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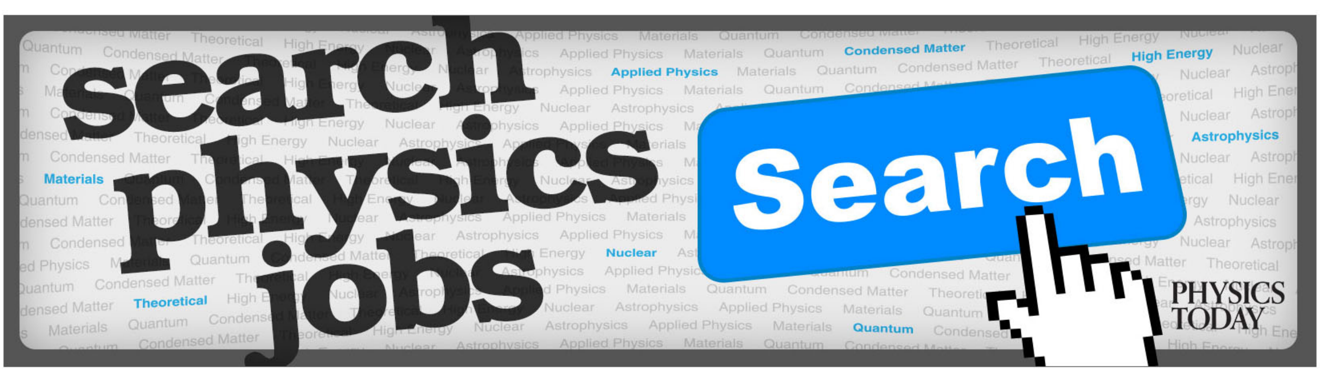

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Development of a charge exchange recombination spectroscopy method for determination of ion temperature from H_α line broadening in the Hanbit mirror device

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Ion temperatures can be determined from H_α line broadening measured by charge exchange recombination spectroscopy on Hanbit, a mirror device. Since the H_α line emission from hydrogen atoms in plasma edges is much larger than that of the charge exchange recombination emission of ions, the line shape of the latter is submerged into the former when measured by an array detector such as a CCD detector. Thus, a notching filter in front of a detector is needed to block out the central region of the emission line. An optical fiber array detector, which works as a notching filter as well as an array detector, has been developed, since the transmission characteristics of commercial notching filter are not suitable for the line-broadening measurements. The design concept of the optical fiber array detector is described, and the feasibility to determine ion temperatures from the H_α line broadening measurements is estimated. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1537445]

I. INTRODUCTION

The ion temperature is one of the main parameters of a fusion-relevant plasma, and various methods have been developed to measure this quantity. For contemporary large fusion plasma devices, charge exchange recombination spectroscopy (CXRS)[1] has become a standard method to measure ion temperature profiles. Since CXRS is normally applied to spectral lines emitted from hydrogen-like light ion impurities such as C, O, He, etc., it is difficult to apply CXRS to a plasma device in which the plasma temperature is not high enough to fully strip light impurities.

Hanbit is a magnetic mirror device in the Korea Basic Science Institute.[2] Although the target parameters for the Hanbit device are a 1 keV ion temperature, a 200 eV electron temperature, and a plasma density of 5×10^{12} cm^{-3}, only the plasma density target has been reached. CXRS is not normally applied to the Hanbit plasma, since the light impurities are not fully stripped due to the low electron temperature, and since it has various ionization stages the passive emission lines of which fall on the CXRS emission lines and disturb the local information of ion temperatures. Even conventional methods, such as passive emission spectroscopy and the charge exchange neutral particle analyzer (CX-NPA), are also problematic in the Hanbit plasma, where the ion temperature is less than 100 eV. The line shape of impurities measured by passive emission spectroscopy tends to be distorted by unknown impurity lines, the CX-NPA does not work well due to too low stripping efficiency, and in the case of the time-of-flight method, it is difficult to calibrate the neutral particle sensor for an energy less than 100 eV.[3] What is worse, these methods measure a line-integrated quantity, even though the measurement can be performed. Thus, a method to apply CXRS to the main ions, that is hydrogen ions in the Hanbit device, has been developed.

