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MULTICHANNEL EUV SPECTROSCOPY OF HIGH TEMPERATURE PLASMAS

By

R.J. Fonck

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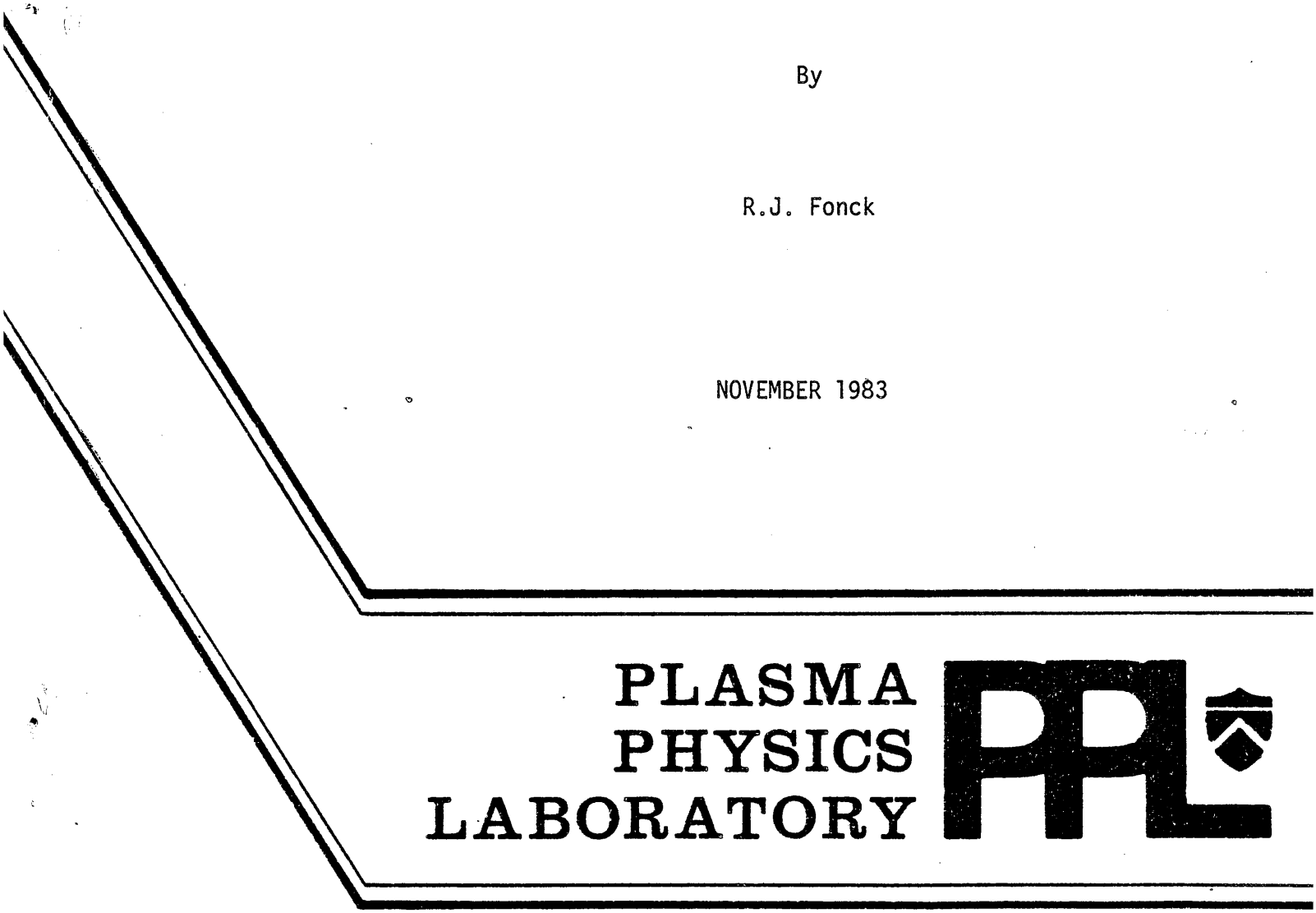

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MULTICHANNEL EUV SPECTROSCOPY OF HIGH TEMPERATURE PLASMAS*

Raymond J. Fonck

Plasma Physics Laboratory, Princeton University

Princeton, New Jersey 08544

ABSTRACT

Spectroscopy of magnetically confined high temperature plasmas in the visible through X-ray spectral ranges deals primarily with the study of impurity line radiation or continuum radiation. Detailed knowledge of absolute intensities, temporal behavior, and spatial distributions of the emitted radiation is desired. As tokamak facilities become more complex, larger, and less accessible, there has been an increased emphasis on developing new instrumentation to provide such information in a minimum number of discharges. The availability of spatially-imaging detectors for use in the vacuum ultraviolet region (especially the intensified photodiode array) has generated the development of a variety of multichannel spectrometers for applications on tokamak facilities.

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I. INTRODUCTION

The measurement of extreme ultraviolet radiation (EUV) emitted from magnetically confined fusion plasmas deals principally with the study of line emissions from highly ionized impurities in the hot plasma.[1] The 500-1600 Å spectral range includes the major $\Delta n = 0$ transitions of common intrinsic low-Z impurities such as carbon and oxygen, while the 100-500 Å range contains the principal lines from highly ionized metals such as Fe, Ti, and Ni. In a hot plasma with central electron temperatures on the order of several keV, the low-Z impurity radiation comes mainly from the cool plasma periphery while the metallic radiation is emitted from the hotter core region of the plasma. Measurement of these emissions can provide sensitive local diagnostics of plasma properties. Determination of the absolute intensities of spectral lines is coupled with impurity transport models[2,3,4] to provide estimates of total radiative power loss due to the impurities. Even relative measurements under changing discharge conditions can be used to interpret the effects of plasma-wall interactions. Finally, plasma properties such as ion temperature and rotation velocities can be obtained through high resolution studies of impurity spectra.

A given fusion-grade plasma, whether it is in a tokamak, magnetic mirror, or other magnetic confinement device, will, in general, contain several impurity species, and all ion stages of a given atomic species will be present somewhere in the discharge. This of course leads to very complex spectra which must be measured and analyzed. For example, Fig. 1 shows an EUV spectrum obtained from the PDX tokamak, and the prominent lines of O, C, Fe, and Ti ions are indicated. The large background at short wavelengths is due principally to unresolved lines from several ion stages of the impurities. Measurements of the time histories of the absolute intensities of the

designated spectral lines in Fig. 1 during the transient plasma discharge would be the minimum amount of information needed for a semi-quantitative idea of impurity radiated power. To obtain more detailed information, such as the transport of impurities across the magnetic field lines in the tokamak, both spatial and temporal distributions of these lines and several others would have to be measured.

Clearly, this becomes a formidable task requiring a large number of reproducible discharges when done with conventional monochromators. As fusion experiments become more expensive and less accessible to the experimenter, reliable multichannel spectrometers are becoming essential to obtain appropriate information on discharge conditions. Even more important than the detailed studies of impurities alluded to above is the ability to give immediate feedback on impurity behavior and content under rapidly changing conditions. In the largest magnetic confinement devices, such as the TFTR tokamak, this "machine monitor" mode of operation will be an indispensable aid to guide the variation of discharge operation.

In this paper, we discuss the requirements for multichannel EUV detectors for studies in controlled thermonuclear research (CTR) plasmas. The emphasis is on obtaining spectra from tokamak experiments, but considerations for magnetic mirrors are similar. We mention several types of detectors used in the 20 to 1700 Å range in CTR, but only the most common, the intensified photodiode array, will be discussed in detail. These detectors are usually placed at the focal surface of an EUV spectrometer, which can range from a conventional normal or grazing incidence system with a single spherical diffraction grating to more exotic optical systems designed to perform specific measurements. Examples of both types of uses will be given.

II. GENERAL CONSIDERATIONS

There are several criteria which are used to evaluate multichannel detectors for use in CTR. Some of those are:

(A) Sensitivity

(B) Stability

(C) Uniformity

(D) Spatial Resolution

(E) Dynamic Range

(F) Time Resolution

(G) Susceptibility to harsh electromagnetic environments

(H) Storage space requirements

(I) Radiation hardness.

