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HIGH-RESOLUTION DUO-MULTICHANNEL SOFT X-RAY SPECTROMETER
FOR TOKAMAK PLASMA DIAGNOSTICS

By

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ABSTRACT

A high-resolution, time-resolving soft X-ray multichannel spectrometer (SOXMOS) that permits the simultaneous measurement of emission in two different spectral ranges has been developed and tested extensively for tokamak plasma diagnostics. The basic instrument is a high-resolution, interferometrically adjusted, extreme grazing incidence Schwob-Fraenkel duochromator. The instrument is equipped with two multichannel detectors that are adjusted interferometrically and scan along the Rowland circle. Each consists of an MgF_2 coated, funneled microchannel plate, associated with a phosphor screen image intensifier that is coupled to a 1024-element photodiode array by a flexible fiber optic conduit. The total wavelength coverage of the instrument is 5-340 Å with a measured resolution (FWHM) of about 0.2 Å when equipped with a 600 g/mm grating, and 5-85 Å with a resolution of about 0.06 Å using a 2400 g/mm grating. The simultaneous spectral coverage of each detector varies from 15 Å at the short wavelength limit to 70 Å at the long wavelength limit with the lower dispersion grating. The minimum read-out time for a full spectral portion is 17 ms, but several individual lines can be measured with 1 ms time resolution by selected pixel readout. Higher time resolution can be achieved by replacing one multichannel detector with a single channel electron multiplier detector. Examples of data from the PLT and TFTR tokamaks are presented to illustrate the instrument's versatility, high spectral resolution, and high signal-to-noise ratio even in the 10 Å region.

INTRODUCTION

The role and importance of spectroscopic diagnostics of hot plasmas produced in controlled thermonuclear fusion research have been extensively discussed in recent years.^{1,2} In particular, the behavior of impurities in magnetically confined tokamak plasmas have been widely studied, mainly because of the role impurities play in power balance estimates³ and their use in particle transport studies.⁴ Moreover, local values of major plasma parameters, such as particle density and temperature, can be measured using the line emissions of various ionization states of impurity atoms.^{5,6} As fusion plasmas become hotter by using auxiliary heating (electron temperatures of the order of 5 keV and ion temperatures of 8 keV and, recently, up to about 20 keV have been measured in tokamaks^{7,8}), the domain of interest for spectroscopic diagnostics shifts towards the XUV range as highly ionized atoms of heavy impurities emit their brightest lines in the 1 - 400 Å range. Traditionally, plasma spectroscopy has been developed in the visible and VUV ranges, and spectra recorded either on photographic plates or by means of photomultipliers in mono- or duochromator instruments. The first method of detection lacks time resolution and the second needs several reproducible discharges in order to measure accurately the spectral profile of the lines and their brightness relative to the adjacent background. As tokamaks become larger, less accessible, and the discharge repetition rate becomes lower, fewer discharges are available for experiments. Furthermore, the need to monitor simultaneously lines belonging to various ionization states in particle transport studies,⁹ together with the shift in emphasis towards the soft X-ray range, made obvious that new spectroscopic instruments needed to be built to record large spectral ranges in a single discharge, in combination with the time histories of the recorded lines.

Consequently, during the last five years, a new type of detector has come into use in tokamak spectroscopy. A microchannel plate image intensifier¹⁰ coupled to a photodiode array¹¹ (or to other types of multichannel photoelectric devices - see ref. 12 for a comprehensive discussion) allows the recording of large spectral ranges with simultaneous time resolution. The first instrument with such a detector, built by Bell, Finkenthal, and Moos,¹³ covered a broad range in the VUV. A normal incidence spectrometer, it was provided with several gratings to allow either the coverage of large spectral ranges ($300 - 2200 \text{ \AA}$) with low spectral resolution ($4 \text{ \AA}$), or smaller domains (e.g., $300 - 550 \text{ \AA}$) with improved spectral resolution ($0.7 \text{ \AA}$). The next step was to couple this type of detector to a commercially available grazing incidence monochromator with the microchannel plate detector mounted on a 1 m Rowland circle.¹⁴ The overall wavelength coverage of this instrument is $15 - 360 \text{ \AA}$ and the spectral resolution $0.7 \text{ \AA}$. Also developed was a survey spectrometer equipped with two interchangeable toroidal gratings with flat focal fields.¹⁵ This alleviates problems due to the movement of the detector on the Rowland circle and makes it possible to focus the entire spectrum on the flat microchannel plate. The spectral coverage is $100 - 1100 \text{ \AA}$ or $160 - 1700 \text{ \AA}$, with a $2 \text{ \AA}$ spectral resolution using the high dispersion grating. Another similar multichannel, time-resolving instrument has been built recently at the Massachusetts Institute of Technology on the same principles for plasma spectroscopy studies in the Alcator C tokamak.¹⁶

All the above-mentioned time-resolving spectrometers have relatively low spectral resolution. It was felt that high resolution was not really required when the instruments were used in the survey mode, i.e., to

monitor the general features of the spectrum over a large range, or to detect unusual or unexpected impurities in the fusion plasma. Power loss estimates, however, depend more critically on line-blending problems. In fact, plasma spectroscopy experiments performed on various tokamaks during recent years have shown that practically all the diagnostics based on the line emission of heavy impurities, from particle transport to power loss estimates in high temperature plasmas, are affected by the lack of better spectral resolution.^{17,18} Furthermore, an entirely new development fostered efforts to improve seriously the spectral resolution of this type of instrument: during the last few years tokamak plasmas have been used as laboratory sources for basic research in atomic spectroscopy. Spectra of highly ionized heavy elements ($Z = 30$ to 80) have been obtained from these hot plasmas and a large body of line classification work has been performed (see, for instance, the recent review paper by Fawcett¹⁹). Also, because electron temperatures and densities are accurately measured in tokamaks, independently of spectroscopic observation, models used in astrophysics to predict these parameters can be tested by measuring line intensity ratios.²⁰⁻²² This work relies heavily on accurate line brightness measurements, and therefore requires high spectral resolution in order to reduce line blending.

Another critical problem, especially with the use of grazing incidence spectrometers, is the high background level in the short wavelength region. The signal-to-noise ratio becomes very poor below about $30 \text{ \AA}$ in all the above-mentioned grazing incidence instruments. Yet, this is a very important spectral range: the HeI and HI-like lines of low- Z impurities, the $\Delta n = 1$ transitions of intermediate- Z elements ($Z = 20 - 30$), and the $\Delta n = 0$ (3-3) transitions of heavy elements ($Z = 40 - 60$) are all

emitted between 5 and 50 Å. This domain is very significant for spectroscopic diagnostics of tokamak (and any other fusion) plasmas. In many diagnostics it is even desirable to measure this soft X-ray emission simultaneously with that at higher wavelengths. For instance, while studying the interaction of neutral beam injection with the target plasma through charge-exchange processes, it is very important to measure simultaneously lines emitted in transitions marginally affected by the charge exchange process (like Ly α or Ly β in H-like low-Z elements) in the 10 - 30 Å range, together with those originating from transitions between higher excited levels strongly populated in the process and emitted above 100 Å.