Several problems also arise on the application of CXRS to the main ions:[4] energy dependence of the cross section for charge transfer,[5] the halo effect,[6] and interference of the strong edge emission.[4] The first one can be ignored for an ion temperature much less than the injected neutral beam energy and for a nonrotating plasma. The second one is also negligible in plasmas with low ion temperatures of less than several kilo-electron-volts.[7] However, the third one can hardly be avoided. The emission line intensity in the plasma edge is much larger than that of the CX emission line. The very strong edge emission does not allow a high sensitivity of the spectrometer system, since otherwise the detector may saturate in an uncontrolled manner. Thus, a fiberoptic array detector has been developed in order to obtain a CX emission line shape without the strong edge emission. The design concept of the optical fiber array detector is described, and the feasibility to determine ion temperatures from the measured H_α line broadening is estimated.

II. CONCEPT OF OPTICAL FIBER ARRAY DETECTOR

A spectrometer is usually equipped with a CCD detector, since the CCD detector has a great advantage to simultaneously register the entire spectral band transmitted through the spectrometer. In the case of the CXRS measurement, the CCD detector registers the line intensities emitted from both hot neutral atoms of the CX recombination and cold neutral atoms residing in the plasma edge. The edge emission contributes mainly to the line center and the CX emission to the wings of a measured spectral line. The edge emission intensity is normally much higher than that of the CX emission, so the latter intensity may be submerged into the former one. If the gain of detection system is increased to obtain a better

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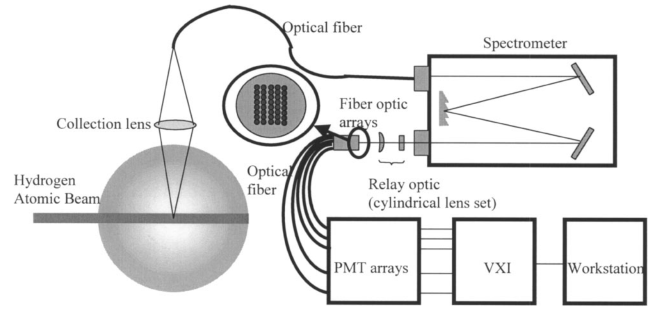

FIG. 1. Schematic of CXRS system with fiberoptic array detector.

signal from the line wings, the CCD detectors may saturate due to the line center intensity. In order to get a better line wing signal with a moderate gain of the detection system, the intense line center has to be blocked out by a notching filter that ideally blocks the spectral band in a square form. However, this type of notching filter does not exist at present.

A fiberoptic array can be used for such an ideal notching filter. The fiberoptic array consists of a number of fiber bundles, each of which corresponds to a spectral channel, and is connected to a photomultiplier tube (PMT) as shown in Fig. 1. Figure 2 shows schematically how the fiberoptic array detector works. In Fig. 2(a), the solid line is the original line shape and the closed circles indicate the measured line shape with the complete set of spectral channels of the optical fiber array. Since the gain of each PMT can be adjusted independently, the gains of the PMTs corresponding to the line center region have only to be set to zero in order for the line center region to be blocked out, as shown by closed circles in Fig. 2(b). On the other hand, the gains of the PMTs corresponding to the line wings can be increased to a degree to obtain a better signal of the line wing, as shown by open circles in Fig. 2(b). Thus, the full line shape of CX emission can be reconstructed by fitting the data points of the measured line wings.

The spectral channels for which the gain should be set to zero can be chosen by comparing the contribution of the edge emission with that of the CX emission. Assuming all the line shapes are Gaussian, the spectral distance $\Delta\lambda_{0.1}$ between the line center λ_0 and a spectral location $\lambda_{0.1}$, where the intensity ratio $I_a(\lambda)/I_{\mathrm{cx}}(\lambda)$ of the edge emission to the CX emission is less than 0.1 (equivalent to an error of 10% in the measurement) is

$$\Delta\lambda_{0.1}=|\lambda_{0.1}-\lambda_0|=\sqrt{\frac{\ln(10I_{a,0}/I_{\mathrm{cx},0})}{T_i/T_a-1}}\sqrt{\frac{2T_i}{mc^2}}\lambda_0. \quad (1)$$

Here, m, c, $I_{\mathrm{cx},0}$, $I_{a,0}$, T_i and T_a are the atomic mass, the velocity of light, the CX emission intensity at the line center, the edge emission intensity at the line center, the ion temperature, and the cold atom temperature, respectively.

