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Status of two-dimensional ion velocity measurement system in NSTX

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A two-dimensional ion velocity measurement system is being developed under a US-JAPAN collaborative activity. The diagnostic is used to determine Doppler shifts from the intensity ratio of a visible line from the same light source, measured with two interference filters that have different transmission pass bands. A fast visible camera is used as two-dimensional detector. The system was tested using an NSTX He discharge, and images of the plasma in He II light were successfully obtained. The intensity ratio over a 1cm^2 region on the center stack remained almost constant, and the intensity ratio of a 1cm^2 region near plasma edge changed during the discharge. The next step is to get a two-dimensional ion velocity map after the system is calibrated.

Keywords: two-dimensional ion velocity, fast camera, NSTX

1. Introduction

It is widely believed that turbulence in the plasma periphery is closely related to plasma confinement. The turbulence, in turn, depends on conditions in the plasma edge. This includes the presence or absence of plasma flows. A conventional method for measuring their spatial dependence would be to send signals from individual sightlines into a large number of spectrometers. They would provide the spectral resolution required to determine the Doppler shift of an emission line, and hence to determine the plasma velocity requires large arrays of individual detectors.

A much simpler and economical approach has been developed by one of authors (S. Paul). He showed that the Doppler shift can be deduced by taking the ratio of the intensity of line emission passed through two filters, each of which have pass bands that are slightly shifted relative to each other. The feasibility of the approach was demonstrated with discrete detectors, using the He II (468.6nm) line (Shifted Wavelength Interference/Filters Technology [1]). The technique is now being extended to two-dimensional measurements, using a fast visible camera in place of an array of individual detectors.

The work began as a US-JAPAN collaborative activity on the National Spherical Torus Experiment (NSTX) at the Princeton Plasma Physics Laboratory in 2005. In this paper, the status of this program is reported, including recent progress involving He II emission images that were taken in NSTX He discharges using this system. The analysis results show that this measurement system will be effective after careful calibration, and this measurement is very promising for two-dimensional ion velocity measurements.

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2. Sensitivity calibration of optical system without filters

Principle of measurement of this system is described in appendix. To test this system, it had to be installed with horizontal view that included the center stack to measure the plasma flow near the inner major radius of the discharge. Figure 1 shows a schematic for the installation on NSTX. Before installation, the relative sensitivity and signal noise had to be checked.

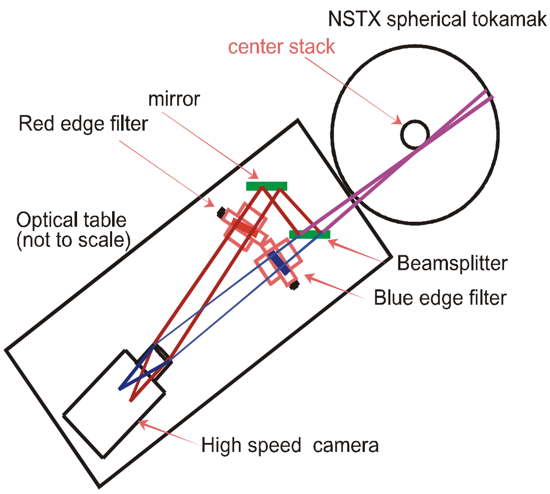

Fig. 1 Two-dimensional ion flow measurement system in NSTX

The intensity ratio is the key issue for this measurement. For an ideal calibration, the whole system should be checked with He II light (~468.6nm, blue color). However, we did not have any strong He II light source, so we prepared a blue sheet with a white light (DC battery light: commercial product) behind it instead, and took images without interference filters. Then we can almost get the sensitivity for blue color region of the camera sensor. The transmission rate of the filters was already measured. Therefore, the total sensitivity was obtained by simply multiplying the sensitivity of the optics without filters, from the blue sheet and white light, and transmission rate of filters, adjusted for the angle of incidence of the light passing through them.

Figure 2 shows a typical blue sheet image without any interference filters. The upper figure has 1024x1024 pixels, taken at 1000FPS (Frames per second). Near the center, two blue sheet images are seen. The images correspond to the two paths shown in Fig.1.

At the center pixel in both images, the intensity ratio from left to right is 29.1-33.4%. This value depends on time and calculation region size. The main reason for this error is sensor noise. Figure 3 shows time dependence of the intensity in the center region at various sizes. The intensity decreased with time due to DC battery consumption for the light; therefore, a third degree polynomial least squares fit to each data set was performed.

The standard deviations of total intensity at various sizes with different calculation points are shown in Fig. 4.