The above-mentioned arguments led us to build a high-resolution, duo-multichannel, time-resolving soft X-ray spectrometer (SOXMOS),^{23,24} that works at extreme grazing incidence and incorporates the desired requirements discussed above. Due to an interferometric adjustment of both the grating and the microchannel plate detector on the Rowland circle, this novel instrument achieves a very high resolution over the whole spectral range covered. Pre-adjusted interchangeable grating mountings allow changes, with new adjustment, in the overall spectral coverage from 5 - 85 Å at high resolution (typically 0.05 Å, using the 2400 g/mm grating) to 5 - 340 Å (with a 600 g/mm grating and a resolution of 0.2 Å). Moreover, this instrument can easily be switched from a spectrograph mode using photographic plates to the duochromator or the multichannel mode. This third mode has two options. In the first option, one detector is a multichannel detector (MCD) with simultaneous coverage varying from 15 Å at the short wavelength limit to 70 Å at the long wavelength limit, and the second detector is a single channel electron multiplier (SCD)

which can be used as a monitor positioned on a given spectral line or for higher time-resolution operation. In the second option two similar MCD detectors covering simultaneously two different spectral ranges are used. A relatively large Rowland circle diameter (2 m) with a very small grazing incidence angle (1-1.5 degree) and an auxiliary slit to eliminate UV stray light provide a high signal-to-background ratio, even at the short wavelength side (10 - 30 Å) of the spectral domain covered. Very recently, a high resolution multichannel grazing incidence spectrometer was built by Cromer et al.²⁵ This new accurate instrument, specially developed for absorption studies, covers a spectral range which does not extend much below 40 Å and, since it is based on a monochromator mount, it does not have the ability to simultaneously cover two different ranges of the spectrum, a very desirable feature for tokamak diagnostic applications.

Finally, the moderate dimensions and weight of the present instrument permit scanning of the minor diameter of the plasma by rotating the entire instrument.²⁶ It can be positioned either horizontally or vertically on the tokamak.

The multichannel detector system was first developed and installed on a Schwob-Fraenkel soft X-ray spectrometer at the Princeton Plasma Physics Laboratory and operated on the PLT (Princeton Large Torus) and on the TFTR (Tokamak Fusion Test Reactor) tokamaks. Since then, similar instruments have become operational on other tokamaks: TFR (Tokamak Fontenay-aux-Roses) in France and JET (Joint European Torus) at Culham U.K.

This paper is organized as follows: Sec. I describes the basic instrument in the spectrograph and duochromator modes. The second and

third sections describe and discuss the multichannel detector system, its components, data acquisition, and its adjustment and wavelength calibration. The fourth section presents the performance of the instrument with emphasis on the high resolution and the signal-to-noise ratio, using examples of time-resolved tokamak spectra recorded under various experimental conditions.

I. THE BASIC INSTRUMENT

The basic instrument is a high-resolution 2-m grazing-incidence Schwob-Fraenkel spectrometer built at the Hebrew University of Jerusalem,²⁷ operating in two modes: spectrograph or duochromator.

A. Spectrograph

The main body of the instrument consists of a monobolic duraluminum piece with an accurately machined cylindrical surface (with a precision better than 10 microns), which materializes the Rowland circle, as shown in Fig. 1. The grazing incidence angle can be varied from less than 1° to $2\frac{1}{2}^\circ$ by moving the carriage supporting the main entrance slit S_1 along the cylindrical surface (see Fig. 1). In the present work an angle of $1\frac{1}{2}^\circ$ was chosen. An accurate mounting accepting pre-adjusted grating holders enables grating interchange without any further optical adjustment; this allows a quick change of wavelength range and spectral resolution. When equipped with a 2400 groove/mm concave grating, the instrument covers an overall spectral range of 5 to 90° Å, and with a 600 groove/mm grating, the overall wavelength coverage extends from 5 to 360° Å. The spectra presented in this paper have been obtained using a 1° -blazed 2400 g/mm and 1° 31'-blazed 600 g/mm, gold-coated Bausch and Lomb ruled gratings.

Other gratings with 1200 or 300 g/mm were also used in some other experiments. A 36-mm-wide cut machined along a chord in the cylindrical surface of the spectrometer block allows the recording of the diffracted spectrum on commercially available 10-to-14-inch-long photographic plates (101 or SC5 Kodak), which are directly pressed against the cylindrical surface by means of an elastic holder system, or which can be housed in an optional, more sophisticated portable cassette. A front slit S_2 limits the incident beam acceptance angle to the instrument aperture; another auxiliary slit S_3 , mounted between the main entrance slit and the grating, serves to eliminate visible and UV light diffracted from the main slit.

The spectrometer is adjusted by an interferometric method developed by Filler and Schwob.²⁷ This method is fast, more accurate, and more convenient (the adjustment of the spectrometer block being made outside the vacuum chamber) than the usual trial-and-error adjustments using successive exposures in vacuum. The adjustment is achieved by means of a Michelson-type interferometer using white-light fringes. Slots were cut through the body of the spectrometer, so that portions of the Rowland circle can be viewed from the region of the axis of the cylinder. A rotatable plane mirror, placed on the cylinder axis, bends one arm of the interferometer, which terminates at a reflecting surface in the spectrometer which should lie on the Rowland circle, e.g., an aluminized photographic plate or the grating. The other arm of the interferometer ends at a plane reference mirror.

When the aluminized plate is illuminated, white-light fringes can be obtained by translating the reference mirror. Then the grating can be set on the same circle by moving it towards or away from the cylinder

axis, until it shows white-light fringes with the same position of the reference mirror as for the plate. The adjustments are then correct to 1 μm . The tilt of the grating is aligned by making the circular fringes at the grating concentric with the grating mount (in fact, this can be performed more conveniently at an earlier stage using monochromatic light). Finally, positioning of the entrance slit on the Rowland circle is achieved by making the zero-order image and the slit distances to the grating center equal (by illuminating the slit with visible light). This method, with no further adjustments, consistently gives spectra showing almost the theoretical spectral resolution ($0.006 \text{ \AA}$ at $20 \text{ \AA}$, when using a 2400 g/mm grating and a 3- μm -wide entrance slit).

Spectra from tokamak, vacuum-spark, and laser-produced plasmas obtained with this instrument have permitted the identification of lines of highly ionized heavy elements, for both atomic spectroscopy and plasma diagnostic purposes (see, for instance, refs. 28 and 29).

B. Duochromator Mode

The photoelectric system can replace the photographic attachment without further optical adjustment. It employs two carriages, each of which carries an exit slit coupled to a single channel electron photomultiplier detector (SCD). Adjustment of the exit slit on the Rowland circle is performed by means of the same zero-order image method, as described above for the entrance slit (in this case the exit slit carriage is set in front of the grating in place of the entrance slit carriage).

The two exit slit carriages are moved independently along the machined cylinder, driven by two stepper motors acting on high precision leadscrews which are attached to a swivel joint at the long wavelength end of the

spectrometer block. The carriages are pressed against the cylinder surface by means of springs acting on a guide arc. A double limit switch security system prevents collisions with the fixed parts at the extremities of the scan range and between the two carriages themselves. The location of each carriage along the leadscrew is indicated by means of a mechanical counter mounted on the transmission shaft. The exit slits can be positioned along the Rowland circle within a relative accuracy of 5 μm . A discrepancy of less than 25 μm is observed when reaching a chosen position from opposite directions of the detector carriage move or after removing and reassembling the entire photoelectric attachment. This "absolute accuracy" is achieved owing to a backlash-free transmission system and by using, when assembling the system, a reference contact pin, which can be mounted on the guide arc. The mechanical counter is thus set to a given value when the carriage is brought into contact (through a Feeler gauge) with the calibration pin. This precision in reproducibility corresponds to a wavelength accuracy of 0.005 $\text{\AA}$ at 20 $\text{\AA}$ with a 2400 g/mm grating, i.e., to about a tenth of the line width (FWHM) when using typical 20 μm width slits.²⁶ This is extremely useful in tokamak diagnostics, since the detector can be set directly on the intensity peak of a line, without needing several reproducible discharges to scan the line profile, as in the case of conventional instruments.