When a line shape is measured by the fiberoptic array as shown in Fig. 1, the entrance slit of the spectrometer is imaged at the exit of the spectrometer and the slit image is then transferred onto the fiberoptic array through relay lenses with a relevant magnification. By adjusting the magnification factor, the spectral resolution $\Delta\lambda$ of a channel of the fiberoptic array can be determined easily by

$$\Delta\lambda=\frac{1}{D_\lambda}\frac{d}{M}, \quad (2)$$

where D_λ is the linear dispersion of spectrometer (mm/Å), M is the magnification factor of the relay lens, and d is the diameter of optical fiber (mm).

III. FEASIBILITY OF OPTICAL FIBER ARRAY DETECTOR ON HANBIT

The fiberoptic array for the measurements on Hanbit consists of 15×50 fibers. There are 15 spectral channels, and each channel consists of 50 fibers. The 50 fibers constitute five spatial channels, each of which consists of 10 fibers. Thus, due to the five spatial channels, five spatial points in the plasma can be measured simultaneously. Each channel is connected to a PMT in a PMT array; that is 15 columns of PMTs for 15 spectral channels and 5 rows of photomultiplier tubes for 5 spatial channels. All the channels are calibrated relative to each other.

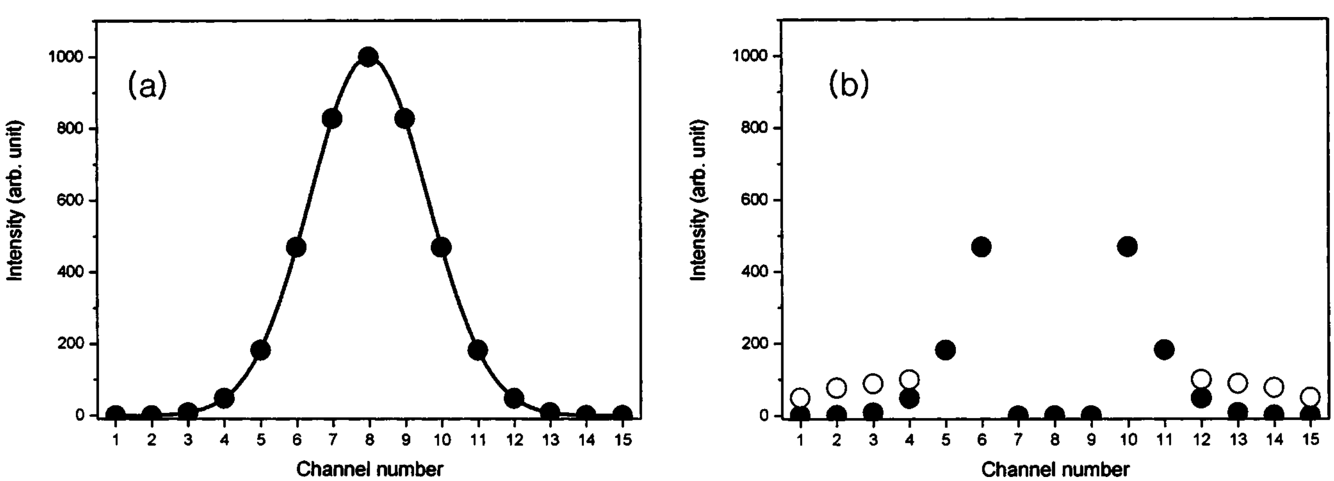

FIG. 2. Concept of the fiber optic array detector. (a) A spectral line (solid line) and the data points measured by the fiberoptic array detector with all the channels biased at high voltage (closed circles). (b) Central region blocked out by setting the PMT gain to zero (three center closed circles) and enhanced line wings by selectively increasing the PMT gain (open circles).