Several of these properties are interrelated, and the importance of a given feature depends in large part on the proposed application. We concentrate here on applications to broad spectral band monitoring of CTR plasmas to provide qualitative and quantitative survey spectra.

The spectral range of interest is typically anywhere from 20 to 1500 Å for general impurity monitoring, and a detector must have good sensitivity over at least a large fraction of that range. Since absolute intensity measurements are routinely required, the stability of a detector's response over long periods is especially crucial for minimizing the required maintenance and recalibration efforts. This requirement becomes more important as tokamak facilities become larger and less accessible. For a given spectrometer, the spatial resolution of the detector determines, in large part, the ultimate spectral resolution of the system consistent with the spectrometer apertures being large enough to admit a detectable light flux. In addition to resolution as specified by the full width at half maximum

(FWHM) of a spectral line profile, the contrast afforded by the detector (i.e., how fast the wings of the line profile drop away from the line center) is an important factor in determining the ability to detect weak lines in close proximity to very strong lines. Typical line intensitives range from 10^{12} to 10^{15} photons/cm^2 s sr, and experience on several tokamaks indicates that spectrometer slits with at least 20 to 50 μm widths are required for reasonable signal-to-noise ratios. Hence detectors with FWHM < 50 μm are desirable to obtain 2 to 3 detector resolution elements within the instrumental line profile. Transient events in hot plasmas can occur on time scales of ~ 0.1 ms (e.g., impurity spectra produced by laser ablation injection,[5] or excitation of impurity spectra by pulsed diagnostics neutral beams[6]), while for routine monitoring of impurities, a time resolution of ~ 10 ms is sufficient. Finally, CTR experiments present noisy electrical and magnetic environments for operation of sensitive imaging detectors, and care is required to provide appropriate shielding and isolation. Steady-state and transient magnetic fields on the order of 1 kG are present in diagnostic areas, and large electromagnetic pulses are present near the machines (some of the larger perturbations being due to faults or abrupt terminations of several MW neutral beam sources or to the presence of several MW radiofrequency sources for heating the plasma). The near future will see CTR plasmas which emit large levels of energetic neutrons, and detectors must be hardened for radiation noise and damage.

The generic one-dimensional imaging device used for EUV plasma spectroscopy employs a microchannel plate (MCP)[7] image intensifier/converter placed at the focal surface of the spectrometer. This provides an imaging device which converts EUV photons to electrons and amplifies the electron current with gains of 10^3 to 10^6. These detectors have a very fast time

response [8,9] and are easily available from several commercial sources. The main disadvantages to the MCP seem to be the available dynamic range, especially at high gain, and to a lesser extent, the achievable spatial resolution in a typical MCP proximity focussed intensifier. Both of these areas of concern are presently being addressed and improved upon by the MCP vendors.

The conversion of the electron signal out the back of the MCP to a useful signal is achieved via two approaches: 1) the electron current is read directly with some sort of multi-anode structure, which allows operation in either a pulse-counting or analog current measurement mode; and 2) the electrons are accelerated into a phosphor to produce visible photons which are then detected by a multichannel visible light detector. The latter approach is almost always used in an analog mode for broad band magnetic fusion spectroscopy. We give most of our attention to this second approach because it is the most widely used and offers the greatest flexibility in a given detector.

Several visible detectors have been used in CTR research as the encoding device behind an MCP for EUV spectroscopy. These have included a gated Vidicon,[10] a CID camera,[11] and, most commonly, a self scanning photodiode array (PDA).[12,13] The self scanning PDA has achieved widespread use and has shown itself to be a very useful and flexible detector. It is discussed in some detail in the next section.

III. INTENSIFIED PHOTODIODE ARRAY

An intensified photodiode array (IPDA) detector for one-dimensional spatial imaging in the EUV is shown in Fig. 2. This type of detector was originally described by Riegler and Moore.[14] It consists of a microchannel

plate whose output is optically coupled to a self-scanning photodiode array. An incident photon produces a photoelectron which is subsequently amplified by the MCP. The exiting electrons are proximity focussed onto a phosphor layer which converts the electron energy to visible photons. Proximity focussing is accomplished by applying a 5 kV potential across the small gap (~ 1 mm) between the back of the MCP and the phosphor. P-20 phosphor is typically used for maximum signal and good matching to the photodiode array response. This phosphor is coated on the face of a fiber optic image conduit which is optically contacted to the PDA.

The photodiode array most commonly used is the Reticon 1024SF which has 1024 pixels on 25 μm centers. Each pixel is 2.5 mm high, which gives an aspect ratio (height to width) of 100:1 and is well suited for acting as an exit slit for a grating spectrometer. The large pixel size allows a large dynamic range (maximum signal/readout noise) in a single scan. These features make the intensified photodiode array a very attractive detector for simultaneous observation of intense and weak emissions.

Requiring at least 2 pixels per resolution element gives a maximum of 512 resolution elements across the array. Readout times of the PDA can vary greatly, depending on the driving electronics, and scan integration times from 1 to 50 msec are readily achievable. The PDA has virtually no image lag on successive scans, which is an important feature when observing rapidly varying spectra. Since the effective spectral range is determined by the photocathode material on the MCP, and since the PDA responds only to the phosphor output, the IPDA can serve as a general detector ranging from the soft X ray to the far visible. The response of an IPDA with a CuI photocathode is shown in Fig. 3.

Another attractive feature of the PDA is the flexibility in readout pattern available with a single detector. By selectively collecting data from

predetermined pixels or groups of pixels, time resolution can be increased and required memory space can be minimized.

The resolution of the IPDA detector is determined chiefly by spreading of the electron cloud as it exits the back of the MCP and is accelerated towards the phosphor. Ignoring space charge effects, which are unimportant for a single MCP run at a gain of 10^4 or less,[15] simple orbit theory gives the charge spreading due to a point source of electrons in the channel to be

$$Y = 2 \sin (2\theta) \frac{Us}{V_{ph}} \left(\sqrt{1 + V_{ph}/U\cos 2\theta} - 1 \right) . \qquad (1)$$

In Eq. (1), Y is the diameter of the electron cloud at the phosphor surface, θ is the effective angle at which an electron is emitted relative to the MCP channel axis, s is the separation between the phosphor surface and the MCP, U is the mean electron energy at the end of the channel, and V_{ph} is the potential difference between phosphor and MCP. Although this description grossly oversimplifies the actual physical processes occuring at the MCP phosphor interface, it provides a remarkably good semi-quantitative estimate of the net detector resolution. Figure (4) shows the measured FWHM of a spectral line profile measured with an IPDA on the output planes of two VUV spectrometers with similar instrumental functions. The solid line is given by Eq. (1) with a 50 μm offset added to account for the channel-to-channel separation of the MCP (15 μm) and the spectrometer resolution due to the finite slit width (~ 30 μm) . The values of U = 30 eV and θ = 10.5° used for the fit to the data are typical for a single stage MCP intensifier.[16]

In practice, the detector resolution is limited by the value of s, the MCP-phosphor separation, since electrical breakdown eventually occurs if V_{ph} is kept at a reasonably high value of ~ 5 kV. Values of s down to 0.4 mm are possible with V_{ph} = 5 kV if sufficient precautions are taken to ensure a clean vacuum and that the phosphor and MCP surfaces are sufficiently smooth.

Although a FWHM of 40 μm or less is achievable with the IPDA, the line profile obtained with this detector is not optimal for quantitative spectroscopy of dense spectra. Figure 5 shows the line profile (at 304 Å) obtained with an IPDA on a grazing incidence spectrometer. The solid line is a least squares best fit of the data to a convolution of the PDA response function (a trapozoid of base width 37.5 μm and top width 12.5 μm) and a Lorentzian function. The fact that a Lorentzian gives a good description of the line profile from the intensifier indicates that the wings of the instrumental function decrease rather slowly as one moves away from the line center. This presents severe problems when trying to separate weak lines from nearby strong lines (cf. Fig. 1). In effect, the intensified PDA suffers from relatively poor contrast and, in many cases, this property can be its chief defect.

The time response of the IPDA is usually determined by the decay time of the phosphoresence of the phosphor layer. For P-20 phosphor it usually takes about 2 ms for the output to decay to 10% of the initial value. A typical decay characteristic for an MCP intensifier is shown in Fig. 6. The decay is not exponential. Faster decays can be obtained using other phosphors, but phosphor efficiency and optimal matching to the PDA response may then be compromised.

