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Use of optical filters for Tokamak plasma spectroscopy

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Abstract A description is given of a method for using narrow-bandpass optical interference filters to make a number of simultaneous chord observations of plasma radiation from a Tokamak. Employed with the Canberra Tokamak LT-3 the method has been applied to provide measurements of O III, O IV and O V impurity radiation from a hydrogen plasma.

1 Introduction

Considerable information can be gained about a plasma from spectroscopic measurements of its emitted radiation. For cylindrical or toroidal laboratory plasmas one often requires radial profiles of the rate of emission, per unit plasma volume, of photons corresponding to specific atomic or ionic transitions. As such profiles are generally derived from a number of chord observations their reliability in the case of time-varying plasmas rests on the shot-to-shot reproducibility of discharge characteristics, unless all observations can be made simultaneously. As an alternative to the previous employment of a monochromator, for making single-chord, single-shot measurements (Bowers *et al* 1971), a method has been developed which enables the radiation intensity, within selected wavelength intervals, from different ion species within the plasma to be determined from a number of chord observations taken during a single discharge in our Tokamak, LT-3. For each chord observation narrow-bandpass interference filters discriminate in favour of wavelength regions which include relatively intense lines of interest.

In monitoring various aspects of the behaviour of our hydrogen plasma we have found oxygen impurity ion lines of use, in particular those of O III, O IV and O V. For this reason filters were selected which provided maximum transparency for prominent and conveniently positioned lines of each of these ion species. A battery of seven similar filters and their associated optical elements and photomultipliers are collectively referred to by the convenient misnomer 'filterscope'. The number seven merely reflects the number of adjacent ports available for chord observations through the plasma.

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2 Description of filterscopes

The filterscopes are discussed with reference to figure 1. In 1(*a*) are shown the partial plan and sectional elevation of the toroidal vacuum chamber together with a schematic arrangement of the filterscopes. The O III filterscope, shown in the view XX′, is omitted from the plan view for clarity. The LT-3 vacuum chamber has a major radius of 0·40 m and a minor radius of 0·10 m. The plasma extends to a minor radius of about 0·09 m, its boundary being indicated by the broken circle in view XX′. Seven horizontal and seven vertical optical ports are provided for viewing the plasma. These are indicated by H and V, respectively, in the figure. The optical ports consist of tubes of length 100 mm and internal diameter 6 mm.

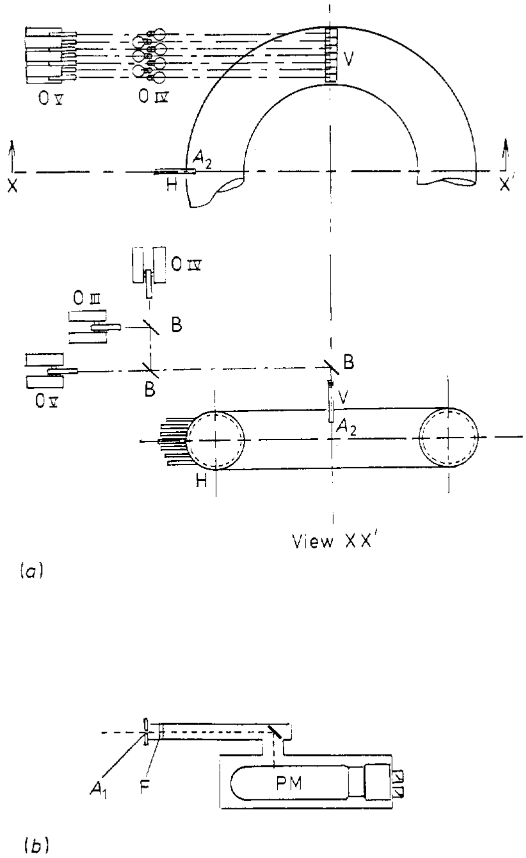


Figure 1 Filterscopes: (*a*) arrangement of filterscopes relative to the LT-3 torus; (*b*) a filterscope element.

They are closed with fused silica windows and for the experiments with filterscopes had 3 mm diameter apertures (A_2) fitted at their inner ends.

