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A multichord spectrometer using an 8×8 anode photomultipliera)

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A multianode photomultiplier (8×8 anodes of 2.5×2.5 mm²) is used to detect a collection of spectra in a high dispersion echelle spectrometer. A cylindrical lens is placed at the output slit to increase the dispersion at the photomultiplier. The cross talk between adjacent spectra is non-negligible (although <5%), resulting in some interspectral distortion. This is removed by solving a system of simultaneous equations, one for each channel, obtained from the measured cross-talk coefficients. The spectrometer has been used on the COMPASS-D tokamak to measure ion temperatures and fluid velocities. © 1995 American Institute of Physics.

I. INTRODUCTION

The behavior of plasma rotation has been of interest in magnetic confinement plasmas almost since their conception.1 Frictional force balance between the various particle species was used2 in interpreting some of the early Doppler-effect results, especially in relating impurities to the background ions, but the role of radial electric field was also appreciated and indeed the Doppler-effect results were used to diagnose the internal electric fields in a plasma.3 Momentum confinement4 and the effects of error fields on the plasma rotation5-7 were also studied and, more recently, the role of radial electric field profiles in L- to H-mode transitions8-10. There are many plasma (e.g., poloidal viscous damping11 and atomic physics features (e.g., elapse time from excitation to decay12) which have to be considered in interpreting the observations, while taking due account of instrumental effects (e.g., spatial cross talk12). All of these considerations place great demands on the design of the apparatus, detector specifications, and analysis software.

Many of the changes to the fluid velocities in a tokamak plasma can occur over small extents in the spatial and temporal domains. In using Doppler-effect spectroscopy this requires multichannel spectrum detectors at many spatial positions and with very fast time resolution. Here we avail of an echelle grating diffractor,13 providing large solid angles of collected light. Dispersion in the detector plane is further enhanced by using a cylindrical lens at the output slit. A multispectrum fast response system is provided by incorporating a two-dimensional anode array in a single photomultiplier. The cross talk is negligible beyond neighboring pixels and so allowing the reliable use of an algebraic method of deconvolution. The resulting spectra from the various viewing chords are then analyzed with least-square-fitting techniques which include the effects of the measured spectral instrument functions.


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for both the spectral instrument function and the vertical cross talk (two vertical anodes, ~5 mm, are hardwired for each spectral channel). At the wavelengths of current interest for us (282 nm from the 1s2s(3S) → 1s2p(3P) transition in boron3+) the diffraction order of the echelle is ~20 and the free spectral range is ~15 nm. This allows the use of a relatively high transmittance interference filter16 with peak transmission of 25% and a FWHM of 14 nm to act as a diffraction order selector.

III. SPECTRAL AND SPATIAL INSTRUMENTAL FUNCTIONS

A. Measurement of spectral instrument functions

The spectral instrument response function of each of the photomultiplier channels (in the horizontal direction, say) is measured using a narrow atomic line spectral source. A single input fiber, representing a line of sight from the plasma, is illuminated and the output of the fiber is imaged at the input slit of the spectrometer. The image of the input slit is swept across the front face of the photomultiplier, each channel acting as an output slit, by rotating the echelle grating. The temporal behavior of each of the channels is converted to a spectral response, or instrument function, by simply applying the grating equation. Successive collection fibers can be illuminated and scanned in this way, giving the response for the photomultiplier (spectral) channels to, essentially, spectral delta-function inputs. Examples of instrument functions from six adjacent spectral channels, occupying two rows of anodes, are illustrated in Fig. 2, where a single input fiber is illuminated. These were taken using a mercury lamp (λ=253.6 nm). The outermost channels are broader to collect more light at the spectral wings of the Doppler spectrum and is achieved by hardwiring two adjacent anodes.

D. Measurement of spatial instrument functions

In addition to the spectral smearing, arising mainly from the imaging and dispersion properties of the spectrometer,
there is the more direct smearing due to the cross talk in the photomultiplier channels themselves. If there were only a single spatial view of interest, this cross talk would already have been included in the instrument function measurements above which are all that are required in unfolding the data. With more spatial views the observed spectra will have contributions from more than a single view of the plasma. The pixel-to-pixel cross talk is measured by using narrow entrance and exit slits and rotating the grating as before, while illuminating only one fiber at a time. At each channel peak response (almost “top hat” in form), the cross talk is recorded from all the other channels. This method includes all the cross-talk contributions from the optics, spectrometer, and the photomultiplier. Little or no cross talk is observed between nonadjacent pixels. Thus the spatial instrument functions can be represented by a 3×3 matrix for each of the pixels. The table below lists the spot function for a typical channel:

\[
\begin{bmatrix}
0 & 0.041 & 0 \\
0.0163 & 1.0 & 0.0166 \\
0 & 0.038 & 0
\end{bmatrix}
\]