The major sources of noise in the detector are dark current shot noise and readout noise.[17] A PDA has a fixed pattern noise level due to transient

signals being coupled to the video lines by external stray capacitances and a noise level due to uncertainty in resetting each diode during the readout process. Dark current noise can be made negligible by cooling the PDA (a typical temperature for operation is -20°C using a Peltier thermoelectric cooler). The fixed pattern noise level can be eliminated by subtracting a dark scan from the data scan, as shown in Fig. 7. With careful circuit design, the residual noise level can be reduced to ~ 1000 electron-hole pairs in a controlled environment.

The output of a pixel of the PDA is linear up to at least 2×10^4 times greater than its noise level, and comparison of the ratio between weak and strong spectral lines using the IPDA indicates that the MCP/intensifier output also is linear to ± 5% over this same range. Thus, the dynamic range in a single scan can be as high as 10^4:1, which is very useful since spectra from plasmas can have both weak and strong lines of interest in a given discharge.

The readout and data storage electronics for the IPDA can be quite varied, and two systems presently in use on tokamaks are mentioned here. Figure 8 shows a block diagram of the electronics used in an IPDA system in use at the Princeton University Plasma Physics Laboratory (PPPL) on the PDX and PLT tokamaks. The PDA is controlled by an optical multichannel analyzer system from EG&G Princeton Applied Research Corporation. This system, whose performance is described in some detail by Talmi and Simpson,[17] allows a great deal of flexibility in the output format of the PDA data. The entire 1024 pixels or selected portions thereof can be read (full or partial spectrographic modes of operation); alternately, adjacent pixels can be grouped to a common datum readout and other spectral regions skipped to allow observation of specific spectral lines (polychromatic mode). Minimum scan time for a full spectrographic readout is 16 ms, while up to six or seven

isolated spectral lines (i.e., pixel groups) can be sampled at a 1 kHz clock rate in the polychromator mode. The PARC 1412 detector head and PARC 1218 PDA controller module are interfaced to a mainframe computer system via a CAMAC interface system. The data is read directly into dual port memory modules which act as buffers for temporary data storage. The output register supplies programming commands to specify the PDA readout pattern, and the programmable clock provides a sequence of trigger pulses, each of which initiates a scan of the PDA. The programmable clock allows varying scan integration times for importance sampling during a tokamak discharge (duration ~ 1 sec) and hence helps minimize local memory requirements. The local CAMAC crate is fiber optically coupled to the serial CAMAC highway to eliminate ground loops and noise pickup. The CAMAC system is controlled by a PDP-11 on PDX and PLT. This interface system provides a relatively simple and cheap method of interfacing a PDA detector system to an existing data acquisition system with several separate diagnostic systems controlled by a single computer.

An alternate approach using a dedicated desktop computer has been developed by the Johns Hopkins University spectroscopy group.[13] A block diagram of their system is shown in Fig. 9. The Reticon Evaluation Circuit Board (RC1024S) is used for the scanning circuitry. The digitized (12-bit) data are transmitted to the remote data processor and control unit and held in a buffer memory access. The data is stored on flexible disk and can be processed and displayed on graphical output between plasma shots. This system has the advantages of a dedicated computer system and easy mobility, while the largest disadvantages seem to be cost and lack of general availability. The system shown in Fig. 9 reads out a full scan every 3.7 ms. This increased time resolution comes out at the expense of dynamic range (i.e., 12-bit data versus 14-bit data output from the PARC electronics).

IV. APPLICATIONS OF THE IPDA

The application of IPDA's to spectroscopy of fusion plasmas is a relatively new phenomenon, and we mention here a few of the conventional and unconventional EUV spectrometer systems made possible by the availability of these detectors.

The simplest application of the IPDA is to place it at the output focal surface of a typical vacuum ultraviolet monochromator. Such a system is shown in Fig. 10 and has been employed on the PDX tokamak.[18] The spectrometer is a 0.2 m focal length normal incidence spectrometer which is readily available commercially (e.g., Action Research Corporation, Model VM-502). The orientation of the detector as shown results in substantial defocussing on the edges of the detector plane, but this can be minimized by proper orientation of the detector along the tangential focal surface or by operating at higher f/no and hence large depth of focus. This simple system allows coverage of $\sim$ 900 Å in first order of diffraction with $\sim$ 3 Å resolution. Rotation of the grating allows coverage of the 300-1700 Å spectral range. The holographic gratings employed in the spectrometer provide a sufficiently broad blaze that increased resolution is available with reasonable efficiencies by working in higher orders of diffraction. This spectrometer system has been used to provide a monitor of general machine and impurity conditions. A sample of spectra obtained from the PDX tokamak is given in Fig. 11. The spectrum labelled "Diverted" corresponds to discharges bounded by a magnetic divertor system on PDX which is employed to remove the contact between the hot plasma and a material surface to a remote burial chamber, thus minimizing the production and influx of metallic impurities in the discharge. The second scan corresponds to a discharge with a conventional metallic (titanium) rail limiter in the main plasma chamber to provide the plasma-surface contact

limiter in the main plasma chamber to provide the plasma-surface contact point. The reduction of metallic impurities and increased fueling requirements (evidenced by increased hydrogen emissions) in diverted discharges is immediately obvious from these two spectra.

A much more sophisticated and versatile normal incidence time-resolving spectrograph is described by Bell, Finkenthal, and Moos.[13] They employ a normal incidence spectrometer with seven separate diffraction gratings and an IPDA detector system in place of the exit slit on the Rowland circle. The gratings are blazed and coated to give maximum efficiency in different wavelength intervals. A pre-slit is employed to illuminate a single grating at a time. This system has been employed on the Alcator A and the TFR-600 tokamaks. The wavelength range is 300-200 Å and the resolution varies between 0.7 to 4 Å.

Since many important spectral lines from hot plasmas are emitted at very short wavelengths (< 300 Å), the IPDA has been used increasingly in grazing incidence spectrometer systems on tokamak facilities. Hodge et al.[19] have placed an IPDA tangent to the Rowland circle on a 1-meter focal length grazing incidence spectrometer (α = 88°) in order to observe spectra in the 20 to 300 Å range from the PLT tokamak. A desirable feature while working at such grazing angles of incidence on the detector plane is that an electron collection field be employed or the MCP must be funneled to provide a decent detection efficiency.[20] A general impurity monitor for tokamak plasmas has been developed by the author and co-workers by employing a Type IV toroidal diffraction grating in a grazing incidence spectrometer (α = 71°).[12] The gratings are aberration corrected to give a flat focal surface which matches the input face of an IPDA. A schematic of such a system is shown in Fig. 12. This spectrometer provides spectra over the 100-1100 Å range with 2 Å resolution. A full spectrum such as shown in Fig. 1 is recorded every 20 ms.

The flexibility and utility of these spectrometers with IPDA detectors is quite obvious. Figure 13 shows a time evolution of low wavelength spectra from the PDX plasma using the spectrometer in Fig. 12. Only one half of five of the full thirty-five recorded scans is shown here. The abrupt appearance of the TiXI and XII lines and a group of lines at 200-300 Å in scan 13 is indicative of an influx of titanium into the discharge. Within 20 msec, these ions have diffused into the hot plasma core and ionized up to produce strong TiXIX and XX lines. Before these atoms leave the plasma, another burst of Ti influx occurs in scan 15. Throughout these random bursts of Ti influx, it is noted that the oxygen radiation is unaffected. This wealth of information is obtained in a single shot, while a standard monochromator would have required a large number of reproducible discharges to produce similar information.

Operation in the polychromatic mode allows the determination of the time evolution of individual ion species. Figure 14 shows polychromatic data obtained with the spectrometer of Fig. 12 on the PDX tokamak. For this data, several groups of pixels, ranging in sizes from 4 to 8 pixels and each covering a spectral line of interest, were sampled with a 2 msec integration time. The sudden rise in the ScXI and ScXVII lines is due to a short burst of scandium influx induced via laser ablation of a thin Sc film from a glass slide. As Sc moves into the discharge it ionizes upward until it reaches a terminal stage of ScXVIII or XIX in the center of the discharge. The subsequent decay of these central ions is due to the loss of Sc from the discharge and is a measure of the impurity confinement time. The fact that the OVI radiation remains unchanged throughout this process indicates that the injection process is nonperturbing. Again, the number of discharges required to get the salient data is significantly reduced by using the IPDA/spectrometer system instead of conventional monochromators.