Figure 1(*b*) shows an element of a filterscope. Its overall length is about 180 mm. One of the BNC sockets at the base of the housing for the side window photomultiplier (EMI type 9661B) is for the cable bringing the HT supply to the photomultiplier and the other is for connecting its output to an oscilloscope. Each of the seven elements of a filterscope consists of an aperture of cross-sectional area A_1 (diameter 1·5 or 3 mm), a filter (F in figure 1(*b*)) of transparency $F_{s,n}{}^{m}$ and a photomultiplier of average sensitivity $P_{s,n}{}^{m}$ (A photon^{-1}). The superscript m identifies the filterscope as being of type O III, O IV or O V depending on which ion emits the line at peak transparency; the first subscript, s, identifies the element of the filterscope (1–7) and the second subscript, n, identifies the wavelength corresponding to some line contributing to the signal from the photomultiplier, for which filter transparency and photomultiplier sensitivity are expressed. A second aperture of cross-sectional area A_2 is used at each optical port at a distance $L_{1,2}$ from A_1. The radiation from the plasma through each of the ports A_2 is divided into three by means of two beam splitters (B in figure 1(*a*)) so that the filterscopes receive radiation from identical sources.

If the rate of emission of photons of wavelength $\lambda = n$ is $\dot{N}_n(x)$ per unit volume of plasma at a distance x from A_2, the number of photons per second passing through the aperture A_1 is given by

$$\dot{N}_n(A_1) = B_s{}^m F_{s,\,n}{}^m \int_{x_1}^{x_2} \dot{N}_n(x) \frac{\Omega}{4\pi} A(x)\, \mathrm{d}x \qquad (1)$$

where $B_s{}^m$ is the fraction of radiation passed by the beam splitters between the plasma and the *m*th filterscope, $A(x)$ is the area of plasma, perpendicular to the aperture axis and at distance x from A_2, from which photons can pass through A_2, and Ω is the solid angle subtended by A_1 at x. The plasma extends from x_1 to x_2. It is assumed that $\dot{N}_n(x)$ is constant across $A(x)$. Since $A_1 \ll L_{1,2}{}^2 \gg x^2$ the quantity $\Omega A(x) \approx A_1 A_2 / L_{1,2}{}^2 = \text{constant}$ and equation (1) may be expressed as

$$\dot{N}_n(A_1) = B_s{}^m F_{s,\,n}{}^m G_s{}^m \dot{N}_{s,\,n}{}^m(X)$$

where the geometrical factor $G_s{}^m = A_1 A_2 / 4\pi L_{1,2}{}^2$ and $\dot{N}(X) = \int_{x_1}^{x_2} \dot{N}(x)\, \mathrm{d}x$. The purpose of the measurements is to determine relative or absolute values of $\dot{N}_{s,\,n}{}^m(X)$ from which, if desired, $\dot{N}_n{}^m(r)$ can be obtained, where r is the plasma radius.

The temperature of the LT-3 plasma for all operating conditions of interest is such that the ratios of radiation intensities from different multiplets of the same ion species are constant. This was confirmed by numerous measurements with the Hilger medium quartz spectrograph fitted with a direct reading head. Relationships between the intensities of various lines of each oxygen ion species were obtained from measurements with a monochromator which had been calibrated against a standard light source. In practice, comparisons need only be made between intensities of single lines of different multiplets, the relative intensities within the multiplets being known since the multiplets are identifiable (Wiese *et al* 1966, Bockasten and Johansson 1968). For convenience, line intensities within a species are expressed as ratios, $R_n{}^m$, of each line to one near the filter's peak transmission, whose 'intensity' is $\dot{N}_{n(0)}{}^m(X)$. These lines, at $\lambda = n(0)$, are the ones used with monochromator monitoring of ion species. They are the O III line at 326·45 nm, the O IV at 338·45 nm and the O V at 278·10 nm.