The standard deviation at one pixel is typically a few percent. However, it decreases with increasing number of calculation points, and at 25 calculation points the standard deviation is less than 0.5%. This suggests that there is not any correlation with pixel noise. In fact, the correlation between the calculation at one pixel and its adjacent pixels was nearly zero (a few %). Also, it appears that with more intensity, the higher the signal-to-noise (SN) ratio.

Fig.2 Blue sheet image with white light (1000FPS) Plastic blue sheet (commercial product) was used instead of white paper.

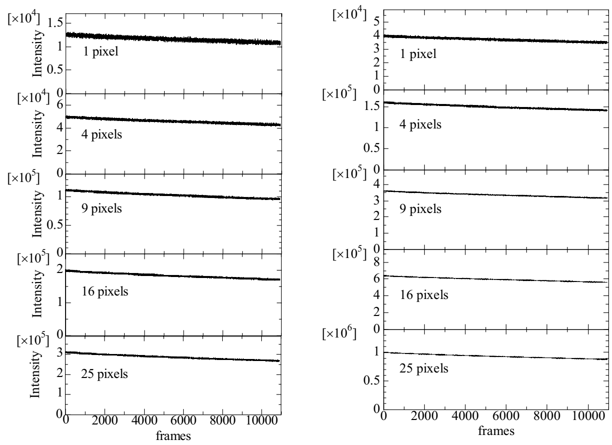

Fig.3 Total intensity at the center region of left and right images

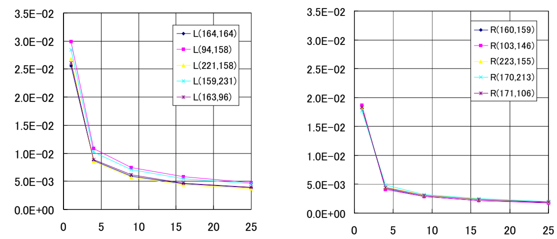

Fig.4 Standard deviation of total intensity at various sizes 5 calculation pixels were chosen at the center and 4 positions at the periphery in both images.

If we take 25 pixels (5x5 pixels), the intensity ratio is 30.0-31.5%. The relative intensity accuracy is 0.75% (=(31.5%-30%)/2). The resolution of absolute velocity of this measurement depends on the relative intensity accuracy of both images. Therefore, in this case the resolution of ion velocity is ~7.5km/s without the effect of interference filters (see Appendix).

3. Results and discussion

The first attempt to get He II emission images has done using NSTX He discharges. Figure 5 shows a typical waveform of an NSTX He discharge.

In this experiment toroidal magnetic field is below 0.38T, because the camera was affected by the magnetic field. In the near future a shield for magnetic field is needed.

Figure 6 shows two He II emission images obtained with 250 FPS. The right image shows the center stack and tiles clearly; however, in the left image the boundaries between tiles are not clear. It seems the right image is in focus, but the left image is out of focus. The reason for this is that the optical paths of the left and right images are different (see Fig. 1). The result of this out-of-focus effect is that a pixel in the right image corresponds to ~3x3 pixel region in the left image. Therefore, the He II emission of a pixel in the right image is somewhat distorted in the left image. Comparing the tile image and its actual size, the spatial resolution is determined to be ~2mm/pixel. Therefore, it is necessary to calculate the region over which the light intensity does not change abruptly over a 2mm scale.

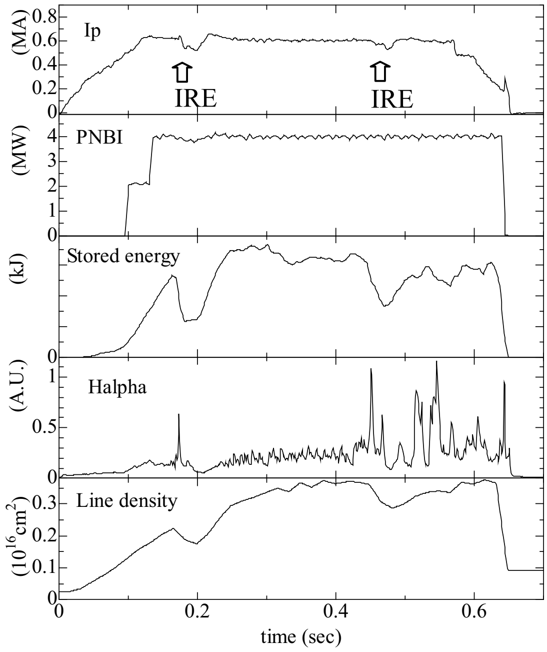

Fig. 5 Typical waveform of He discharge parameters
During NBI IRE occurs at ~0.18s and after IRE there are many ELMs.