V. DISCUSSION

A notable multichannel spectrometer which does not use an IPDA is the SIDS (Spatial Imaging Detector System) spectrometer system developed by Richards et al.[21] This system uses a discrete anode array behind a high gain MCP combination to provide a photon counting detector with 19 separate channels. Placing this detector behind the exit slit of a conventional normal incidence EUV spectrometer allows one-dimensional images of the plasma to be recorded at a given wavelength with relatively high time resolution (~ 0.1 msec). This system has been used extensively on the Alcator tokamaks and on the TMX magnetic mirror experiment.

The above discussion is presented merely to give an idea of the types of EUV detectors and their applications in use on present fusion plasma experiments. It is by no means an exhaustive list of possibilities. Indeed, several different detectors are in use or being planned in future experiments. Resistive anode encoders will probabaly see more use in fusion experiments as they become commercially available. However, the low count rates available (~ 10^5 to 10^6 sec^{-1}) will result in these detectors being used mostly for line profile studies (e.g., ion temperature measurements via Doppler broadening measurements). Intensified CCD arrays (back-illuminated or otherwise), vidicon or CID systems, lens-coupled intensifiers, and anode detectors have all seen some use on tokamak experiments or are planned for the near future, but they have not been widely used as yet. However, in terms of availability, pixel format, dynamic range, insensitivity to magnetic fields, compact package, and moderate cost, the IPDA remains the most versatile multichannel EUV detector for plasma spectroscopy.

An interesting development of the IPDA has recently been reported by Benjamin et al.[22] They use a high gain ($\sim 10^7$) MCP combination coupled with a rapid readout of the PDA to allow detection of individual photons. Centroiding of the photon pulse allows spatial resolutions less than the pixel width. Also, a P-46 phosphor is used for fast time response. This system may be quite useful for line profile measurements in the EUV, where low counting rates can be tolerated.

Improvements in the IPDA would be desirable in the areas of resolution and contrast. The high wings in the line profiles from some intensifiers should be eliminated if possible, perhaps by adjusting the end spoiling depth of the MCP or tailoring the phosphor thickness to reduce light scattering in the phosphor. Finally, a large problem looming on the horizon for the use of these detectors in fusion research is the performance and reliability expected in high radiation environments. Even in the relatively protected areas near the next generation of fusion experiments (e.g., TFTR, JET, JT-60), fast neutrons (14 MeV) and the resultant gamma rays will provide a fairly hostile environment. Considerations of noise, degradation and damage to the PDX, and deterioration or coloring of the fiber optics will have to be addressed in the near future.

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FIGURE CAPTIONS

FIG. 1 EUV spectrum from the PDX tokamak showing prominent impurity emission lines (from Ref. 12).

FIG. 2 Intensified photodiode array detector for one-dimensional UV spatial imaging (from Ref. 13).

FIG. 3 IPDA detector response for an MCP with a CuI photocathode. Ordinate is in units of electrons produce in the photodiode array per photon incident on the MCP. Taken from Ref. 13.

FIG. 4 Resolution obtained with an IPDA as a function of intensifier parameters. Solid line is from Eq. (1) with U = 30 V and θ = 10.5° plus an offset of 50 μm. The grating resolution for the two spectrometers was as noted. The area noted MCP reflects the channel to channel spacing of the MCP (from Ref. 12).

FIG. 5 Line profile obtained with an IPDA detector system. Open circles are signals from individual pixels while the solid line denotes the best fit of data to a convolution of a Lorentzian function with the PDA response function and the entrance slit width. FWHM of the fitted Lorentzian is 1.84 pixels (from Ref. 12).

FIG. 6 Decay characteristic of an intensifier phosphor output when a steady source is chopped off at t = 0. The intensifier had P-20 phosphor (from Ref. 12).

FIG. 7 Example of fixed background compensation: a) raw data from an IPDA on a grazing incidence spectrometer; b) data in (a) with a dark scan subtracted. Spectrum obtained on the PDX tokamak (from Ref.12).

FIG. 8 Block diagram of electronics used to couple the PARC photodiode array readout electronics to a local data acquisition system (from Ref. 12).

FIG. 9 Block diagram of a self-contained electronics control system for an IPDA detector. Components to the left of the dashed line are incorporated into the detector package on the spectrometer, while those to the right are located in the tokamak control room (from Ref. 13).

FIG. 10 Simple VUV spectrometer system with an IPDA detector attached. Accessible spectral range is 300 to 1700 Å.

FIG. 11 Spectra obtained from the PDX tokamak with the normal incidence spectrometer system shown in Fig. 10. Integration times are 50 ms for each scan. Most of the lines observed are in higher orders of diffraction.

FIG. 12 Optical schematic of an aberration-corrected toroidal diffraction grating spectrometer designed for use with an IPDA detector system (from Ref. 12).

FIG. 13 Time evolution of low-wavelength spectra showing bursting of titanium radiation in a PDX discharge (from Ref. 12).

FIG. 14 Polychromatic output of the spectrometer in Fig. 12 showing the time evolution of Sc spectral lines arising from laser blowoff injection of Sc in a tokamak discharge. Integration time is 2 msec (from Ref. 12).

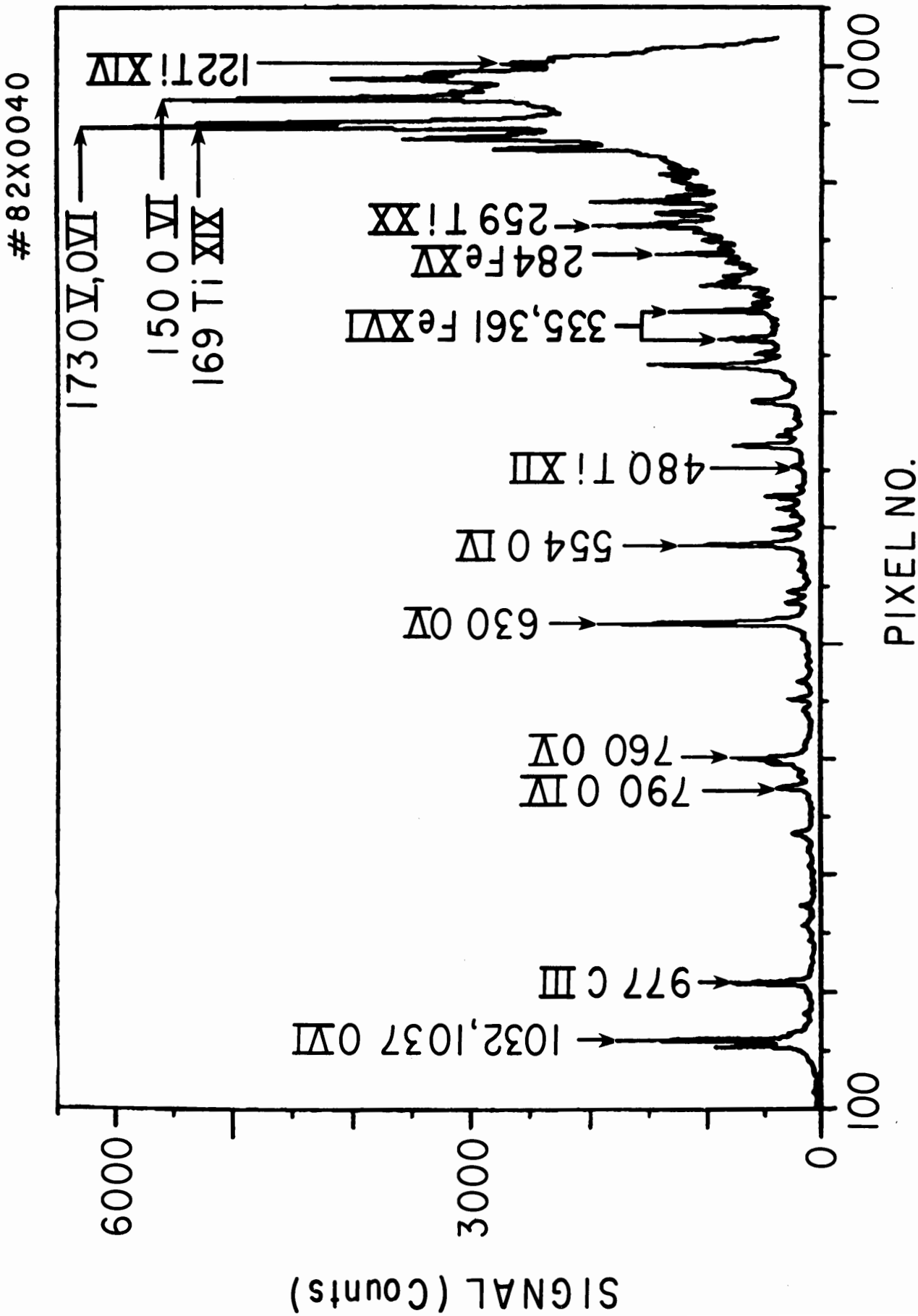
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Fig. 1