A stepper motor remote controller-indexer module measures through incremental pickups the position y of each carriage along the leadscrew. This module is coupled to a wavelength converter which includes a microprocessor programmed to give a direct readout in wavelength units for the two channels, according to the set values of the spectrometer parameters. The relation between y and the wavelength λ can be derived

from the grating equation and geometrical considerations (see Fig. 2):

$$k\lambda_{[A]} = \frac{10^7}{N} \left(\cos \frac{x_1}{R} - \cos \frac{x}{R} \right), \quad (1)$$

$$(y_c - y)^2 = \ell^2 + \left(\frac{R}{2} + h\right)^2 - 2\ell\left(\frac{R}{2} + h\right) \cos \frac{2(x_L - x_S - x)}{R}, \quad (2)$$

where k is the diffraction order, N the grating groove density per mm, and R the Rowland circle diameter. The parameter x_1 and the variable x represent the distances along the Rowland circle from the grating apex G to the entrance slit S_1 , and to the scanning exit slit S , respectively. The geometrical constant ℓ represents the distance JO between the leadscrew swivel joint center and the center of the Rowland circle, and the constant h is the distance NH from the nut pivot to the Rowland circle. The two constants x_L and x_S are the lengths of the arcs GL and SH , respectively. y_c is a calibration factor (chosen so that the indication of the mechanical counter is $y = 200.000$ mm, when the detector reaches the calibration pin).

The duochromator mode is particularly suitable for time-resolved measurement of the intensity ratio of two lines during one discharge. This may be a sensitive diagnostic of tokamak plasma parameters, as for instance with the He-like resonance and intercombination lines of oxygen and carbon emitted in the range $20 - 40 \text{ \AA}$.²⁶ It can also record the time history, especially in the submillisecond domain, of emissions from the successive ions of injected impurities for line identification or transport studies purposes, using one channel as a monitor.³⁰ Furthermore,

it was employed for comparative measurements of line intensities in soft X-ray laser research experiments down to the nanosecond regime.^{31,32}

II. MULTICHANNEL DETECTOR MODE

In the multichannel detector (MCD) mode, either one or both single channel electron multipliers of the duochromator mode are replaced by microchannel plate detector(s). The various combinations of detectors are discussed later on; the point emphasized here is that the change from one type of detector to another is simple and obtained without further optical adjustments.

A. The Microchannel Plate Detector

The head of the detector is composed of a flat rectangular 50-mm-long microchannel plate (MCP), manufactured by Galileo Electro-Optics Corp. This is coupled to a phosphor (P20) screen image intensifier, as shown in Fig. 3. The incident XUV photons produce photo-electrons at the MCP face which are subsequently multiplied inside the microchannels. A negative voltage of up to -1 kV is applied to the MCP input face, leading to a gain of up to 10^4 . The exiting electrons are then accelerated and proximity focussed onto the P-20 phosphor screen which converts the electron signal to visible photons. Focussing is achieved by applying a voltage of +3 to +5 kV across the 1-mm gap between the MCP output face and the phosphor layer. This voltage also enables an efficient conversion in the phosphor.

The MCP used here has 25- μ m-diameter channels, with a 32- μ m center-to-center spacing. It has been selected to have a relatively high strip current allowing for a large dynamic range of operation, and

its front surface is MgF_2 coated in order to enhance the quantum efficiency in the soft X-ray region.^{33,34} The MCP input face is funneled to enlarge the open area from 55% to 70% of the total MCP input surface. Moreover, according to measurements performed by Malina,³⁴ the funneling led to an enhancement of the detector quantum efficiency for grazing incidence angles (which otherwise is very low). In the present instrument, the MCP operates at extreme grazing incidence, from 3 to 12 degrees. A cut is machined in the MCP holding frame, so as to avoid the shadow cast on the MCP input face at extreme grazing incidences. In order to increase the efficiency, the MCP has also been oriented in such a way as to reduce the angle between the direction of the microchannels (bias angle 8 deg.) and the incident beam.

The phosphor screen which is deposited on a fiber-optic faceplate is optically coupled to a fiber-optic taper. This is attached to a coherent flexible fiber-optic conduit which transfers the visible photons produced by the phosphor to a Reticon photodiode array (PDA), as shown schematically in Fig. 3. The use of an optical reducer permits the actual MCP length to be matched with the 25.6-mm-long PDA, allowing for a larger simultaneous spectral coverage with only a small reduction in the spectral resolution, as discussed later on. The flexible fiber-optic bundle and the PDA are optically coupled by removable coupling mounts through a fiber-optic window, which constitutes the vacuum seal interface. Thus, the electronics controlling the PDA are entirely located outside the vacuum, enabling the use of conventional commercially available components.

The MCP detector housed in an adjustable cradle located inside a carriage is interferometrically adjusted to be tangent at the center of its input face to the Rowland circle. This MCD carriage is attached

to the leadscrew (in place of an SCD carriage), as shown in Fig. 1, and can be accurately moved along the machined Rowland cylinder as described in Sec. I. As in the duochromator mode, the detector carriage is pressed by means of the guide arc against the cylinder surface, thus enabling either horizontal mounting of the spectrometer (with horizontal or vertical entrance slit), or vertical mounting of the entire instrument.

The coupling of two MCP detectors moving on the Rowland circle to the PDA through flexible coherent optical conduits constitutes a unique feature specific to this instrument. This allows both a simultaneous wide wavelength coverage composed of two different portions of the spectrum and a high spectral resolution to be obtained, while still using a fairly conventional means of data acquisition and detector control.

B. Optical Multichannel Analyzer

The visible light signals at the fiber-optic conduit output are analyzed by a Reticon (1024 SF) linear 1024-pixel self-scanned silicon photodiode array which is controlled and read out by a commercially available optical multichannel analyzer (OMA) system produced by EG&G Princeton Applied Research Corp. This includes a PARC 1412 F detector tube which incorporates the Reticon PDA, and a PARC 1218 controller unit (replaced recently by an upgraded PARC 1461 module). The only modification to the standard PARC 1412 detector tube is the use of a windowless detector using a fiber-optic-faced PDA (this is now commercially available).

The performance of the OMA system has been extensively studied and described by Talmi and Simpson,¹¹ and for a similar plasma spectroscopy application by Fonck et al.¹⁵ The spectral resolution of the system depends on the distance between two adjacent pixels of the Reticon PDA;

each pixel here is 2.5-mm long by 25- μ m wide. This gives an aspect ratio of 100:1, requiring a good alignment to make the spectral lines parallel to the pixels. As it will be shown later on, the main limitation of spectral resolution of the entire MCP + OMA system lies in the proximity focussing at the phosphor and in the various optical couplings.

The data acquisition and data display system is very similar to that described by Fonck et al.¹⁵ The design of their interface electronics and the necessary software were made available to us and were adapted to our system. The time resolution of the system is limited by the serial scan of the PDA through the PAR package. In the (multichannel) spectrograph mode, i.e., the readout of the entire PDA array, the fastest scan is made in 16 ms, allowing, for instance, about 50 spectral scans during one discharge in the PLT tokamak and even more in large tokamak machines. This time resolution can be improved when operating in the ploychromator mode: by a selective readout a groups of pixels and by skipping other spectral regions, several individual spectral lines may be simultaneously recorded with 1-ms time resolution.

One interesting feature of this detection system is the very large signal-to-noise ratio. The dark current noise of the PDA can be reduced to 3 count/sec rms (1 count corresponds to about 1000 electrons) when cooled to -20°C by the Peltier cooler. The intrinsic fixed patter noise can be eliminated by subtracting a dark scan from each data scan. Owing to the wide linear range of the PDA output, the final dynamic range can reach 10^4 , which allows the recording of intense and weak lines in the same spectrum.

C. Various Detector Configurations

One advantage of the present instrument over other multichannel spectrometers is its versatility. Once the carriages holding the single or multichannel detectors are interferometrically adjusted on the Rowland cylinder, they can be easily interchanged without further adjustments.