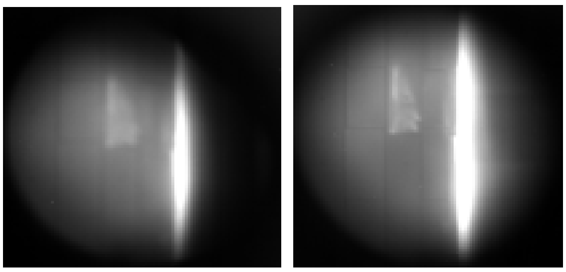

Fig. 6 He II emission from NSTX He discharge with 250FPS
Right image is taken through a blue edge filter and left image is obtained through a red edge image.

Intensity ratios were taken over 5x5 pixel regions. Figure 7 shows the row of 5x5 pixel regions in the two images. Each row has 28 columns. This means 140x5 pixels in total in the region in the right image. The apparent vertical length and horizontal length are about 1cm and 28cm, respectively. In the left image, the horizontal distance corresponded to about 145 pixels; therefore, the left image is 3% larger than the horizontal distance in the right image. The two images are almost symmetric about the center; therefore, the distortion effect may be small. Apparent vertical lengths in the right and left images are about the same.

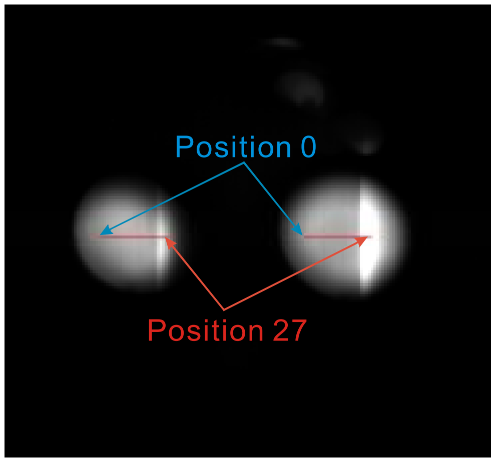

Fig. 7 He II emission images with 2000FPS
ROI is shown with red line.

The regions are numbered from 0 to 27 from left to right. The total intensities of these regions were compared. Information on the region numbered 0 and 27 are shown in Fig. 8 and 9, respectively. They show the total intensity of these regions and the ratios of the total intensity in the left image to the total intensity in the corresponding right image. In Fig. 8, the region numbered 0 is on the CS tile, and that of 27 is near inner wall plasma edge in Fig. 9. If the ion velocity did not change during the discharge, the ratio should not change. On the other hand, if the ion velocity changed during the discharge, the ratio should change.

The ray from the region numbered 0 is almost normal to this system. Therefore, it is reasonable that ion velocity along to the ray direction should be small. As a result, the ratios from these positions should be almost constant. In Fig. 8 the ratio looks constant except at 0.1~0.15s, and 0.2-0.25s. Also the ratio oscillates frequently during ELMs of 0.25s to 0.45s. The first period corresponds to NB injection, and the second period corresponds to recovering period after the first IRE, which occurs at 0.165sec at stored energy. The common reason of these two periods is that the intensity of the left image is very small. There is no change during the second IRE before 0.5s.

In general during IREs and ELMs, there could be enhanced illumination of the tiles that are associated with MHD phenomena. Such effects must be investigated further before definitive conclusions about flow velocities can be made. However, during IRE the ratio was almost constant in Fig.8. In the raw images during these periods the first half period was very bright due to MHD phenomena, but the last half period was dark because plasma was diminished. If the detection lights through both filters were almost random reflection from other region, there would be ‘no Doppler shift’ light. This should be accounted for in future work.

Figure 9 shows the ratio near the inner wall (center stack) plasma edge. The ratio rapidly changed at the NB injection time, IRE and ELMs periods, and discharge end. Except ELMs periods, total intensity of left image is also very small. That was the common reason for every 28 regions numbered 0 to 27 in Fig.7.

The ratio corresponding to 'no Doppler shift' expected by multiplying the interference filter transmission rate and calibration result should ~0.5 in this time; unfortunately, this ratio was not included for the tile region shown in Fig. 7. Possibly, the interference filter angle was not normal to the central ray. However, it was reasonable that the interference filter did not move during the discharge, because the constants to be assumed in Fig.8 and 9 did not change.

As already mentioned, the 'no Doppler shift' ratio depends on the location of the region because the rays directed to the system are different in relative orientation. The time dependence of these ratios, however, seems to be reasonable.

