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Combination of multichannel detection and fast time response in a multichord spectrometer

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(Presented on 19 March 1992)

A high resolution spectrometer has been used to measure simultaneously plasma impurity ion temperatures and rotational velocities, with submillisecond temporal resolution. The dual requirements of detailed spectral detection and fast time response are satisfied by having two detection systems viewing the same dispersed spectrum. The first is a multichannel system (e.g., a two-dimensional charge coupled device camera, for multichord detection) and the other an assembly comprising of three photomultipliers. A matched double spectrometer ($f=1.26$ m) is used to disperse the spectrum and giving an overall inverse dispersion of 0.04 nm/mm. The dispersive power is about $20\times$ greater than the more conventional systems and has a corresponding increase in *etendu*, or light throughput, for the same resolution. The combination has been successfully used for magnetohydrodynamics mode locking experiments on COMPASS-C tokamak where velocity shifts of ~ 30 km^{-1} were measured to an accuracy of ~ 1 km s^{-1} with a 40 μs time resolution.

I. INTRODUCTION

Observations of plasma fluid rotation in tokamaks, using Doppler spectroscopy of impurity ions, have been profitably used to measure momentum confinement,[1] radial electric fields,[2] and to investigate the effects of mode locking.[3] Recent interest[4,5] in all these areas has centered on the *changes* of toroidal and poloidal rotation, particularly during transitions between low to high energy confinement regimes (L- to H-mode transitions). Such observations require high temporal resolution.

Relatively fine scale effects such as poloidal rotation or toroidal rotation without neutral beams, require high accuracy and therefore high spectral resolution. Both of these criteria can only be met if the light intensity is sufficient to give an acceptable S/N ratio, to allow fine scale temporal and spectral measurements. This further requires a high *etendu* or light gathering ability from the diagnostic.

A high resolution spectrometer,[6] with a large *etendu*, has been used on the COMPASS-C tokamak[7] to measure simultaneously the rotational velocity and the ion temperature with submillisecond temporal resolution.

II. DESCRIPTION OF THE APPARATUS

A. The dispersive instrument

To achieve the high spectral resolution, two 1.26 m Czerney–Turner SPEX spectrometers are coupled together in series (see Fig. 1). The first spectrometer (3600 gr/mm grating) acts as a predisperser and limits the bandwidth entering the second spectrometer to ~ 1 nm. The second spectrometer contains a high dispersion *echelle* grating (79 gr/mm) operated in high order (~ 80). Together these give an inverse linear dispersion at the final image plane of 0.04 nm/mm (at ~ 300 nm). A beam splitter placed just prior to the exit of the final spectrometer allows simultaneous examination by two complementary detectors. One is a multichannel detector [an optical multichannel analyzer (OMA) or charge coupled device (CCD)] which is primarily for detailed spectral analysis [$\lambda/\Delta\lambda \sim 3\times 10^5$ in the ultraviolet (UV)], and the other, an arrangement of three photomultipliers, is for fast temporal resolution (~ 40 μs).

B. The triple photomultiplier detector

The dispersed Doppler broadened spectral line is divided into approximately three equal regions, by a pair of 45° knife edge mirrors (chevron slit). The three images fall

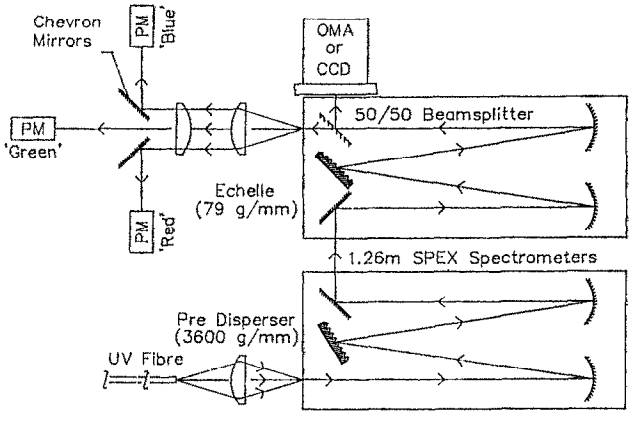

FIG. 1. Schematic illustration of the double spectrometer, showing the coupling of the predisperser and the high resolution echelle instrument. The system incorporates a CCD multichannel detector, for detailed spectral analyses, and a three channel photomultiplier system for fast time response.

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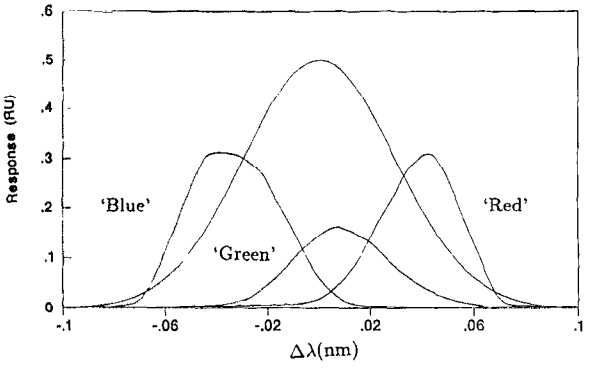

FIG. 2. The measured instrument function of the triple photomultiplier detector, with a typical calculated 100 eV Doppler broadened boron^{3+} (282.1 nm).

onto separate photomultipliers, here called the "red," "green," and "blue" channels.

