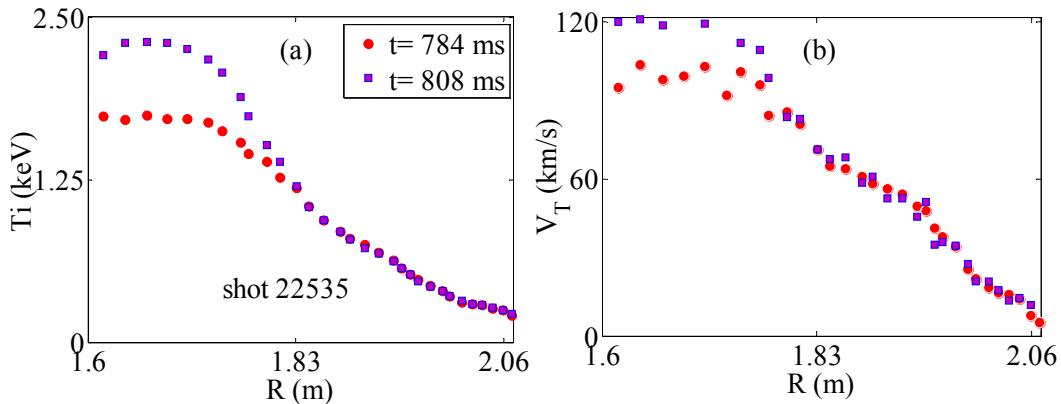


Figure 6 Typical ion temperature and toroidal rotation profiles

The spectrometer also can be utilized as main part of motional Stark effect (MSE) polarimetry. By applying four sets of collection optics and four polarizers orienting respectively at 0, 45, 90 and 135 degrees with respect to the horizontal direction, the magnetic field pitch angle can be derived [2]. The magnetic field pitch angles at 7 spatial points in the plasma are obtained during the pilot experiments. As the Stark-effect of the Balmer-alpha ( $H_\alpha/D_\alpha$ ) pattern of hydrogen is obtained, both the direction and the strength of the magnetic field can be measured simultaneously. More details of the magnetic field pitch angle are under analyzing.

### 3. Summary

A 32/64-channel CXRS system has been developed; the temporal and spatial resolutions are up to 8 ms and 1 cm, respectively. The system also can be used as MSE polarimetry, and 7 spatial channels of magnetic field pitch angle are available.

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### References

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