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First Charge Exchange Recombination Spectroscopy Diagnostic in HL-2A Tokamak *

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Spatially resolved measurements of ion temperature are crucial for understanding plasma dynamics. A charge exchange recombination spectroscopy diagnostic system based on a heating neutral beam is installed on the HL-2A tokamak. An optical collection system is designed in accordance with the actual geometry of HL-2A and the CVI 529.2 nm ($n = 8 \rightarrow 7$) charge-exchange recombination line. Preliminary measurements show that the CX signals have enough signal-to-noise ratio (SNR). The ion temperature and its profiles are obtained through this system for the first time.

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Ion temperature and its profiles are not only important parameters in tokamak plasma, but also necessary for a better understanding of plasma dynamics, especially for the estimation of the thermal transport of ions. Several diagnostics have been developed to measure the ion temperatures and profiles. Charge exchange recombination spectroscopy (CXRS) is one of the standard diagnostics equipped with neutral beam injection (NBI) in several magnetic fusion devices.[1−8] After the neutral beam injects into plasma, the electron is transferred from a neutral atom (e.g. hydrogen or deuterium) to an impurity ion which is fully stripped (e.g. C^{6+}, O^{8+}). During this transfer, the electron typically winds up in an excited state (high energy level) of the impurity ion, and then the ion will emit radiation at discrete energies. These line emissions are Doppler-broadened as a result of ion thermal motion. These emission line shapes are used to extract values for the impurity ion temperature. The measurements of CXRS can be made with good spatial resolution because the light emission due to charge-exchange excitation is localized at the space occupied by the neutral beam.

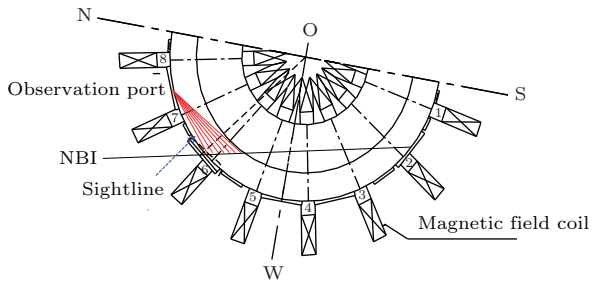


Fig. 1. Arrangement of NBI and CXRS diagnostic on HL-2A.

The HL-2A device with two closed divertors is the first divertor tokamak in China.[9−11] It was successfully constructed in 2002. The major radius is $R = 1.65$ m and the minor radius is $a = 0.4$ m. The fixed and movable limiters and two domes of the divertors are covered with the graphite tiles. The surface of the shielding plates for the multipole coils has been covered with 2-D carbon fiber composite since the year of 2005. Therefore the carbon originating from the graphite wall is a dominant intrinsic impurity in HL-2A discharge. As a result, the CVI 529.0 nm ($n = 8 \rightarrow 7$) charge-exchange recombination (CXR) line is chosen as the preliminary wavelength for CXRS measurements because the fruitful carbon impurities will produce enough intensive signals to measure. Meanwhile, visible spectra allow multi-chord measurements to use visible spectrometers coupled to the plasma with lenses and relatively inexpensive fiber optic.[4,5]

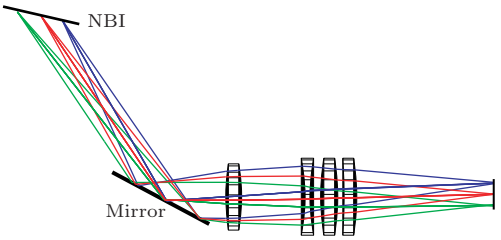


Fig. 2. Optical collection system and its ray tracing.

A wide-view CXRS diagnostic is designed in HL-2A to measure the ion temperature and profile in the equatorial mid-plane as shown in Fig. 1. The direct observation of the NBI-plasma interaction is difficult due to the port geometry, so a specially designed collective optical system is needed. Figure 2 shows the schematic diagram of this collective optical system.

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A part of the collective system, composed of a metal mirror and a lens, is constructed inside the vacuum chamber. This structure can effectively converge light flux and ensure the light emitted from edge through the windows. In order to keep a higher transmission of the optical system, a small window with a shutter is developed to protect the mirror and lens in vessel. The window is closed by the mechanical shutter and can be opened when needed. All lenses are well designed to reduce spherical aberration and coma.