IV. ALGEBRAIC DECONVOLUTION

A. Principles

The smearing implicit in all experimental data, such as due to the finite resolution of a spectrometer or finite bandwidth of an amplifier, is often conceived as an analog phenomenon and so involving integrals in the mathematical description. However, the problem of smearing can be equally considered in terms of summations of discrete values rather than continuous integration, especially when analyzing experimental data. This approach easily allows for each detector channel to have a unique instrument function. The basic idea is to describe a smearing problem, perhaps multidimensional, in terms of a set of linear equations, one equation for each detector channel. The number of terms in each equation is just the number of input channel locations that contribute to that particular detector channel due to smearing. However, in contrast to other approximate means of deconvolution, this approach requires that there is an equal number of equations to unknowns, represented here by the input intensity channels. Thus the effect of smearing must not extend beyond the number of data channels, or that the intensity values outside this range are known (e.g., = 0). This can be achieved in prac-
The measured instrument functions in Fig. 2, and incorporating the calculated Zeeman splitting and after removing the effects of detector cross talk.

Intensity-averaged ion temperatures and relative velocity using the calculated Zeeman splitting and after removing the effects of detector cross talk.

Deconvolution then consists of solving the simultaneous equations for the input intensities, given the measured instrument functions and signal data.

To illustrate the principles, the algebra is restricted here to two spatial dimensions, appropriate to our present needs. Suppose we have an $M \times N$ matrix of detector signals, each represented by $S_{mn}$, with a corresponding array of image intensities $I_{mn}$ that we wish to determine. Each input coordinate, $(m,n)$, will have an associated instrumental matrix, of size $J \times K$, whose elements are represented here by $a_{mnjk}$.

The dimensionality of all the matrices may be reduced by joining up the rows, say, in sequence. (A similar process can obviously be used for higher dimensions.) The new matrix elements are represented by $S_{mn}$, $I_{mn}$, and $a_{mnjk}$, where $\nu=(m-1)N+n$ and $1 \leq \nu \leq M \times N$. The relationship between the column vectors $\mathcal{S}$ and $\mathcal{I}$ is given by $A \times \mathcal{S} = \mathcal{I}$, where $A$ is of size $(M \times N)^2$. It can be shown that the $A$ matrix elements $A_{\mu\nu}$ are obtained from the instrumental matrix elements; viz. $A_{\mu\nu}=a_{mnjk}$, where $j,k$ is the solution pair to the integer equation:

$$jN+k=(\mu-\nu)+N \frac{J+1}{2} + \frac{K+1}{2}.$$
fleets the $8 \times 8$ construction of the detector matrix and the effect of truncated instrument functions at the boundaries.

C. Data reconstruction

The main concern here is to remove interspectra cross talk. Signal spillover between the individual channels in any one spectrum is of less concern as this can be included in making best fits to the data, including the directly measured instrument functions. These latter will include all the smearing effects (e.g., spectrometer finite resolution and focusing effects) and including the cross talk between the detector elements. To avail of the directly measured instrument functions (composite) we first remove the detector element cross talk and then reinsert the cross talk between the spectral channels.

V. EXPERIMENTAL RESULTS

Initial raw data are shown in Fig. 5 from two poloidal views of the COMPASS-D device. The wavelength is 282.2 nm from the heliumlike boron$^3+$ impurity. Examples of interpreted data, in terms of velocity and temperature, are shown in Fig. 6 using data from the first of the chords in Fig. 5. The error bars are obtained from a least-squares fit of a single Gaussian spectrum together with a background pedestal and convolved with the measured instrument functions and the Zeeman splitting ($B = 1 \rightarrow 2T$) of the boron$^3+$ transition $[1s2s(S^3) \rightarrow 1s2p(P^3)]$. Before fitting to the data, the spatial cross talk is removed as described above. The error bars shown are for time intervals greater than the temporal smearing from the electronics (i.e., when the measurements can be regarded as independent of each other). The small errors in both the ion temperature ($\approx 15$ eV) and velocity ($\approx 0.3$ km s$^{-1}$) show the importance of obtaining good photoelectron statistics for the fast time resolution by having relatively large spectral channels and large spectral dispersion.

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14 OP Fibres, Germany.
15 Haraeus Silica and Metals Ltd., Germany.
16 Glen Spectra, interference filter 282BP14.