Typical transmission curves for filters are shown in figure 2,

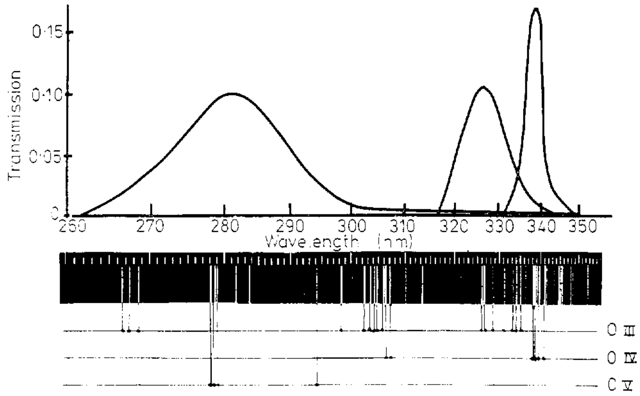


Figure 2 Typical transparency curves for optical interference filters. The ordinate shows the fraction of radiation transmitted, the abscissa the wavelength corresponding with the LT-3 plasma spectrum.

together with a portion of the spectrum of lines radiated by the LT-3 plasma. The main oxygen ion lines are indicated by their extensions below the spectrum. The unmarked lines either are too weak to be significant or appear very early in the discharge (e.g. the C II line at 283·7 nm) before the higher ionised states of oxygen are formed. Recognising that the O III and O IV lines within the window of the O V filter contribute to the O V filterscope signals, and noting that no O V lines fall within the O III or O IV windows, then the signals $S_s{}^m$ from filterscope photomultipliers are determined by the relationships

$$S_s{}^{03} = B_s{}^{03} G_s{}^{03} \Big(\dot{N}_{s,\,i(0)}{}^{03}(X) \sum_i P_{s,\,i}{}^{03} F_{s,\,i}{}^{03} R_i{}^{03} + \dot{N}_{s,\,j(0)}{}^{04}(X) \sum_j P_{s,\,j}{}^{03} F_{s,\,j}{}^{03} R_j{}^{04} \Big) \qquad (2)$$

$$S_s{}^{04} = B_s{}^{04} G_s{}^{04} \Big(\dot{N}_{s,\,i(0)}{}^{03}(X) \sum_i P_{s,\,i}{}^{04} F_{s,\,i}{}^{04} R_i{}^{03} + \dot{N}_{s,\,j(0)}{}^{04}(X) \sum_j P_{s,\,j}{}^{04} F_{s,\,j}{}^{04} R_j{}^{04} \Big) \qquad (3)$$

$$S_s{}^{05} = B_s{}^{05} G_s{}^{05} \Big(\dot{N}_{s,\,i(0)}{}^{03}(X) \sum_i P_{s,\,i}{}^{05} F_{s,\,i}{}^{05} R_i{}^{03} + \dot{N}_{s,j(0)}{}^{04}(X) \sum_j P_{s,j}{}^{05} F_{s,j}{}^{05} R_j{}^{04} + \dot{N}_{s,\,k(0)}{}^{05}(X) \sum_k P_{s,k}{}^{05} F_{s,k}{}^{05} R_k{}^{05} \Big) \qquad (4)$$

where arabic numerals have replaced roman for values of m, and n has been replaced by i, j or k according to whether the line indicated comes, respectively, from an O III, O IV or O V ion. Solutions of these equations provide values of $\dot{N}_{s,n(0)}{}^m(X)$.