The ray tracing of Fig. 2 shows how the optical system puts the beam onto an image plane. The light emitted from the region of beam-plasma interaction is received by the periscope window, reflected by the metallic mirror with diameter of 50 mm and focused through 4 lenses onto the fiber optic array. Then the light is conducted to the spectrometer by 35 m optical fibers. The distance from the lenses to the image plane matches the numerical aperture of the fiber optics. Each fiber has a core diameter of 200 μm. The fibers are placed vertically at the entrance slit of astigmatically corrected Czery–Turner spectrometer with a focal length of 0.5 m and an aperture of $f/8.0$. In order to optimize throughput and minimize stray light, the Optical Fiber Adaptors installed on a spectrometer, matches the $f/\#$ of the optical fibers to the $f/\#$ of the spectrometer. The optical charge exchange radiation is detected by an electron multiplying CCD (EMCCD), which utilizes a 1600×400 array of 16 μm square pixels. During the experiment, the grating of 2400 grooves/mm is used. The spatial resolution of the optical system, determined by the viewing chord-flux surfaces intersection at the beam position, is about 3 cm in the plasma core and about 1 cm at the edge. There are 9 horizontal viewing lines for profile measurements in this experiment. A low pressure Neon lamp is applied for the wavelength calibration and determination of spectrometer dispersion about this system. Figure 3 shows the typical spectrum taken by the system.

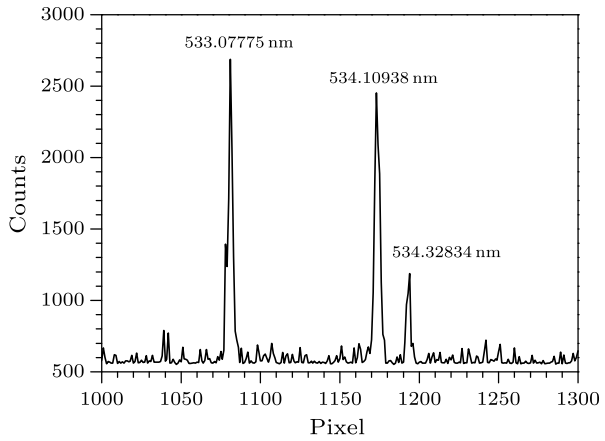


Fig. 3. Spectrum lines of Neon used to calibration.

Figure 4 shows the typically emission detected by the CXRS system (integration time: 50 ms). The useful signal CXRS diagnostics is radiation related to charge exchange with the neutral beam, while the background noise is the bremsstrahlung continuum. In order to assess this diagnostics. Figure 4 also shows the intensity of the signal and the noise during the measurements. CXRS measurement experiences at JET show that reliable CXRS measurements are possible when SNR reaches or goes above the value of about 10.[12] As seen from Fig. 4, the measurement results satisfy this request. During the neutral beam injection, in addition to the strong local active CX (ACX) emission at the beam intersection, there is an unwanted background which names passive charge exchange (PCX). The PCX emission layer locates inside the separatrix.[13] The PCX emission is from the processes, i.e. excitation by impact reactions and PCX reactions with neutrals from the wall. The typically emission intensity is shown in Fig. 5. The signal is given by the difference of the signals detected with and without beam injection (integration time: 50 ms). A narrow spectrum of PCX is observed to be representative of the low temperature at the edge. Normally the ACX intensity is 60% of the detected signal as shown in Figure 5 on HL-2A. The ratio between this active signal and the background plasma emission (A/P ratio) is about 2, and it can make the measurements available.[14]

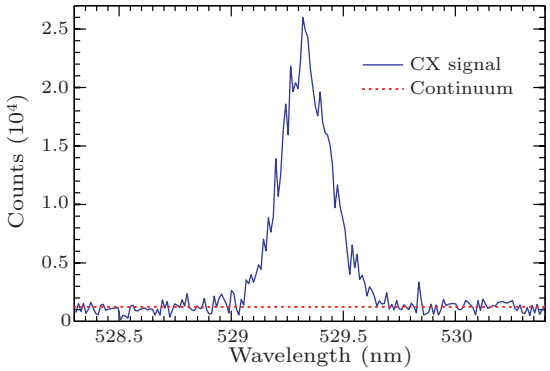


Fig. 4. Typical detected signal by CXRS system.