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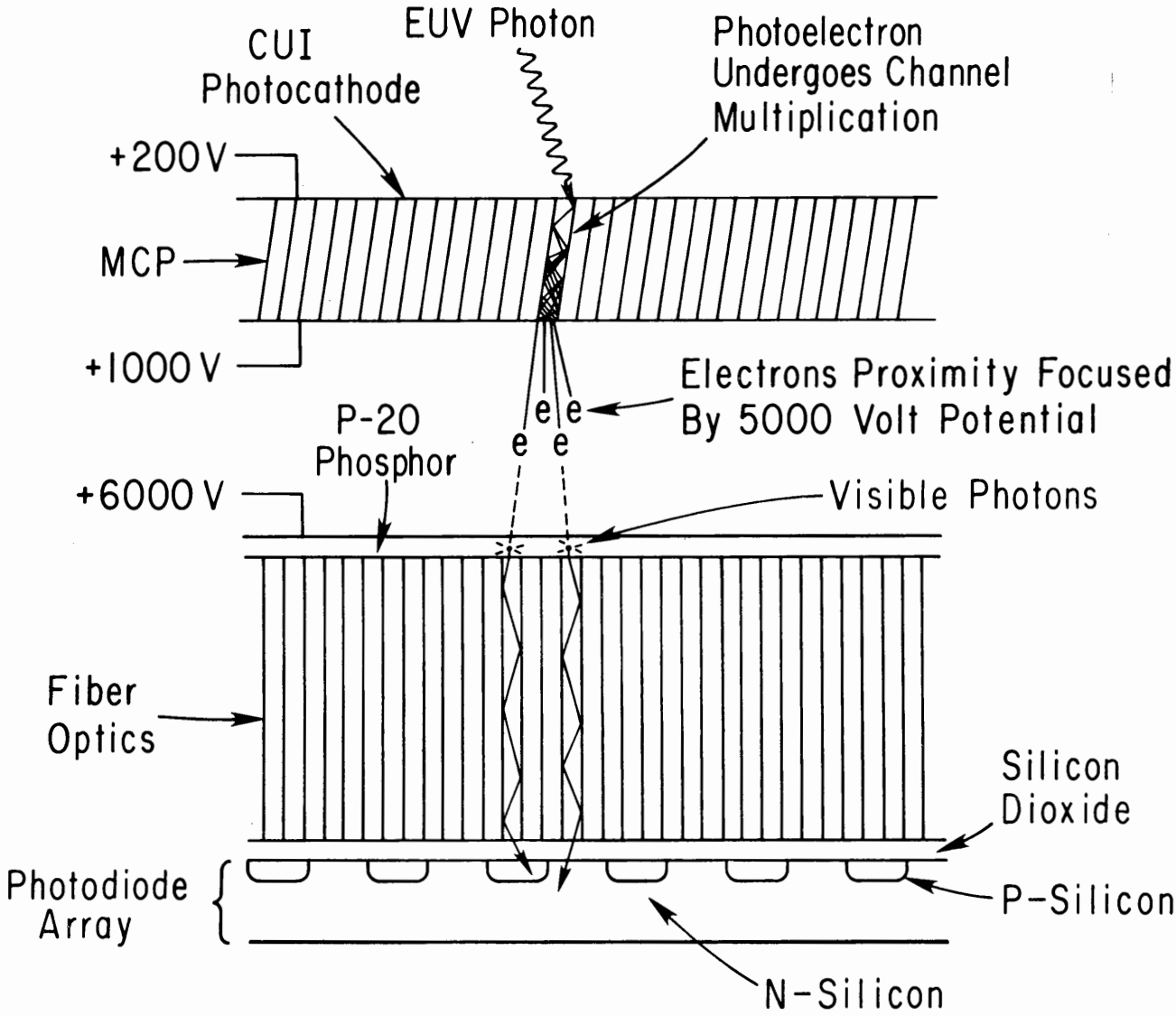

Fig. 2

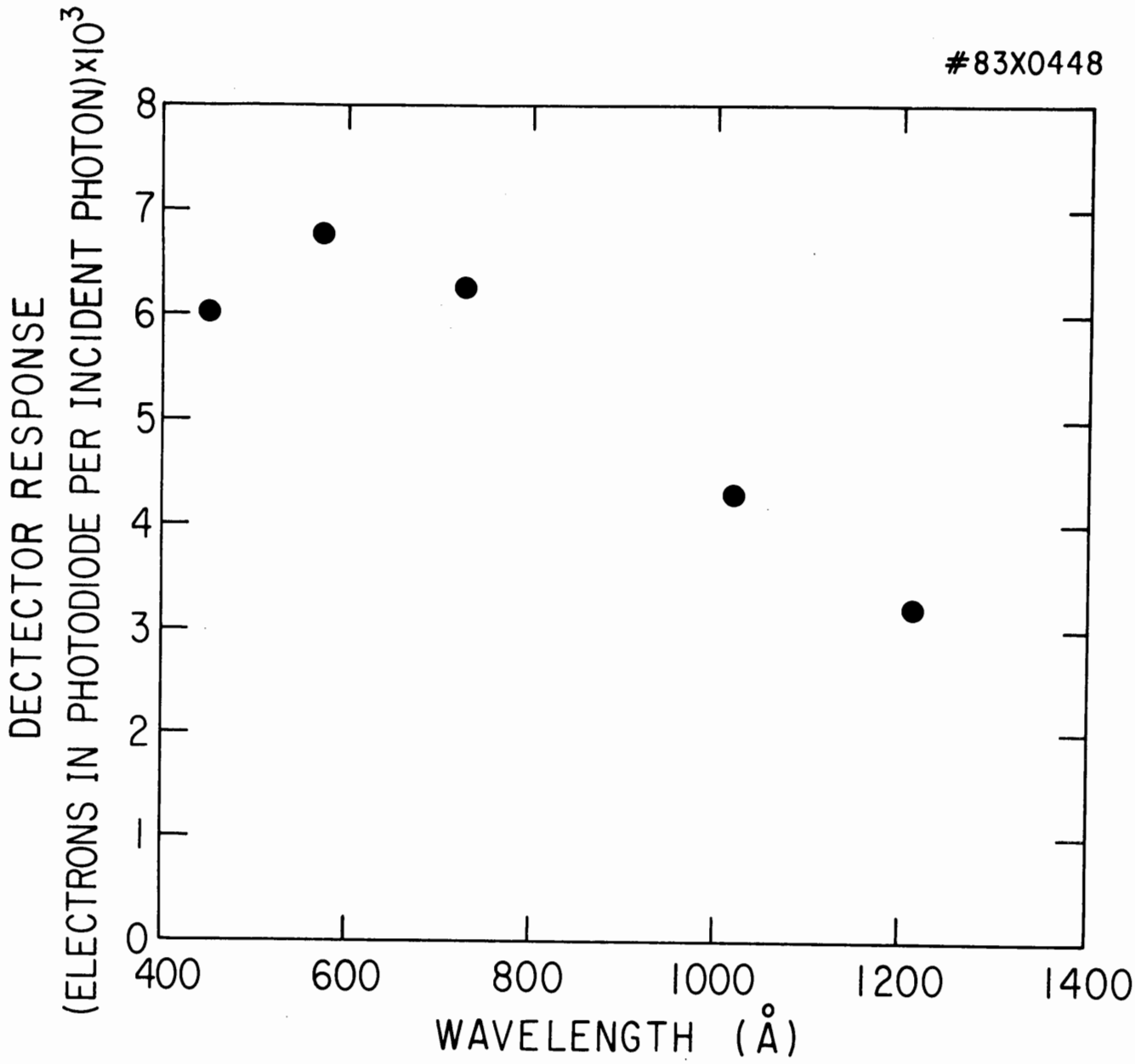
#83X0448
DECTECTOR RESPONSE
(ELECTRONS IN PHOTODIODE PER INCIDENT PHOTON)x10^3
0
1
2
3
4
5
6
7
8
400
600
800
1000
1200
1400
WAVELENGTH (Å)