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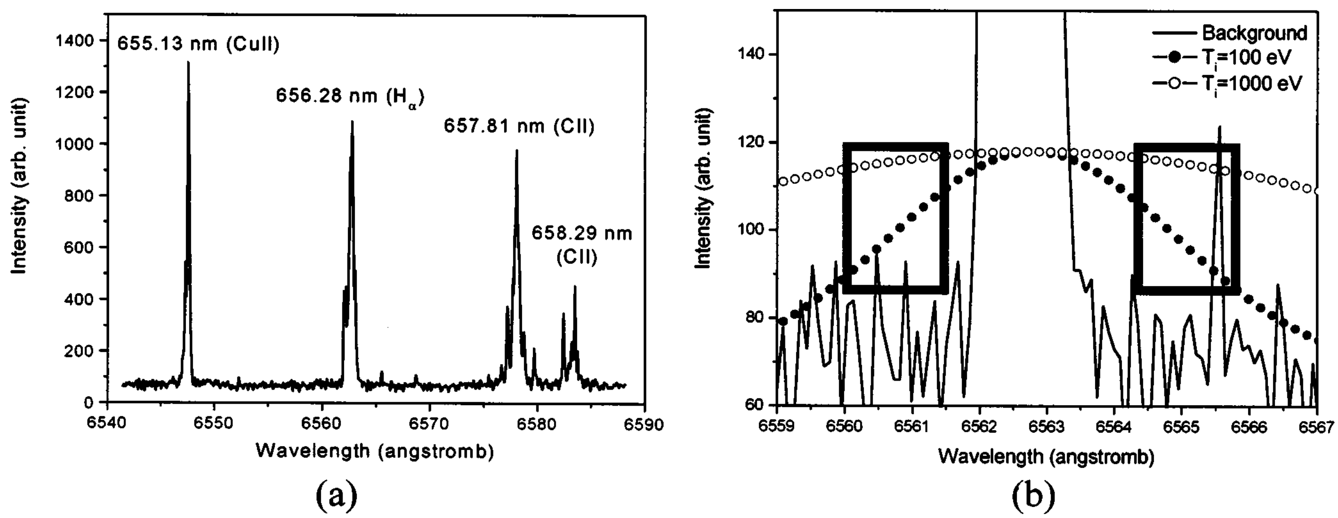

FIG. 3. (a) Measured background spectrum around H_α line in the Hanbit plasma. (b) Detection window and simulation of the CX emission lines for ion temperatures of 100 and 1000 eV.

The fiberoptic array is connected through a relay lens to the exit of a 1-m-focal length Czerny–Turner spectrometer equipped with a grating of 1200 grooves/mm. According to Eq. (2), the spectral resolution of each channel is 0.21 Å for a magnification factor of 4, since the linear dispersion of the spectrometer is 0.12 mm/Å and the diameter of an optical fiber is 0.1 mm. The spectral bandwidth of 15 channels with a distance of 0.1 mm between channels is 6 Å.

Since many of hydrogen atoms in the plasma edge are Franck–Condon atoms,[8] each hydrogen atom departs with an extra kinetic energy of 2.3 eV owing to the H_2 dissociation energy of 4.5 eV. Thus, from the conservative point of view, the kinetic energy of 2.3 eV can be taken as a maximum atom temperature of T_a. For $T_i = 100$ eV, the spectral distance $\Delta\lambda_{0.1}$ is 1.41 Å with a peak intensity ratio $I_{cx,0}/I_{a,0}$ of 10^{-3} in case of the H_α line emission according to Eq. (1). This means that the intensity of the line wing at a spectral distance larger than 1.41 Å in a measured spectral line has originated mainly from CX emission. The spectral distance of 1.41 Å is equivalent to seven spectral channels in the central region of the fiberoptic array in the case of a spectral resolution of 0.21 Å per channel, and thus four channels on each side are active for line wing measurements. Figure 3(a) shows the measured background spectrum around the H_α line, and Fig. 3(b) shows the data acquisition windows in rectangular shapes on both sides of the line center, according to the above calculation of the spectral distance and spectral bandwidth.