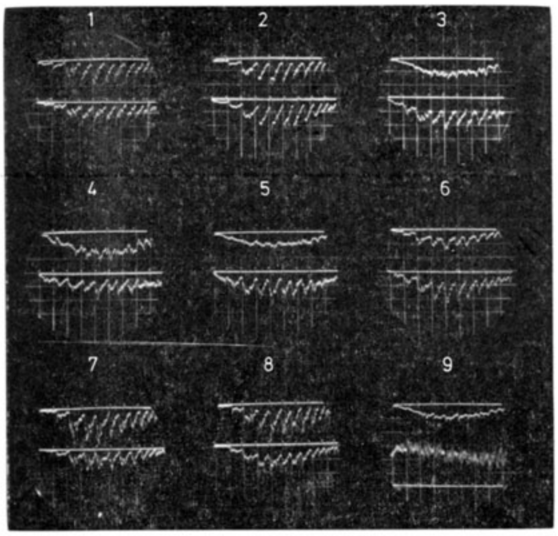
3 Measurements with filterscopes

Figure 3 shows signals from filterscopes receiving radiation from the Tokamak plasma. The quantities in (*a*) and (*b*) are the same but correspond to different discharges. In (*a*) the oscilloscope sweep rate is 1 division per 500 μs, in (*b*) it is 1 division per 100 μs with the signals in (*b*) starting at a time corresponding to about the centre of the time axis in (*a*). The oscillographs are referred to by numbers 1–9. Traces 1–7 are from vertical chord observations, symmetrical about the 4th. The upper traces are from the O V filterscopes, the lower ones from the O IV. The upper and lower traces of 8 and the upper of 9 are from the lower three chords of a second O V filterscope viewing horizontally. The lower trace of the oscillograph 9 shows the Tokamak plasma 'volts per turn' signal.

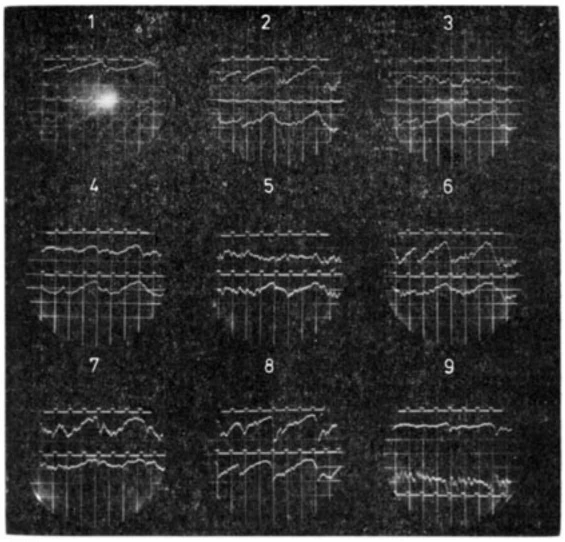
Each of the signals shown in figure 4 represents a measurement of radiation originating from one optical port. The traces in 4(*a*) start 0·5 ms after the initiation of the discharge and extend for 2 ms. The upper trace is from an element of an O III filterscope with the next two respectively from O IV and O V filterscopes. The bottom trace is of an O VI line signal from a monochromator. The finite O IV and O V filterscope signals occurring during about the first half-millisecond are due to O III radiation. In the case of the monochromator signal (O VI), that occurring at time zero is due to x-rays striking the photocathode of the photomultiplier and the subsequent signal during the first millisecond sweep is dark current. Figure 4(*b*) shows a comparison between monochromator and filterscope signals. The upper signal is from the monochromator set on the O V line at 278·1 nm. The lower signal is from the O V filterscope taken at a time during the discharge when little O III radiation was in evidence. The oscilloscope horizontal sweep rate is 1 division per 100 μs; the Y sensitivities are adjusted to give roughly the same average deflection for both signals.

4 Discussion

Although the use of the filterscopes considerably reduces the tedium in recording experimental data, this was not the main purpose of their development. Rather, it was to improve the

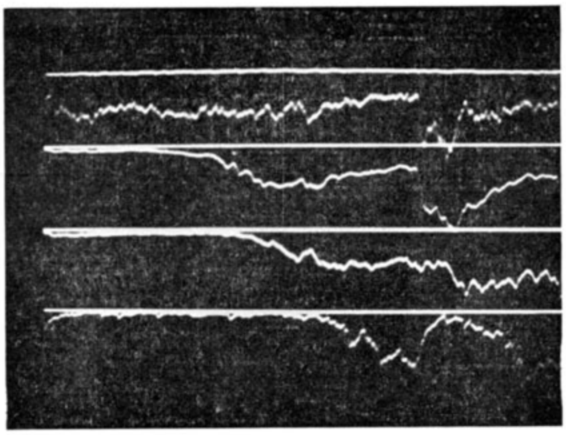


(*a*)