The instrument-function profiles of the triple photomultipliers are measured by scanning mercury spectral lines (253.6 and 280.3 nm) across the chevron slit. This is shown in Fig. 2 with an example (calculated) 100 eV boron^{3+} impurity spectral line overlaid.

The operation of the triple photomultiplier system can be illustrated by considering, for example, if one started with a centered (nonrotating) spectrum at a particular temperature, as is shown in Fig. 2. Changes in the balance between the signals of the normalized red and blue channels (which are looking at the wings of the spectral line) would indicate shifts in the central wavelength location and therefore a shift in the drift velocity. Conversely, uniform changes that appear in both the normalized red and blue channels, relative to the central green channel, would signify changes in the full width at half-maximum (FWHM) of the spectral line, i.e., temperature variations. This is illustrated in Fig. 3, which shows the contrast between the photomultiplier channels as a function of drift velocity for a typical COMPASS-C impurity. In this case the impurity line is boron^{3+} (282.1 nm) present in

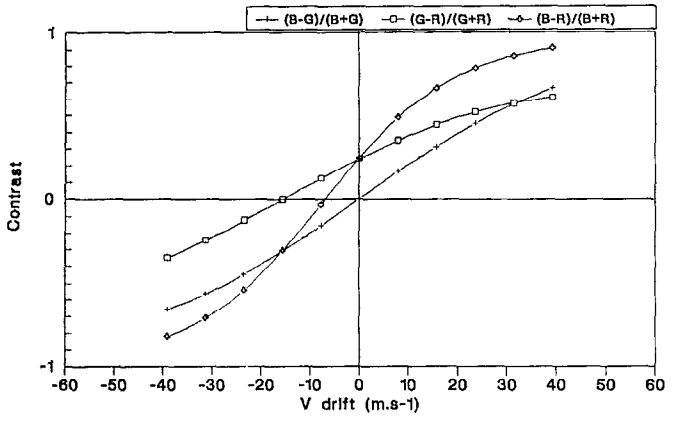

FIG. 3. The sensitivity of the triple photomultiplier signals to changes in impurity drift velocity, for boron^{3+} (282.1 nm) at a temperature of 60 eV.

COMPASS-C since boronization of the vacuum vessel.[8] In practice, there may be simultaneous shifts in temperature, drift velocity, and light intensity which complicate the analysis and is dealt with below.

C. The multichannel detector

The triple photomultiplier assembly alone cannot detect the presence of any interfering spectral lines, or other deviations from a presumed Gaussian line shape. To prevent this a multichannel detector is placed in parallel with the triple photomultipliers to view the spectrum in detail.

Multichannel detectors, such as optical multichannel analyses (OMAs) and charged coupled devices (CCDs), one- and two-dimensional photodiode arrays, generally have the disadvantage of being too slow. With the high dispersion, a typical boron^{3+} impurity spectral line occupies around 100 OMA channels. This allows velocity changes of 1 km s^{-1} to be discerned. However, to accumulate sufficient signal *per channel* so that the statistical $S/N \sim 10$ requires an integration time of a few ms. By comparison, each of the photomultipliers covers approximately 30 OMA channels which affords a faster time response of 100 μs.

Thus, the two detectors are complementary, the OMA/CCD providing the detailed spectral resolution and the triple photomultipliers providing the time resolution.

III. COMPUTATIONAL ANALYSIS

For the OMA/CCD data a least-squares Gaussian fitting method is used in locating the central wavelength and the FWHM and hence the impurity drift velocity (v_d) and ion temperature (T_{imp}). The absolute wavelength calibration is checked regularly by collecting light from opposing toroidal views of the plasma on alternate discharges.

To interpret the signals from the three channel system, in terms of drift velocity and ion temperature, the measured instrument functions of the three individual channels are first convolved with Gaussians, representing Doppler broadened spectra. The widths and positions of these Gaussians follow from a set of discrete ion temperatures T_{imp} and drift velocities v_d which lie within the ranges that are expected experimentally. (We also include Zeeman splitting effects but this only marginally affects the measurements at the wavelengths and magnetic fields used here.) This procedure generates a dataset of simulated channel responses which depend on the selected temperatures and drifts. The responses are "normalized" by taking interchannel contrast factors

$$C_{BG}(n)=\frac{S_B(n)-S_G(n)}{S_B(n)+S_G(n)}$$

and

$$C_{GR}(n)=\frac{S_G(n)-S_R(n)}{S_G(n)+S_R(n)},$$

where $S_B(n)$, $S_G(n)$, and $S_R(n)$ are the convolved Gaussians in each of the three channels for the nth case of a pair of T_i and V_{drift} values. It is clear that C_{BG} and C_{GR} are