In the simple multichannel configuration, only one microchannel plate detector (MCD) is in use for scanning the entire spectral range. This mode was used for the first series of measurements on the PLT tokamak,^{24,25} and is presently in operation on the TFTR tokamak.^{35,36}

Figure 4 shows schematically the other different possible configurations. In the mixed configuration, as seen in Fig. 4a, one SCD is associated with the MCD, either at the long wavelength or at the short wavelength side. This SCD can be very useful as a monitor, in that it can record during the same discharge a line of interest that lies in a region far from the spectral portion observed by the MCD. The SCD also can be desirable for submillisecond measurements (down to the nanosecond regime). This mixed configuration is in use in soft X-ray laser experiments.³⁷

The duo-multichannel configuration is represented in Fig. 4b. Each MCD is coupled to its own OMA system. This mode (selected in the instrument installed on the JET machine) permits observation of two extended wavelength ranges with a high spectral resolution. It appears to be suitable, for instance, for monitoring in the same discharge the short wavelength domain (18 to 41 Å) containing the H-like and He-like transitions of the light elements O and C, and simultaneously a longer wavelength region where the lines of highly ionized metallic impurities are emitted.

Finally, an interesting alternate configuration, shown in Fig. 4C, employs two MCD's, but the visible output signals are transferred through an additional optical reducer of 2:1 magnification (as shown in Fig. 1) to the same PDA-OMA system, each spectral portion covering 512 pixels only. This configuration used on the PLT tokamak presents less than 50% loss in spectral resolution (since the principal cause of resolution loss is the proximity focussing and various optical interfaces). Moreover, owing to the easily removable optical coupling mounts, one of the MCD's has been directly coupled to the PDA, when higher spectral resolution was desirable.

III. OPTICAL ADJUSTMENTS AND CALIBRATION

A. Optical Adjustment of the MCP

The flat MCP is brought to a position at which it is tangent at its middle point to the Rowland cylinder. This adjustment is performed by means of the same interferometric method used to adjust the grating, described in Sec. IA. For the purpose, the spectrometer block is installed on the interferometer bench; the MCP is set up in its carriage mounted on the cylindrical surface, and its input face acts as a plane mirror. Although it has relatively low reflectivity because of the funneled pores, this face can be interferometrically adjusted with respect to the reference mirror (which was previously adjusted by means of an aluminum-coated plate pressed against the cylindrical surface, as described in Sec. IA).

First, the interference pattern in monochromatic light is obtained and centered by tilting the MCP cradle inside its carriage in two directions (in the plane of the Rowland circle and in the plane

perpendicular to the Rowland circle). Then a fine translation adjustment along the radius of the Rowland circle is done in white light with an accuracy of $\pm 1 \mu\text{m}$ by means of two differential screws which hold the MCP cradle inside the carriage.

The angular adjustment of the MCP in the plane perpendicular to the Rowland circle is of great importance, since it ensures the parallelism of the spectral lines with respect to the PDA pixels. This is especially critical because the diffracted spectrum is incident at grazing incidence on the MCP face. The accuracy of the parallelism alignment achieved here is about $1/200$ rad (this corresponds to $\frac{1}{2}$ pixel, since the pixel aspect ratio is $1/100$). The next stage of the optical adjustment consists in making the longitudinal median axis of the spectrum, i.e., of the MCP image through the fiber optic conduit, coincide with that of the Reticon PDA, with the same accuracy. This is done by means of a translation and rotation adjustment mechanism incorporated in the PDA holder. Finally, the fiber optic components are cemented to the coupling flanges. Dowel pins ensure the accuracy of replacement of the removable optical coupling system (see Fig. 1), which has been incorporated to permit easy disassembly of the optical chain.

B. Wavelength Calibration

Another feature specific to this instrument is related to the wavelength calibration. Owing to the high precision in the manufacture of the mechanical parts, and to the accuracy of the optical alignment and of the detector motion on the Rowland circle, the wavelength calibration can be entirely based on the grating equation and geometrical computations.

The positioning of the MCD carriage along the machined cylinder is adjusted using the same calibration procedure as for the SCD. The "absolute" accuracy of this adjustment, as indicated in Sec. 1B, is better than 25 μm . This corresponds to about $\frac{1}{2}$ pixel, since the width of a pixel transposed on the MCP plane is about 43 μm (taking into account the taper magnification which is close to 1.7 in the present case).

The geometrical design of the MCD carriage is such that when it is brought into contact with the calibration pin, the middle of the MCP (corresponding to the central pixel $p_0 = 512$) is at precisely the same location as the exit slit of an SCD carriage in its calibration position. Therefore, the same relationship exists between the readout position y of the MCD carriage and the wavelength λ_0 at the central pixel, as between the SCD carriage position and the wavelength λ of the line selected by the exit slit. This relation is therefore given by Eqs. (1) and (2), where x/R is replaced by x_0/R , representing the diffraction angle β_0 (in radians) for the central pixel.

The next step in the wavelength calibration is to establish the relationship between the pixel number p along the linear PDA and the corresponding wavelength λ , for a given position y of the MCD carriage. Figure 5 shows schematically the geometry of the multichannel mode (with only one MCD).

Point T_0 on the MCP is the tangent point to the Rowland circle; this corresponds to the central pixel p_0 . The distance between an arbitrary point T along the MCP and point T_0 , is:

$$TT_0 = (p - p_0) \frac{M}{N} \quad , \quad (3)$$

where M is the fiber-optic taper magnification and n is the number of pixels per unit length on the PDA. The diffraction angle β corresponding to point T is:

$$\beta = \beta_0 + \Delta\beta \quad . \quad (4)$$

Considering the triangle GKT_0 in Fig. 5, one gets:

$$T_0K = R \sin \beta_0 \sin \Delta\beta \quad . \quad (5)$$

In the triangle T_0KT , the same segment can be written:

$$T_0K = \frac{p-p_0}{n} M \sin (\beta_0 - \Delta\beta) \quad . \quad (6)$$

Equating expressions (5) and (6) and solving the resulting equation, we obtain:

$$\Delta\beta = \cot^{-1} \left[\cot \beta_0 + \frac{Rn}{(p-p_0)M} \right] \quad . \quad (7)$$

Taking the grating Eq. (1) for $x/R = \beta$, and using Eq. (4), one finally obtains the relationship between λ and p :

$$k\lambda [A] = \frac{10^7}{N} \left\{ \cos \alpha - \cos \left[\beta_0 + \cot^{-1} \left(\cot \beta_0 + \frac{Rn}{(p-p_0)M} \right) \right] \right\} \quad , \quad (8)$$

where α is the grazing incidence angle and β_0 is the diffraction angle for the central pixel, which is a function of the MCD carriage position y , given by Eq. (2) (in which x/R is replaced by β_0 , as indicated above).

The validity of the calibration Eq. (8) was checked for a series of preselected positions y , using well-known reference lines of intrinsic or injected impurities in PLT. Only small corrections of the geometric parameters had to be introduced in Eq. (2) in order to make the predicted and measured values of λ_0 coincide. It was found that the precision of the computed λ as a function of p from Eq. (8) is very good in the central zone of the PDA (between pixel no. 300 and 800). For a 600 g/mm grating, the discrepancies are of the order of $\pm 0.02 \text{ \AA}$. However, an unexpected feature was noticed: as one approaches the edges, on both sides, a discrepancy in wavelength appears and increases gradually towards the edge. A comparative study of this effect in two different wavelength ranges, centered at $32 \text{ \AA}$ and $150 \text{ \AA}$, indicates that the correction function for the edges (in terms of pixels) is approximately the same in both cases. The same conclusions were obtained in a systematic study by Saoutic,³⁸ using an elaborate software program for the analysis of spectra obtained on the TFR tokamak by means of a similar Schwob-Fraenkel spectrometer. This effect is attributed to image distortions within the fiber-optic chain (mostly in the taper which systematically shows a smaller magnification at the edges). Consequently, a corrective function may be incorporated in the wavelength calibration program in order to take this effect into account with, for instance, a polynomial fit.^{38,39} This correction then yielded the same accuracy in wavelength measurement over the entire pixel domain: $\pm 0.02 \text{ \AA}$ with a 600 g/mm grating,³⁹ and $\pm 0.005 \text{ \AA}$ with a 2400 g/mm grating.