Fig. 3

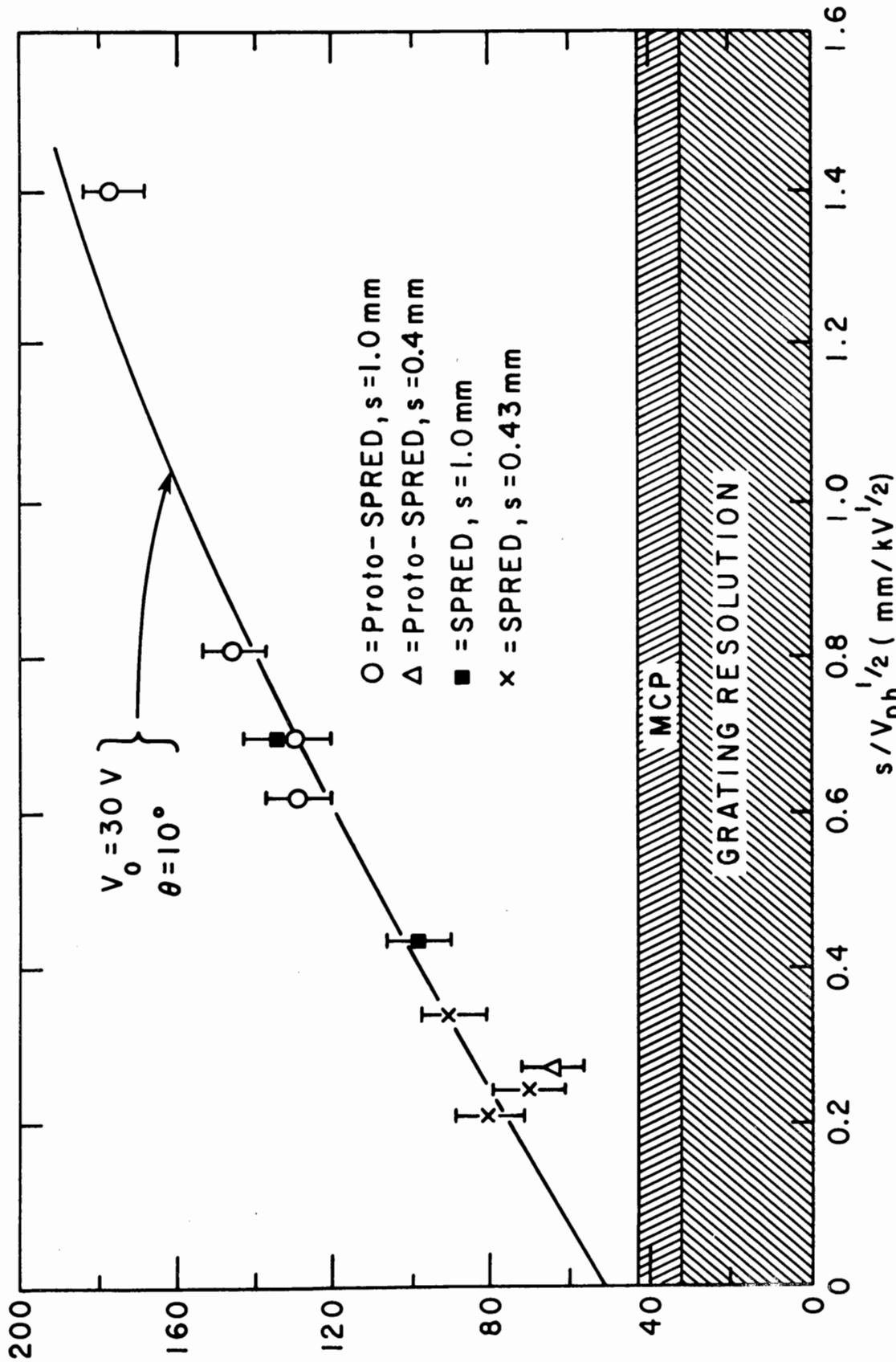
#82X0014
RESOLUTION (FWHM in Microns)
200
160
120
80
40
0
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
s / V_ph^1/2 (mm / kV^1/2)
V_o = 30 V
θ = 10°
O = Proto-SPRED, s = 1.0 mm
Δ = Proto-SPRED, s = 0.4 mm
■ = SPRED, s = 1.0 mm
x = SPRED, s = 0.43 mm
MCP
GRATING RESOLUTION

Fig. 4

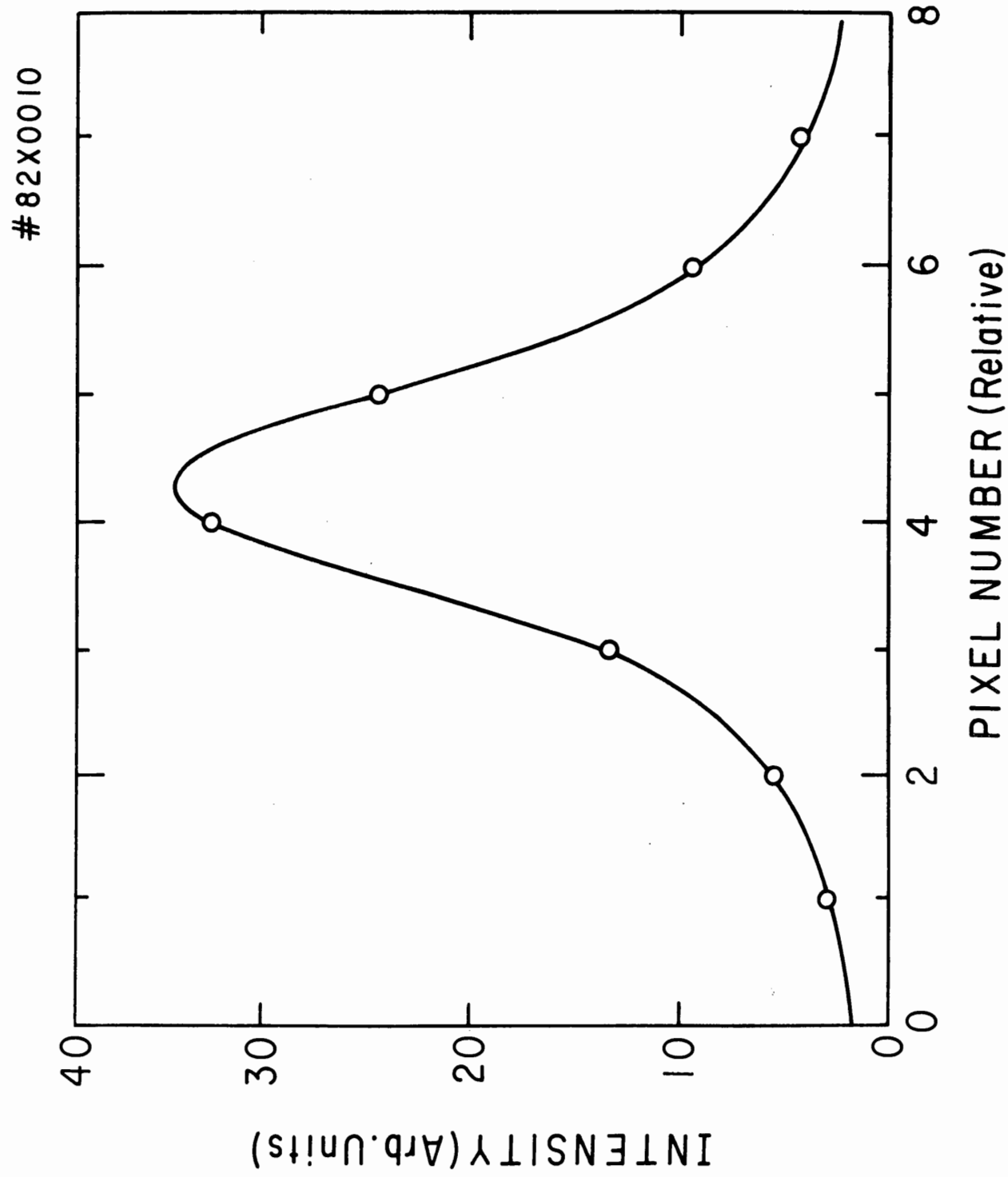
#82X0010
INTENSITY (Arb. Units)
PIXEL NUMBER (Relative)
0
10
20
30
40
0
2
4
6
8