IV. DIAGNOSTIC NEUTRAL BEAM SYSTEM

A diagnostic neutral beam system has been developed to support CXRS.[9] The neutral beam equivalent current is 0.65 A at a maximum beam energy of 29.8 keV. The beam cross-sectional diameter is 10 cm at a distance of 2.3 m from the beam extraction surface of the ion source. The beam divergence is 1.23°. The neutral beam consists of three energy components—, full, one-half, and one-third—and the maximum fraction of the full-energy component is 52%. The neutral beam can be modulated in a frequency of 50 Hz, as

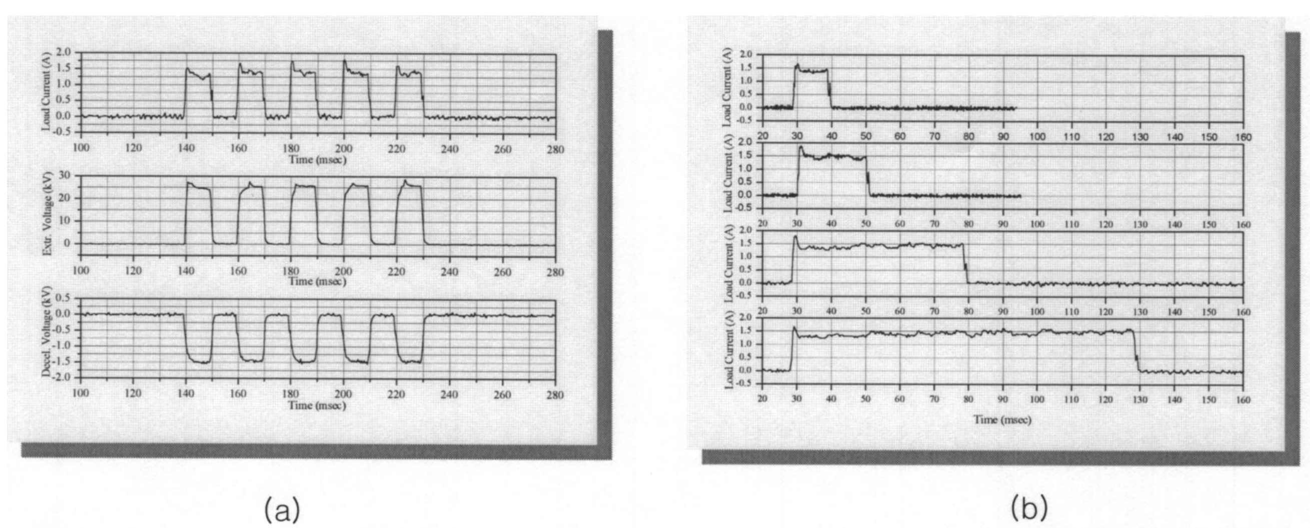

FIG. 4. (a) Wave forms of 50 Hz modulation. (b) Wave forms of pulse width variation.

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shown in Fig. 4(a), in order to obtain a better signal-to-noise ratio by removing the background signals detected in the beam-off period. The neutral beam system also has the capability of extending the beam pulse width from 10 to 100 ms with a single beam pulse, as shown in Fig. 4(b).

V. SUMMARY AND CONCLUSIONS

The main ion temperature profile can be measured with the fiberoptic array detector coupled to a CXRS system. When the gain of detection system is increased to measure low line wing intensity, the problem of the saturation of CCD detectors due to the high central peak intensity can be avoided. The central peak can be exactly removed in the fiberoptic array detector. Very fast temporal resolution of a few nanoseconds to measure transient plasmas can also be obtained by using the fiberoptic array detector.[10]

A diagnostic neutral beam system has been developed to support CXRS with versatile capabilities, such as beam modulation, to enhance signal-to-noise ratios and pulse width variation.

The main ion temperature profiles are ready to be measured in the Hanbit device, since the detection system is equipped with an optical fiber array detector and the diagnostic neutral beam system has been developed and installed.

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