Although the MCD carriages may be positioned at any point along the Rowland circle, a series of preselected 20-mm-spaced positions y were generally used for convenience (or to enable fine corrections in

the wavelength calibration). Table I gives the central pixel wavelength λ_0 and the corresponding spectral coverage $\lambda_1 - \lambda_2$ (for a typical instrument equipped with one MCD) as a function of the detector position y and for the two gratings currently employed. This shows that 9 successive positions are sufficient for a complete coverage of the total spectrum. (The rest of Table I is discussed below).

Finally, an intensity (radiometric) calibration of one of the multichannel spectrometers has been made above $50 \text{ \AA}$ by comparing the intensities of lines emitted from the PLT tokamak which were simultaneously recorded by this instrument and by a 1-m grazing incidence multichannel spectrometer,¹⁴ which was calibrated by means of synchrotron radiation at the National Bureau of Standards.⁴⁰ Intensity calibration may also be performed using the branching ratio method⁴¹ to cover the shorter wavelength ranges.

IV. PERFORMANCE - EXAMPLES OF TOKAMAK SPECTRA

The examples presented in this section are spectra obtained under various experimental conditions from the PLT and TFTR tokamaks, using a spectrometer equipped with one MCD. The spectral range under discussion is 5 to $340 \text{ \AA}$. Usually a $20\text{-}\mu\text{m}$ -wide and, in some cases, a $10\text{-}\mu\text{m}$ -wide entrance slit, and 600 g/mm or 2400 g/mm gratings have been used in the various applications. The spectra have been recorded with time resolutions varying from 16 ms (or even 2 ms in pixel selection mode) to 250 ms.

A. Examples of PLT Spectra

The performance of the instrument in the short wavelength range is illustrated by Figs. 6 - 8 presenting spectra obtained in the overall

range 5 to 41 Å. In all these cases, a Bausch and Lomb gold-coated 600 g/mm grating blazed at 1°31' has been used. Figure 6 shows the hydrogen- and HeI-like Al XIII and Al XII lines around 7 Å, with the OVIII L-α line recorded with a 20-μm-wide slit. Aluminum was injected into the tokamak plasma by a laser blow-off technique⁴² and it appears clearly in the intermediate frame b. Since the integration time is very long, 128 ms, the aluminum emission signal has disappeared in the third frame owing to outward transport of the injected impurity. In Fig. 7, a fragment of the spectrum showing intrinsic impurity lines around 18 Å is given. In order to increase the spectral resolution this spectrum was obtained using a 10-μm-wide slit. The resonance and intercombination OVII lines at 21.602 Å and 21.804 Å, which are suitable for plasma diagnostics are well separated. Figure 8a presents a spectrum obtained with the usual slit (20 μm) between 18 and 41 Å (for y = 120 mm). This range constitutes one of the most important domains in the short wavelength region for tokamak diagnostics, since it contains all the principal lines of the H- and HeI-like ions of the major low-Z impurities, carbon and oxygen, which are present in any tokamak plasma. The 20-μm slit used here does not permit resolution of the two OVII lines in first order, but the corresponding CV lines around 40 Å are well resolved. The intensity ratio of the OVII lines, however, can be measured in second (or higher) order, where they appear very well separated, even while using a 20-μm slit and a 600 g/mm grating. In Fig. 8b, the same spectrum is displayed, but with an expanded intensity scale. This figure demonstrates the very good signal-to-noise ratio, even in this extremely short wavelength domain. This very low background level (except at the limit of the spectrum shown in Fig. 6, very close to the zero-order light) was achieved without any stray-light filter (such as VVNS).

The data presented in Figs. 6 to 8 illustrate how far the instrument coverage can extend into the short wavelengths, even when equipped with the 600 g/mm grating at a $1\frac{1}{2}^\circ$ angle of incidence, although the best performance was obtained with a 1° blazed, gold-coated 2400 g/mm grating (at an angle of incidence of 1°).

Figure 9 presents a different spectral range, in the intermediate wavelength region, between 118 and 165 Å ($y = 260$ mm). The grating and slit width are the same as in Fig. 8. Titanium and iron lines are emitted by the two most abundant metallic impurities for these conditions in the PLT plasma. Note how well the Ti and Fe lines are separated in this region of high line intensity.

B. Spectral Resolution

PLT spectra taken under various instrumental conditions are now presented in order to illustrate the spectral resolution of the instrument. Figure 10a shows an enlargement of the two CV lines around 40 Å, observed using a 600 g/mm grating and a 20-μm-wide entrance slit. The measured width (FWHM) of both lines is $\Delta\lambda = 0.18$ Å (7.2 pixels). This instrumental line width increases very slightly as a function of λ . For the OVI line at 150 Å, for instance, the experimental width is $\Delta\lambda = 0.22$ Å (4.6 pixels).

In order to increase the resolution, especially in the short wavelength range below 30 Å, a 10-μm width slit was used. The observed width of the OVIII 18.969 Å line is $\Delta\lambda = 0.105$ Å (6.2 pixels) as indicated in Fig. 7. In these conditions the OVII resonance and intercombination lines are clearly resolved in the first order. The width of the resonance line, shown in Fig. 10b, is $\Delta\lambda = 0.125$ Å. This experimental value is somewhat larger than the expected value, mainly due to the fact that the line was detected close to the edge of the MCP (as will be discussed later on).

Spectra at higher resolution were recorded using the 2400 g/mm grating. Figure 10c presents the same transitions in CV, observed using the usual 20- μ m-wide slit. The spectral resolution achieved here is $\Delta\lambda$ (FWHM) = 0.067 $\text{\AA}$ (slightly larger than the predicted value 0.057 $\text{\AA}$).

If one compares the spectral resolution of the MCD with that obtained by a photographic plate, several factors inherent to this type of detector besides the spectrometer's intrinsic resolution are found to affect the resolution and have to be taken into account. The instrumental function $\Delta\lambda_{\text{spectr.}}$ is directly correlated to the entrance slit width and is constant all along the spectrum. (With a 20- μ m-wide slit it equals 0.166 $\text{\AA}$ and 0.042 $\text{\AA}$ with the 600 g/mm and 2400 g/mm gratings, respectively.)

The first source of resolution loss in the detector is the size of the MCP pores, which have a 25- μ m diameter. The choice of this standard MCP (rather than one having smaller pores) was dictated by the advantage of having a thicker plate (1.09 mm nominal) for a given diameter-to-length ratio of the microchannels. The thicker plate appears to be less fragile and causes less distortions of the MCP input face when mounted in its frame. Taking into account the funneling, the effective pore diameter is a little less than 30 μ m. This has to be averaged along the spectral line image.

A more significant limit in spatial resolution is caused by the spread of the electron bunch in the gap between the MCP output face and the phosphor screen, mainly as a result of the random nonaxial velocity component of the electrons as they exit the microchannels. The diameter d of the electron bunch spot is approximately given by¹⁵: $d \approx s/v_{\text{ph}}^{1/2}$ where s is the MCP - phosphor distance and v_{ph} is the voltage across the gap. In the present case of a 1-mm gap and $v_{\text{ph}} = 4500$ V, by using the

experimental data from Ref. 15, the spot size is expected to be about 60 μm . The gap could be reduced (to about 0.4 mm) provided some additional precautions are taken, and this has been done in other multichannel spectrometers.^{15,25} Here, considering the relatively large spatial dispersion of the spectrum, it was better to keep the standard rectangular MCP mount (CEMA 6508) with a nominal 1-mm gap, in order to minimize the probability of breakdown between the plate and phosphor. This permits secure operations with a gas pressure of up to 1.10^{-6} Torr.