Fig. 5

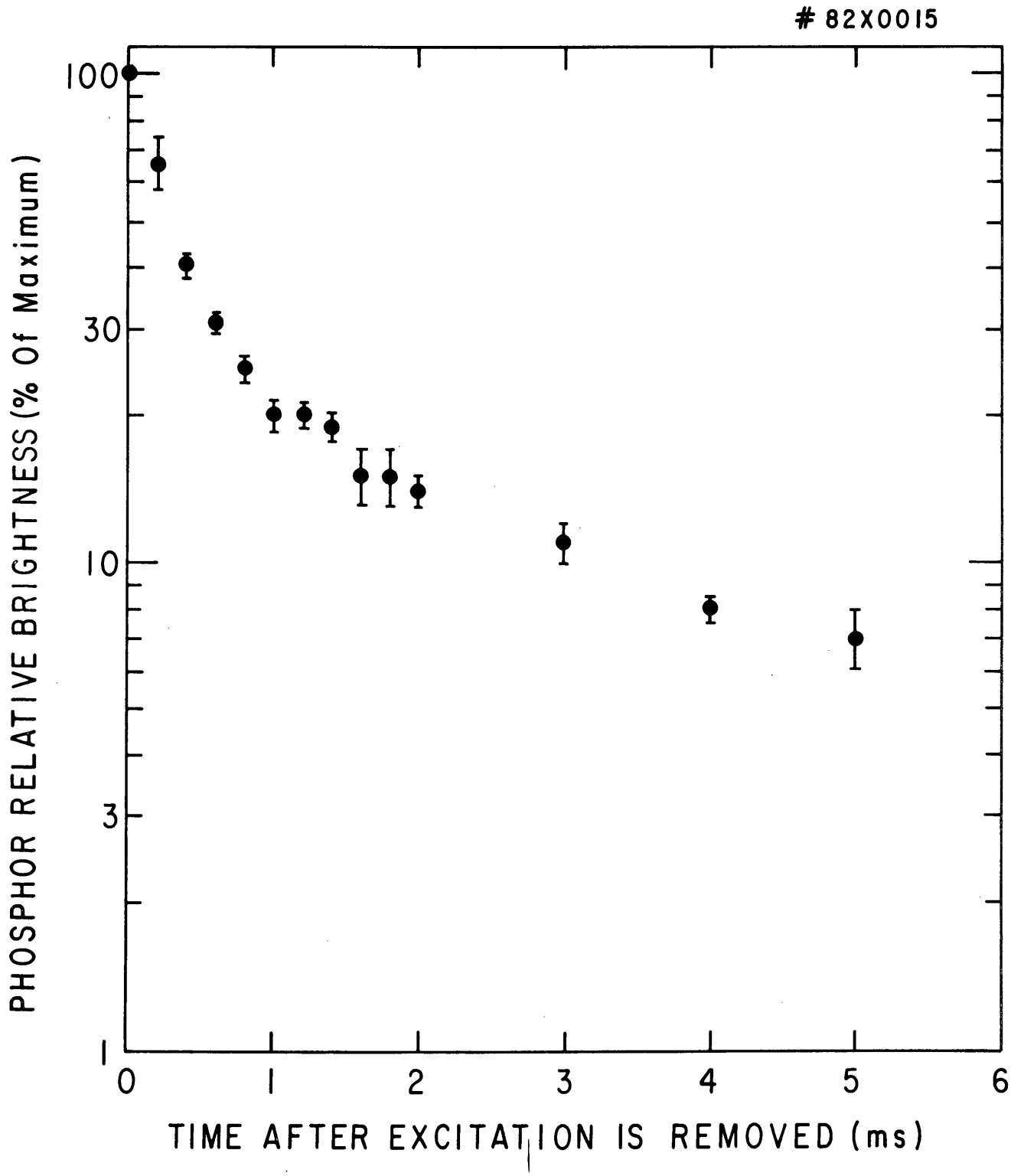
82X0015
100
30
10
3
1
PHOSPHOR RELATIVE BRIGHTNESS (% Of Maximum)
0
1
2
3
4
5
6
TIME AFTER EXCITATION IS REMOVED (ms)