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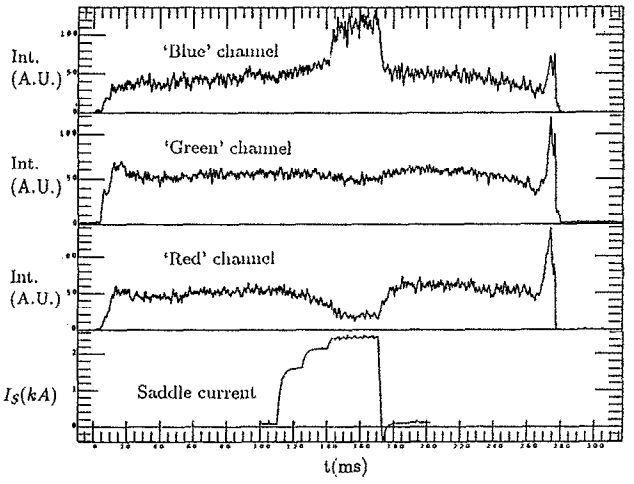

FIG. 4. The time dependence of the three photomultiplier system outputs and the current applied to the $m=3$, $n=2$ coil arrangement on COMPASS-C (which induces a locking of the $m=3$, $n=2$ plasma MHD mode). (Shot 6144.)

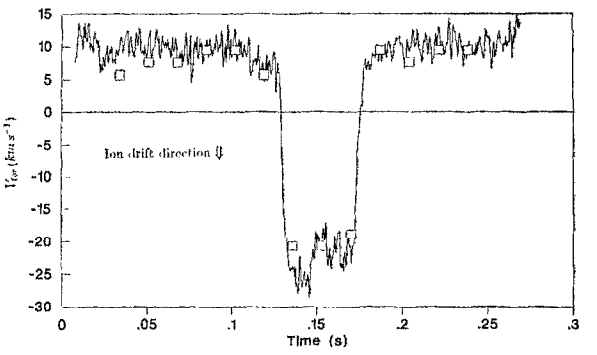

FIG. 5. A comparison between the drift velocities estimated from the three photomultiplier system and from the OMA multichannel detector (discrete points). (Shot 6167.)

functions of T_i and V_{drift} but, equally, where the dependence is monotonic we also have the inverse functions

$$T_i(n)=T_i[C_{BG}(n),C_{GR}(n)]$$

and

$$V_{\text{drift}}(n)=V_{\text{drift}}[C_{BG}(n),C_{GR}(n)].$$

We then obtain the interpolation coefficients (e.g., bicubic splines) of these discrete values from which continuous functions can be generated. When presented with real signals the data unfolding algorithm first calculates the experimental interchannel contrasts factors (C_{BG} and C_{GR}), and, from the previously calculated interpolation coefficients, the corresponding T_is and V_{drift}s are determined. This method provides a rapid and accurate data unfolding which is important in experiments with fast changing T_is, or V_{drift}s. The three channel results can be cross-checked with the detailed spectra provided by the multichannel system.

IV. TYPICAL RESULTS

The time histories of the three channel system are shown in Fig. 4 for an $m=3$, $n=2$ mode locking experiment[3] on COMPASS-C tokamak ($I_p\sim 100$ kA, $B_T\sim 1.1$ T, $\bar{n_e}\sim 1.2\times 10^{19}$ m^{-3}, $T_e(o)\sim 0.7$ keV). A magnetohydrodynamics (MHD) mode may be regarded as being "locked" when it ceases to rotate relative to the laboratory frame of reference. This can be achieved in a tokamak plasma by applying an external helical field which is spacially resonant with the internal magnetic field lines.[3] In the example illustrated in Fig. 4 the line-of-sight is tangential to the toroidal circumference of the torus at the major axis position, and the plasma current is directed towards the observer. During the mode locked phase (from $t=145$ ms$\rightarrow$170 ms) the increase in the signal of the blue channel is accompanied by a reduced signal in the red channel, showing a shift of the boron^{3+} ion drift velocity in the direction of the plasma current. Although the quantity measured is the chord-averaged value of T_{imp} and v_{drift}, transport simulations, using the measured τ_p, indicate that the boron^{3+} emission mainly originates from a shell at 5 cm$\pm$2 cm from the plasma edge.

Figure 5 shows the good agreement between the drift velocities estimated by independent numerical analysis methods, one from the three channel system and the discrete points from the multichannel (OMA) detector. The toroidal velocity can be seen to reverse direction rapidly as the MHD mode locking and unlocking occurs.

V. CONCLUSIONS

A diagnostic which combines the dual requirements of fast time response and high spectral resolution has been successfully used in mode locking experiments on COMPASS-C. Velocity changes of ~ 30 kms$^{-1}\pm 1$ kms^{-1} were recorded with a time resolution of ~ 40 μs. This demonstrates the applicability of the instrument to other experiments where rapid changes in rotation are also expected such as L–H mode transitions in tokamaks.

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