Another source of resolution loss comes from the various optical coupling interfaces along the optical path. One effect is due to the mismatch at each interface of the optical fibers which have a 10- μm diameter. A more significant effect may result from the optical cement layer used by the manufacturer for attaching the optical parts on both input and output faces of the taper. The layer is between 50 and 100 μm thick. Assuming isotropic light inside the fibers and taking into account the maximum acceptance angle, this would correspond to a 35 to 70- μm width rectangular function (which after convolution gives a somewhat moderate contribution to the final line width). This effect could in principle be reduced by mounting removable coupling flange systems which only need a very thin layer of optical coupling compound at these interfaces (as is already done for the f.o. bundle - f.o. window and f.o. window - PDA interfaces). In addition, imperfect alignment (coherence) of the fibers, owing in particular to a shear distortion of the (hexagonal) fiber packets²⁵ may cause image distortion inside rigid f.o. components, such as the taper and window. This should, however, not affect the coherence of the flexible bundle, owing to the special fabrication process used by the manufacturer. Based on previous observations,²⁵ one can estimate that this results in a line broadening of about 10 μm for each component.

Finally, the PDA response function is a trapezoidal pixel profile of base width $37.5\ \mu\text{m}$ and top width $12.5\ \mu\text{m}$.

In order to compute the combined resolution loss, it is convenient to report all these effects to the MCP plane; thus, the above spatial estimates have to be multiplied by the taper magnification (1.7:1) for all components between the taper and the PDA. The observed spectral line profile presents a best fit with a Gaussian shape (except for a slight increase at the very bottom of the line profile, as may be due to cross-talk or scattering). This fit can be seen in Fig. 10a, for instance. This seems to differ from the observed line shape (rather close to a Lorentzian profile) obtained by other multichannel spectrometers. This may be due to the fact that here the (FWHM) width of a line corresponds to a large number of fibers and to many pixels (between 4 and 10, depending upon the spectral range and the slit width used). The final resolution is obtained by convolution of the various effects. For the total detector system, one obtains a spatial profile width between $115\ \mu\text{m}$ and $160\ \mu\text{m}$, depending upon the assumptions made on the probable individual shape profiles. Since the observed line profile is close to Gaussian, one may assume that the component due to the entire detector system also has a shape profile not too far from a Gaussian. The spectrometer function (which is also assumed to be close to a Gaussian) can be convoluted with the detector function to give a predicted line width. We found that a detector function with a spatial FWHM of $130\ \mu\text{m}$ produced the best quantitative fit to the observed line profiles. This detector function is represented in terms of spectral width (for the case of a $600\ \text{g/mm}$ grating) by curve 1 in Fig. 11. Curves 2 and 3 show the spectrometer resolution for $20\text{-}\mu\text{m}$ and $10\text{-}\mu\text{m}$ wide slits,

respectively; curves 4 and 5 give the predicted line widths obtained by convolution. The predicted line widths are also reported on Table I for the central wavelength of each coverage range.

One can see in Fig. 11 that the use of a 10- μ m wide slit is clearly advantageous only in the short wavelength region of the spectrometer. At longer wavelength the gain in spectral resolution is not very significant, while there is a substantial loss in the signal intensity. In the present case a 20- μ m wide slit which gives the same resolution for the spectrometer and the detector functions around the middle of the spectral range seems to be the best compromise between resolution and signal intensity for current diagnostic operations.

The spectral resolution discussed above is for the MCP central part (which has been adjusted to be tangent to the Rowland circle in order to achieve the best resolution in this zone, rather than to have a minimum deviation over the entire range, with the same largest deviation at the center and at the two edges). The deviation from the Rowland circle of the flat front surface of the MCP causes a defocusing of the line image. Owing to the relatively large radius of the Rowland circle, this effect was predicted by ray tracing to be still acceptable for the entire length of the selected MCP. The deviation from the Rowland circle is a quadratic function of the distance from the plate center. At the edges of the active area length (43.35 mm) of the detector front plate, the departure is 235 microns. The resulting defocusing effect has been calculated from geometrical considerations as a function of the detector position, taking into account the actual acceptance of the instrument, limited by the slit S_2 . The results are presented by curve 6 in Fig. 11, for the 600 g/mm grating. This predicts, for instance, a defocusing

of an infinitely narrow line corresponding to $0.20 \text{ \AA}$ for a line at $20 \text{ \AA}$ recorded at either of the edges (pixel no. $p = 1$ or 1024). At $150 \text{ \AA}$ the line broadening at the edges is predicted to be only $0.087 \text{ \AA}$. Assuming a rectangular profile function for this effect, the convolution with the line profile at the MCP center leads to an increase of the line width as represented by curves 7 and 8 in Fig. 11. Using a $20\text{-}\mu\text{m}$ slit the line width increases from $0.18 \text{ \AA}$ to $0.24 \text{ \AA}$ at $20 \text{ \AA}$, and from $0.220 \text{ \AA}$ to $0.228 \text{ \AA}$ at $150 \text{ \AA}$. As an illustration, Fig. 12 presents the observed profile of the OVI $150.1 \text{ \AA}$ line emitted from PLT plasma, recorded (a) close to the detector center ($p=532$) and (b) near the edge ($p=923$): The increase in the line width, predicted to be $0.004 \text{ \AA}$, is not even detectable. The defocusing effect is thus not significant, except at very short wavelengths (or, more precisely, at very small diffracted angles β) where it leads to a moderate loss of resolution, but close to the detector edge only (quadratic effect). Thus, for current use, a more sophisticated, cylindrical-shaped MCP to conform to the Rowland circle is unnecessary. If higher spectral resolution in the very short wavelength range were required (using a narrow slit), one could limit the useful range to the central part ($p=300$ to 700) of the detector.

In conclusion, it seems that for most tokamak diagnostic applications, the 600 g/mm grating (blazed at $1^\circ 31'$) gives the best compromise between wavelength coverage and spectral resolution. The latter reaches a value of $\Delta\lambda/\lambda$ better than 10^{-3} in the long wavelength side of the spectrum. Higher resolution can be achieved in the $5\text{-}100 \text{ \AA}$ range by using higher orders, which are rather intense with this grating, or by employing a 1200 g/mm or 2400 g/mm grating, especially for dense regions in the spectra of injected impurities where the emission in higher orders may interfere with lines in first order. In the $120\text{-}340 \text{ \AA}$ range a 600 g/mm grating

blazed at $3^{\circ}31'$ is more efficient,³⁹ but lines below $80 \text{ \AA}$ are practically undetected (even in high orders) in the spectra thus obtained.

C. Time-Resolved Tokamak Spectra

A few examples related to the physical meaning of the time resolution are now discussed. Figure 13 shows two frames (PDA scans), (a) the spectrum from PLT obtained by using the 600 g/mm grating in the 60-95 $\text{\AA}$ range before the injection of molybdenum, and (b) during and after the Mo injection. Two features have to be pointed out: first, by subtracting the two frames, one can obtain an almost "pure" molybdenum spectrum, and second, the resolution of this dense emission spectrum is good. A comparison of this spectrum with a similar one obtained using another multichannel grazing incidence instrument with a lower resolution shows that difficulties created by line blendings in earlier line identification work can be overcome using higher resolution spectra. Most of the lines were classified as superimposed $3p^6 3d^k - 3p^5 3d^{k+1}$ transitions emitted from several ionization stages.⁴³ Further line analysis on similar Ag transitions has been done using spectra taken with the instrument described in this article.⁴⁴

Figure 14 illustrates the full potential of the multichannel detector, by showing a spectral and time-resolved display of the emission from the TFTR tokamak in the 130-170 $\text{\AA}$ range.³⁵ The first frames show the usual tokamak impurities: low-Z elements, carbon and oxygen, and high-Z, Cr, Fe and Ni introduced by plasma-wall and plasma-limiter interactions. However, at a given moment, around 1.4 sec, a strong signal appears, which we identified as a zirconium emission, characterized by intense lines of highly ionized AlI-, MgI-, and NaI-like ions: $\text{Zr XXVIII } 3s^2$