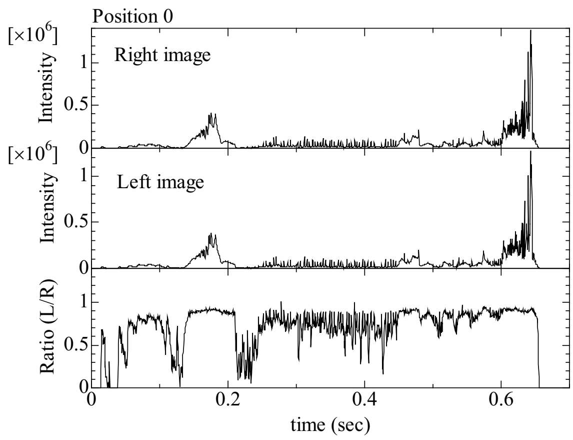

Fig.8 Time evolution of the intensity ratios on tile on the center stack

The ratio was taken to the intensity of left images to corresponding to right images at position 0 in Fig.7

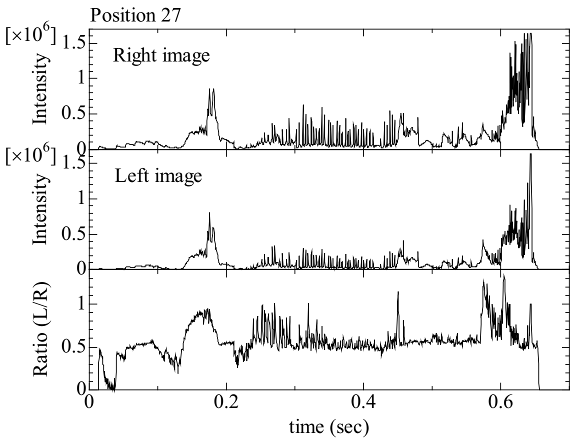

Fig.9 Time evolution of the intensity ratios near plasma inner edge

The ratio was taken to the intensity of left images to corresponding to right images at position 27 in Fig.7.

If the 'no Doppler shift' ratio is determined everywhere in the image and two filters are tightly secured, it should be possible to calculate two-dimensional ion velocity maps. As a matter of course, the calibration should be performed very carefully.

The system can be modified in two ways. One is that the same path lengths between the left image and the right image should be insured. This can be realized using more mirrors (at least one) and/or a coherent image fiber bundle. When a fiber bundle is used, it is very difficult to meet the fiber pixel to the sensor pixel. Therefore, it is preferable to use more mirrors. The second point is the magnetic field shield for the camera. This is a more straightforward problem to solve.

4. Conclusion

Two-dimensional ion velocity measurement system is being developed in NSTX as a US-JAPAN collaborative activity. Here the status of this system is reported, including recent progress. In principle it is concluded that two-dimensional ion velocity maps can be determined after further modifications and careful calibrations.

ACKNOWLEDGMENTS

This work is performed under US-JAPAN collaborative activity.

Appendix Principle of measurement

The detailed analysis of this method is described in Ref [1]. In this paper the brief principle is introduced.

Transmission of two filters used in this system is shown in Fig. A. In Fig.1 a part of detector views through a filter with a positive slope, the other has a negative slope. The Doppler shift is a function of the only the measured signal ratio (see "shifted emission line" in Fig. A). Parameters include the two filter slopes and the relative gain. The relative calibration of the channels to each other means that terms which are constants (the filter, window and lens transmission, detector sensitivity, amplifier gain, and phase shift etc.) do not need to be known absolutely. Data analysis assumes that slope of filter in the region of the Doppler shift is perfectly linear. The Doppler shift is calculated from the change in intensity resulting from the emission line moving across the transmission passband of the interference filters. According to Ref [1] in this system 1km/s resolution needs below than 0.1% accuracy.

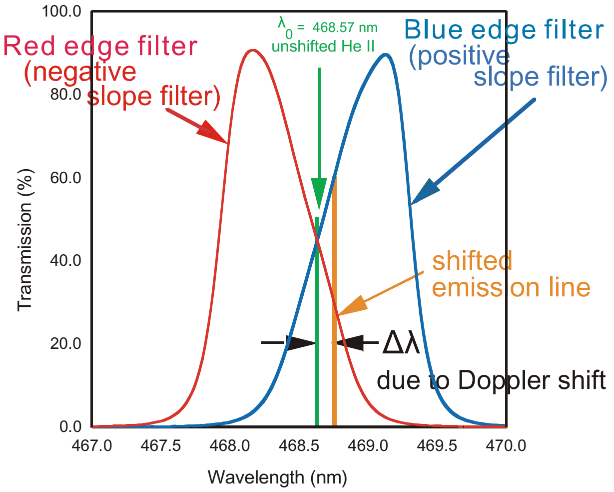

Fig. A Transmission rate of two filters

5. References

[1] S.F.Paul, Rev. Sci. Instrum. 74 (2003) 2098