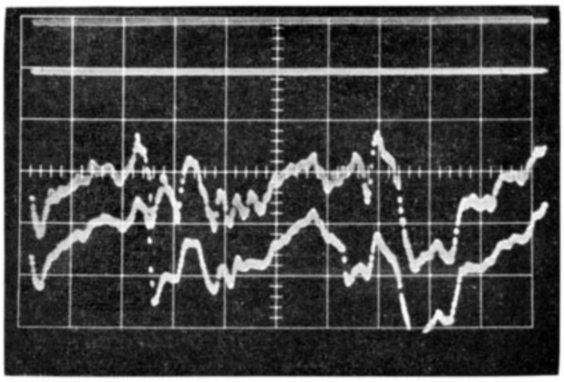


(*b*)

Figure 3 Oscilloscope traces of signals from filterscopes: (*a*) sweep rate of 1 division per 0·5 ms; (*b*) 1 division per 0·1 ms.



(*a*)



(*b*)

Figure 4 Signals from radiation from a single optical port: (*a*) signals from (top to bottom) O III, O IV and O V filterscopes and monochromator on O VI line; (*b*) comparison between signals from O V filterscope and monochromator on O V line.

reliability which can be achieved with some types of spectroscopic measurement. The reduction of the time of recording experimental data is somewhat offset by the amount of data which must be obtained before the experiment, such as the filter transparency curves illustrated in figure 2 and the calibrated response of photomultipliers, together with some post-experiment data manipulation, such as in solving equations (2), (3) and (4).

For the sort of variations shown in the O IV and O V filterscope signals of figure 3 it is obvious that a great deal of detail would be lost in necessary averaging when data are collected over many discharges with a single monochromator. From an examination of the relative phasing of the O IV and O V signals it is possible to distinguish between changes in signal level due to ionisation and those due to geometrical changes in the plasma. Near the hotter centre of the plasma the atoms are ionised sequentially through various levels. Here a fall in level of O IV signal preceding a fall in the level of O V can signify ionisation. The fast increases in signal levels for outer chord observations (elements 1, 7 and 8 in both figure 3(*a*) and 3(*b*)) are associated with the sudden expansion of the plasma about its minor radius at the disruptive instability, identified by the volts per turn signal going negative (lower trace 9 of figure 3). A comparison between the signals of traces 1 and 7 provides information about translation of the whole plasma column as well as its expansion and contraction.

Referring to equations (2), (3) and (4) it will be noticed that the various sums over the terms with subscript i, j or k are simply constant coefficients of the respective $\dot{N}_{n(0)}{}^m(X)$ ($n=i, j$ or k). If we assume filter transparencies similar to those of figure 1 and use manufacturers' values for the quantum efficiencies of photomultipliers (EMI 9661B), relative values of coefficients within each m value, for the LT-3 plasma, would be as shown in table 1. The significance of coefficients other than the 'main' ones, shown as unity in table 1, will depend on the values of $\dot{N}_{n(0)}{}^m(X)$. For the central chords (elements 3, 4 and

Table 1 Coefficients $\sum P_{s,n}{}^m F_{s,n}{}^m R_n{}^m$ of the variables $\dot{N}_{s,n(0)}{}^m$ (equations (2), (3) and (4)).

$n(0)$ (nm)	326·10	338·56	278·10
m			
03	1	0·16	0
04	0·02	1	0
05	0·38	0·06	1

5) viewing the hotter regions of the plasma, $\dot{N}_{j(0)}$ and $\dot{N}_{k(0)}$ might be about equal with $\dot{N}_{i(0)}$ an order of magnitude smaller. This would mean that the O IV filterscope signals would be entirely due to O IV radiation and O V signals would contain small contributions of O III and O IV radiation, while the O III filterscope could be responding more to O IV than O III radiation. These conditions would be expected to apply during the latter half of the oscilloscope sweep in figure 4(*a*), where O IV and O V signals may be regarded as fairly reliable without correction for O III but the O III signal would need to be corrected for O IV. As can be seen in figure 4(*b*) the differences between the O V filterscope signal and that of a monochromator observing an O V line through the same central port, while the plasma is relatively hot, are fairly minor.

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