$3p - 3s \ 3p^2$ at $137 \text{ \AA}$, Zr XXIX $3s^2 \ 1S_0 - 3s \ 3p \ 1P_0$ at $128.52 \text{ \AA}$ and Zr XXX $3s \ 2S_{1/2} - 3p \ 2P_{3/2}$ at $142.82 \text{ \AA}$. The other metallic impurities showed an enhanced emission before the peak of the zirconium burst, while the low-Z emission steadily increased after the plasma recovery. The spectroscopic data (correlated with a high bolometric signal and a drop observed in electron temperature) indicate that there was an interaction at $t = 1.4 \text{ sec}$ between the plasma and components of the Al - Zr gettering system.³⁵

Finally, Fig. 15 shows as an example a combined effect of the two features of the instrument: high spectral resolution and the possibility of monitoring the temporal behavior of spectral lines. Several individual lines emitted from TFTR plasmas were simultaneously recorded, and their time history compared with the integrated bolometric signal (radiated power).³⁶ The high resolution of the instrument allows two lines, OVI at $150.1 \text{ \AA}$ and Cr XXI at $149.9 \text{ \AA}$, to be resolved. The similarity of curves e and g (in particular during the 1-2 sec phase) suggests an interesting physical conclusion: the power loss in this type of discharge is mainly caused by intrinsic oxygen radiation. Under other discharge conditions, however, carbon or metal line radiation appeared to be dominant.

V. CONCLUSION

A novel grazing incidence, time-resolving multichannel spectrometer has been described, and its performance under various experimental conditions has been discussed. The important new features of this instrument are high spectral resolution achieved by an interferometric alignment of the main components and the ability to extend observations

to very short wavelengths (down to $5 \text{ \AA}$) with a good signal-to-noise ratio. The spectrometer capabilities can be enhanced by a grating interchange system. Moreover, two distinct spectral ranges can be simultaneously monitored with two multichannel detectors, or one MCD can be associated with a single channel detector for high time-resolution applications. The various modes under which the instrument can work and its compactness make it highly versatile. Several instruments of that type are currently in operation on different tokamaks (PLT, TFTR, TFR, and JET) and consistently show the same high resolution. Beside its main role in measuring the time-resolved line intensities from highly ionized impurities, its spectral resolution has recently made it possible to measure the ion temperature by Doppler line broadening during high power discharges in TFTR⁸ and in JET.³⁸ This performance seems to be very promising for future fusion plasma diagnostics. A similar multichannel spectrometer is used in a mixed configuration mode to analyze the emission of laser-produced plasmas in the Soft X-Ray Laser Experiment³¹ at PPPL. In some applications, the linear OMA detector can be replaced by a CCD camera for spatial resolution. By gating the high voltage on the MCP, it should be possible to use the instrument for studying extremely short duration laser-produced plasma emissions.

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REFERENCES

1. E. Hinnov, in Atomic and Molecular Processes in Controlled Thermonuclear Fusion, edited by M.R.C. McDowell and A.M. Feredenci, pp. 449-470 (Plenum, New York, 1980).
2. C. De Michelis and M. Mattioli, Nucl. Fusion 21, 617 (1981).
3. D.E. Roberts, Nucl. Fusion 21, 215 (1981).
4. R. Isler, Nucl. Fusion 24, 1599 (1984).
5. S. Suckewer and E. Hinnov, Nucl. Fusion 17, 945 (1977).
6. S. Suckewer, Phys. Scripta 23, 72 (1981).
7. H. Eubank et al., Phys. Rev. Lett. 43, 270 (1978).
8. J.D. Strachan et al., Phys. Rev. Lett. (to be published).
9. S. Suckewer et al., Nucl. Fusion 24, 815 (1984).
10. J.L. Wiza, Nucl. Instrum. Methods 162, 587 (1979).
11. Y. Talmi and R.W. Simpson, Appl. Optics 19, 1401 (1980).
12. J.G. Timothy, Publ. Astron. Soc. Pac. 95, 810 (1983).
13. R.E. Bell, M. Finkenthal, and H.W. Moos, Rev. Sci. Instrum. 52, 1806 (1981).
14. W.L. Hodge, B.C. Stratton, and H.W. Moos, Rev. Sci. Instrum. 55, 16 (1984).
15. R. Fonck, A. Ramsey, and R. Yelle, Appl. Opt. 21, 2115 (1982).
16. O. Manning, J. Terry, and E. Marmar, Bull. Am. Phys. Soc. 28, 1250 (1983).
17. W.L. Hodge, J. Castracane, and H.W. Moos, J. Quant. Spectrosc. Radiat. Transfer 27, 493 (1982).
18. B.C. Stratton, H.W. Moos, S. Suckewer, U. Feldman, J.F. Seely, and A.K. Bhatia, Phys. Rev. A 31, 2534 (1984).
19. B.C. Fawcett, J. Opt. Soc. Am. B 1, 195 (1984).
20. U. Feldman, G.A. Doschek, and A.K. Bhatia, J. Appl. Phys. 53, 8554 (1982).
21. B.C. Stratton, M.W. Moos, and M. Finkenthal, Astrophys. J. 279, L31 (1984).

22. T.L. Yu, M. Finkenthal, and H.W. Moos, *Astrophys. J.* 305, 880 (1986).
23. J.L. Schwob, M. Finkenthal, and S. Suckewer, *Proc. of the 7th International Conference on VUV Radiation Physics, Jerusalem 1983; Ann. Israel Phys. Soc.* 6, 54 (1983).
24. J.L. Schwob, A. Wouters, S. Suckewer, and M. Finkenthal, *Bull. Am. Phys. Soc.* 28, 1252 (1983).
25. C.L. Cromer, J.M. Bridges, J.R. Roberts, and T.B. Lucatorto, *Appl. Opt.* 24, 2996 (1985).
26. TFR Group, J.G. Doyle, and J.L. Schwob, *J. Phys. B: At. Mol. Phys.* 15, 813 (1982).
27. A. Filler, J.L. Schwob, and B.S. Fraenkel, *Proc. 5th Int. Conf. on Vacuum Ultraviolet Radiation Physics, Montpellier, M.C. Castex, M. Pouey and N. Pouey editors, C.N.R.S., Paris (1977), Vol. III* p. 86.
28. J.L. Schwob, M. Klapisch, N. Schweitzer, M. Finkenthal, C. Breton, C. De Michelis, and M. Mattioli, *Phys. Lett.* 62A, 85, (1977).
29. N. Schweitzer, M. Klapisch, J.L. Schwob, M. Finkenthal, A. Bar-Shalom, P. Mandelbaum, and B.S. Fraenkel, *J. Opt. Soc. Am.* 71, 219 (1981).
30. B.C. Stratton, W.L. Hodge, H.W. Moos, J.L. Schwob, S. Suckewer, M. Finkenthal, and S. Cohen, *J. Opt. Soc. Am.* 73, 877 (1983).
31. H. Milchberg, J.L. Schwob, C.H. Skinner, S. Suckewer, and D. Voorhees, in *"Laser Techniques in the Extreme UV,"* Boulder, S.E. Harris and T.B. Lucatorto editors, *AIP Conf. Proc. No. 119* (American Institute of Physics, New York, 1984), p. 379.
32. S. Suckewer, C.H. Skinner, H. Milchberg, C. Keane, and D. Voorhees, *Phys. Rev. Lett.* 55, 1753 (1985).
33. L.B. Lapson and J.G. Timothy, *Appl. Opt.* 15, 1218 (1976).
34. R. Malina, Ph.D. thesis, University of California, Berkeley (unpublished).
35. J.L. Schwob, A.W. Wouters, S. Suckewer, F. Boody, and M. Finkenthal, *Proc. of the 8th International Colloquium on "UV and X-ray Spectroscopy of Astrophysical and Laboratory Plasmas,"* IAU No. 86, G.A. Doschek editor, N.R.L., Washington, D.C., (1984) p. 171.
36. A.W. Wouters, J.L. Schwob, S. Suckewer, F.P. Boody, R. Hulse, and J. Schivell, *Proc. of the 5th Topical Conf. on "High Temperature Plasma Diagnostics,"* Tahoe City, CA, E.M. Campbell and G.W. Leppelmeier editors, *Rev. Sci. Instrum.* 56, 849 (1985).