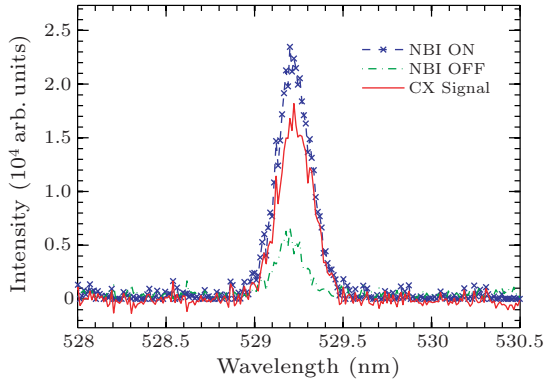


Fig. 5. Typical ACX and PCX signal.

In the experimental campaign, the hydrogen or

deuterium atomic beam at its energy of 35 keV has been injected into the torus. The NBI experiment is performed in the range of plasma density from $0.5 \times 10^{19}\,\mathrm{m}^{-3}$ to $2.5 \times 10^{19}\,\mathrm{m}^{-3}$, plasma current 100–200 kA and toroidal magnetic field 1.0–2.0 T.[15] The ion temperatures and its profiles are observed under different conditions. Furthermore, several shots of helium discharge are also measured. A "Bolm" model is employed to obtain impurity temperature and its profile.[7,16] Normally, the ion temperature T_i in the core is in the range 600–1400 eV during neutral bean injection with deuterium gas discharges measured by CXRS. It is determined by the power of heating (NBI and ECRH), density and other discharge parameters. However, the core ion temperature at a very low electron density (e.g. $0.5 \times 10^{19}\,\mathrm{m}^{-3}$) is usually lower, because the power of neutral beam is hardly absorbed by the plasma.[17,18] The highest core ion temperature we observed is 2.7 keV in the experiment. Figure 6 shows the ion temperature profile of this shot. This shot is helium discharge. In this case the neutral beam is much more efficient to heating ion instead of electron at the power of 35 keV;[17,18] the peak ion temperatures exceed the electron temperature by more than a factor of 2. The H-mode has been obtained successfully in HL-2A under the NB injection power of 0.7 MW with deuterium discharge. Figure 7 shows the ion temperature profile in L-mode and H-mode of shot 11616. The ion temperatures are much higher than the value of the L-mode due to the improvement of the confinement during the H-mode.

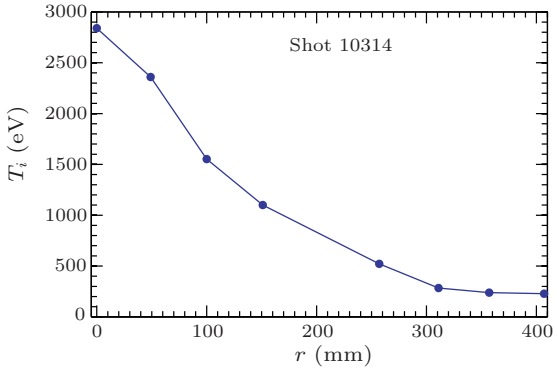


Fig. 6. Highest core temperature and profile in 2008 experimental campaign.

In summary, CXRS has been proved to be very valuable in determining ion temperature during NBI on HL-2A tokamak. Based on the measurements, the signal with enough SNR can be achieved. The raw data also indicate that the reliable T_i measurements can be obtained because the ratio between the active signal and the background plasma emission (A/P ratio) is also adequate. An analytical model for spectral line fitting is developed to accurately extract the parameters for obtaining the ion temperatures and its profiles. This model includes all the Zeeman components of the impurity spectral line, Doppler broadening and convolution with the instrument function of the spectrograph. The ion profiles have been obtained during NBI. However, on HL-2A the fibers are simply inserted between the entrance slit jaws, so the system etendue is determined by the area of the fiber's core and the solid angle or NA of the spectrometer. In order to reach a higher time resolution and spatial resolution in the experiment, especially in the pedestal physics research during the H-mode, either larger core diameter fibers or fiber bundles matching with a high-throughput transmission grating spectrometer are urgently needed. In addition, the measurements of plasma rotation velocity by this system will be carried out in the next step.

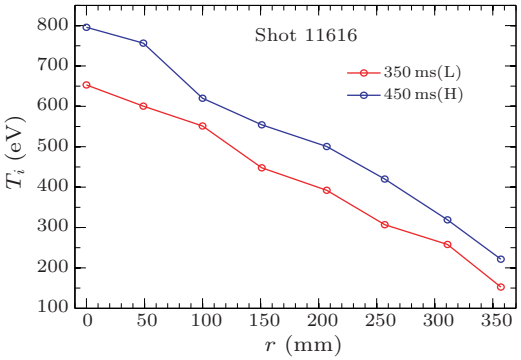


Fig. 7. Ion temperature profiles in the H- and L-modes.

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