37. S. Suckewer, C.H. Skinner, C. Keane, D. Kim, J.L. Schwob, E. Valeo, D. Voorhees, and A. Wouters, Proc. of the First International Laser Science Conf., Dallas, Texas, Nov. 1985, A.I.P. Proc. Series 1986.
38. B. Saoutic, private communication.
39. J.H. Dave, U. Feldman, J.F. Seely, A. Wouters, S. Suckewer, E. Hinnov, and J.L. Schwob, J. Opt. Soc. Am. B. (to be published).
40. B.S. Stratton, private communication.
41. E. Hinnov and W. Hofmann, J. Opt. Soc. Am. 53, 1259 (1963).
42. E. Marmar, J. Cecchi, and S. Cohen, Rev. Sci. Instrum. 46, 1149 (1975).
43. M. Finkenthal, B.C. Stratton, H.W. Moos, W.L. Hodge, S. Suckewer, S. Cohen, P. Mandelbaum, and M. Klapisch, J. Phys. B: At. Mol. Phys. 18, 4393 (1985).
44. J.L. Schwob, A. Wouters, S. Suckewer, S.A. Cohen, and M. Finkenthal, J. Opt. Soc. Am. B. 3, 68 (1986).

Table I Caption

Central wavelength λ_0 . ($p=512$), simultaneous coverage limits λ_1 and λ_2 and spectral resolution $\Delta\lambda(\text{FWHM})$ predicted at central wavelength with 10- μm and 20 μm wide entrance slits, as a function of detector carriage position y along the leadscrew.

TABLE I

600 g/mm grating					2400 g/mm grating			
y[mm]	λ_0^a	Coverage	Spectral resolution (FWHM)		λ_0	Coverage	Spectral resolution (FWHM)	
		$\lambda_1 - \lambda_2$	$\Delta\lambda$ (20 μm)	$\Delta\lambda$ (10 μm)		$\lambda_1 - \lambda_2$	$\Delta\lambda$ (20 μm)	$\Delta\lambda$ (10 μm)
80	13	5 - 20	0.17	0.10				
120	30	18 - 41	0.18	0.11	7.6	5 - 10.2	0.045	0.027
160	55	39 - 69	0.19	0.12	13.7	9.7 - 17	0.048	0.031
200	85	65 - 103	0.20	0.14	21	16 - 28	0.050	0.035
240	121	98 - 142	0.21	0.16	30	25 - 36	0.053	0.039
280	163	136 - 188	0.23	0.18	41	34 - 47	0.057	0.044
320	211	181 - 239	0.24	0.19	53	45 - 60	0.060	0.048
360	265	232 - 296	0.26	0.21	66	58 - 74	0.064	0.053
390	310	274 - 343	0.27	0.23	78	69 - 86	0.067	0.057

a. λ_0 , λ_1 , λ_2 , and $\Delta\lambda$ are expressed in Angstroms.

FIGURE CAPTIONS

- Fig. 1 View of the soft X-ray spectrometer body equipped with two multichannel detectors, both to be coupled to one PDA-OMA system, according to the configuration shown in Fig. 4c.
- Fig. 2 Geometry of the spectrometer equipped with a single channel detector carriage which supports the exit slit S. The nut pivot is attached to the carriage which can be moved along the Rowland circle by rotation of the lead screw; the swivel joint center J is fixed with respect to the spectrometer.
- Fig. 3 Schematic of the multichannel detector system.
- Fig. 4 Schematic of various possible configurations in use in the multichannel spectrometer:
- a - Mixed configuration, including one multichannel detector and one single channel electron multiplier.
 - b - Duo-multichannel detector mode, with two independent PDA-OMA systems.
 - c - Duo-multichannel detector mode, with the two MCD's coupled to the same PDA-OMA system.
- Fig. 5 Geometry of the spectrometer equipped with a microchannel plate (MCP) detector, tangent at the center T_0 of its input face to the Rowland circle. The MCP is coupled through a fiber optic taper to a photodiode array (PDA).
- Fig. 6 Short wavelength part (5-20 Å) of the PLT tokamak spectrum obtained with a 600 g/mm grating and a 20-μm width entrance slit, showing the H- and He-like Al lines around 7 Å emitted during aluminum injection. a, b, and c are three succeeding PDA scans of 128 ms integration time each:
- a - before injection
 - b - including injection
 - c - after injection
- Fig. 7 A fragment of a high resolution spectrum from PLT intrinsic impurity emission between 15 Å and 22 Å obtained using the 600 g/mm grating but with a 10-μm width slit.
- Fig. 8 a- PLT spectrum in the 18-41 Å range, obtained with the usual spectrometer parameters (600 g/mm grating 20-μm width slit), showing the principal lines of the low-Z impurities.
- b- The same, but with an expanded intensity scale.

Fig. 9 PLT spectrum in the 117-163 Å range obtained with the same spectrometer parameters as for Fig. 8 (time interval from 770 to 900 ms).

Fig. 10 a- Profile of the CV resonance and intercombination lines suitable for plasma diagnostics well separated in the first order in usual spectrometer conditions (600 g/mm grating, 20-μm width slit) - The experimental points are signals from individual pixels while the dashed line denotes the best fit of data to Gaussian profiles.

b- OVII resonance and intercombination lines separated in the first order using the 600 g/mm grating but with a 10-μm width slit.

c- CV resonance and intercombination lines was observed with high resolution using a 2400 g/mm grating and 20-μm width slit.

Fig. 11 Spectral resolution (FWHM) as a function of wavelength with a 600 g/mm grating:

1. Multichannel detector response function at the center (p=512) with a 130-μm spatial resolution.
2. Intrinsic spectrograph resolutions with a 20-μm width entrance slit.
3. The same but with a 10-μm width entrance slit.
4. Line width predicted by convolution of both intrinsic spectrograph (2) and detector (1) functions at the detector center with a 20-μm width slit.
5. The same but with a 10-μm width slit (from (3) and (1)).
6. Defocusing component at the detector edges (p=1 and p=1024).
7. Width of a line detected at the detector edge with a 20-μm width slit, obtained by convolution of the profiles indicated in (4) and (6).
8. The same but with a 10-μm width slit (from (5) and (6)).

Experimental profile width obtained with 20-μm and 10-μm width slits respectively, using lines for which the Doppler broadening is expected to be negligible.

Fig. 12 PLT spectrum obtained in usual conditions, showing the spectral profile of the OVI 150.1 Å line:

- a - The line is detected close to the microchannel plate center (p=533).

b - After moving the detector carriage, the line appears near the edge ($p=924$). No appreciable increase in the profile width is observed.

Fig. 13 PLT spectrum in the 58-95 Å range.

a - Before molybdenum injection.

b - After molybdenum injection, showing a region of high line density, mainly due to 3p - 3d transitions from many ionization stages of molybdenum.

Fig. 14 Time - resolved display of the emission recorded from the TFTR tokamak in the 130-170 Å range, showing a sudden zirconium emission due to plasma - AlZr getter interaction.

Fig. 15 a-f: Time evolution of line radiation from various ions in a large TFTR discharge ($R=255$ cm, $a=83$ cm, $I_p=1.4$ MA), compared to the total radiated power from bolometric measurements shown in g (from Ref. 36).

#86X1343

Fig. 1

Fig. 2

Fig. 3

Fig. 4

#86X1344

Fig. 5

Fig. 6

#86X1440

Fig. 7

Fig. 8

Fig. 10(a)

Fig. 10(b)

Fig. 10(c)

Fig. 11

Fig. 12

Fig. 13

#84X1425

Fig. 15

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