Fig. 6

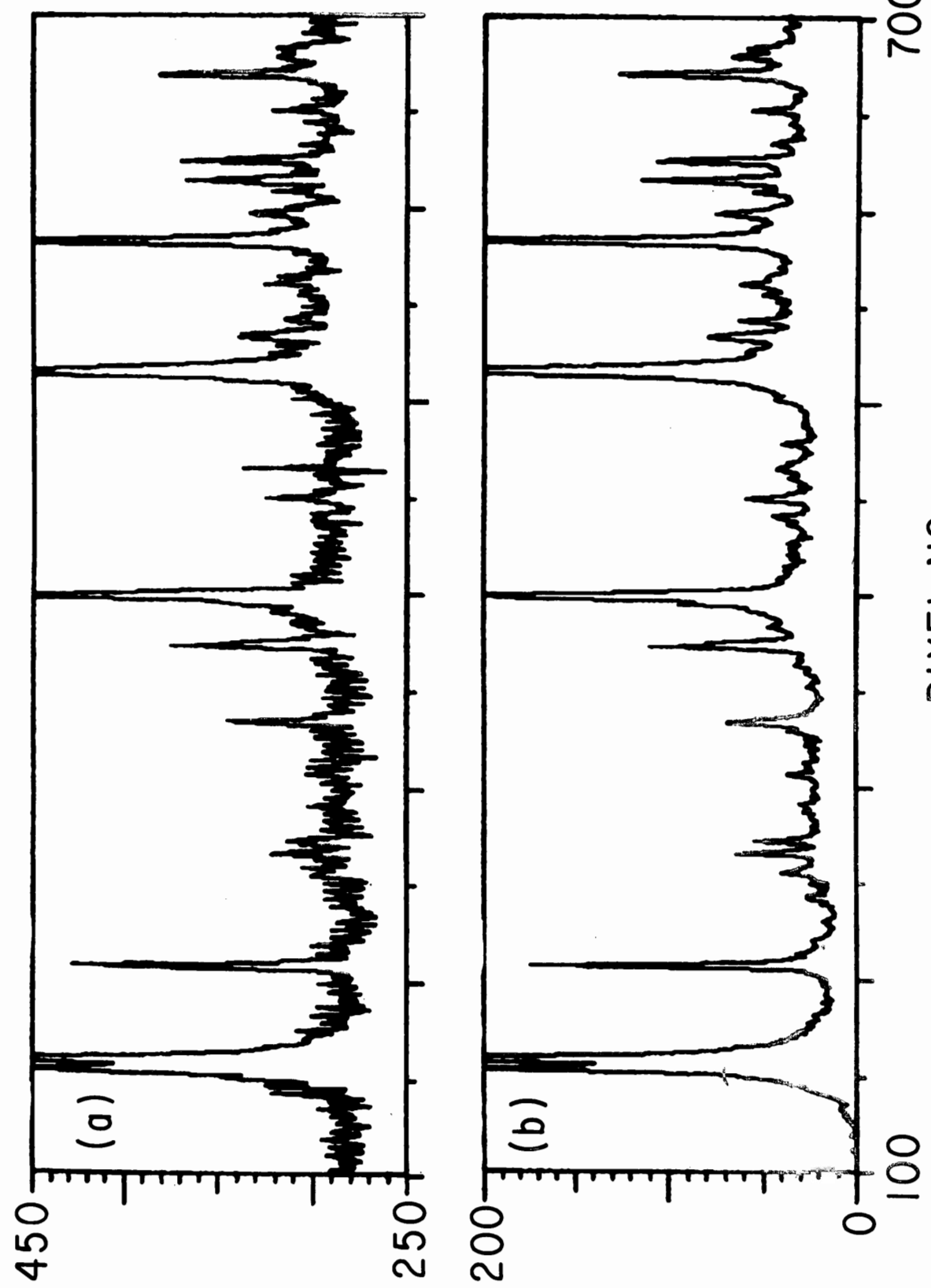

Fig. 7

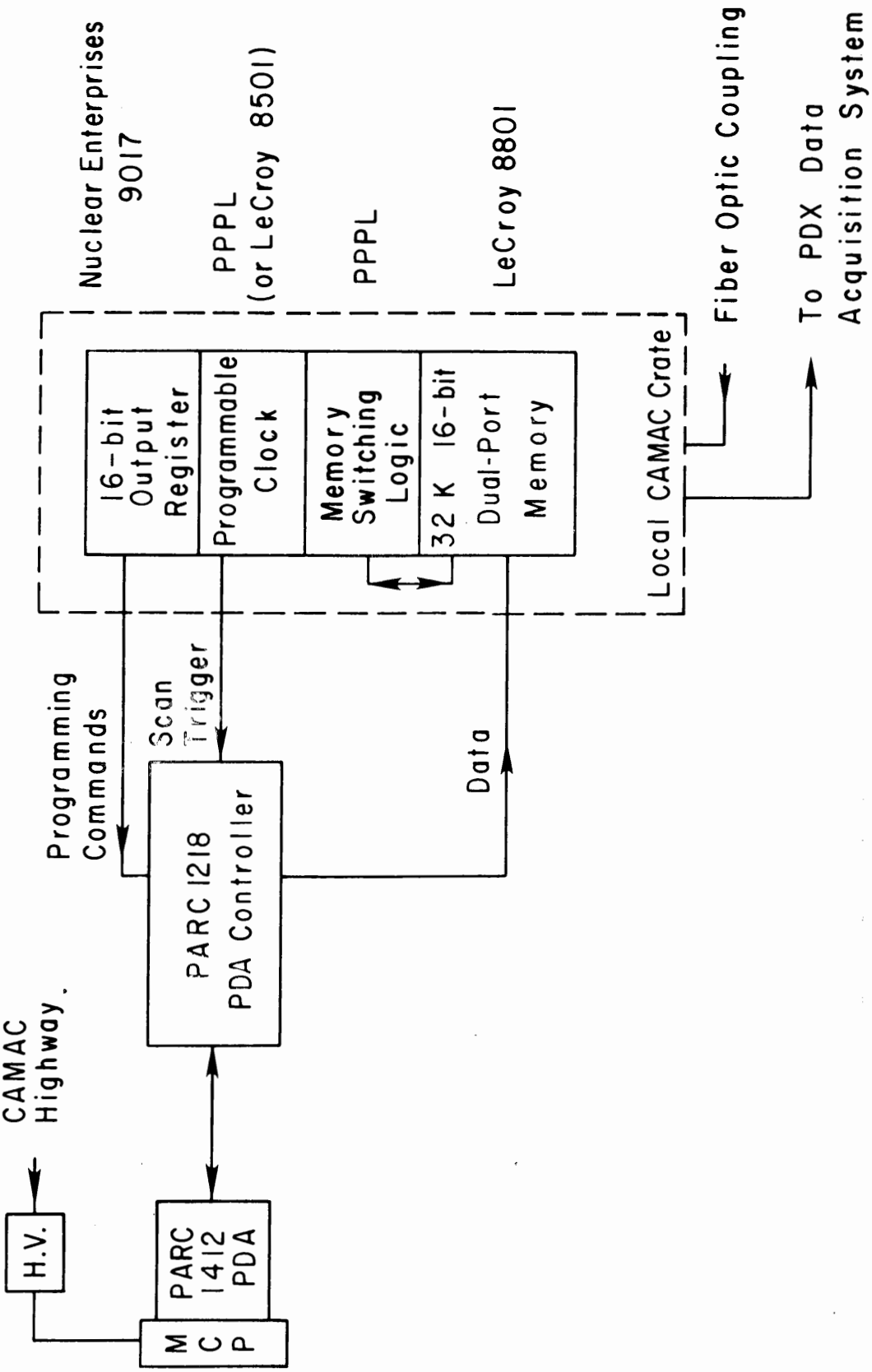

Fig. 8

#83X0446

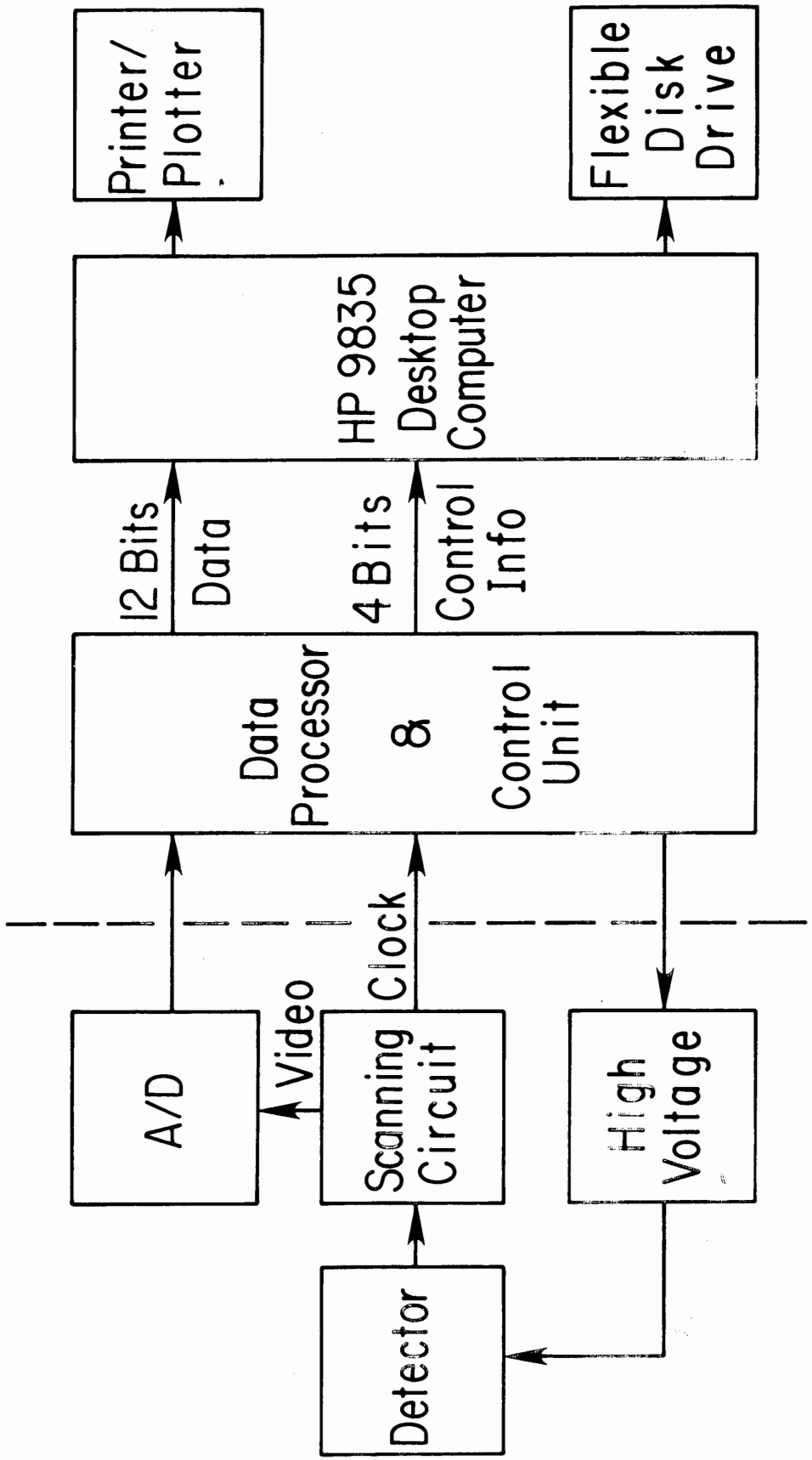

Fig. 9

#83X0445

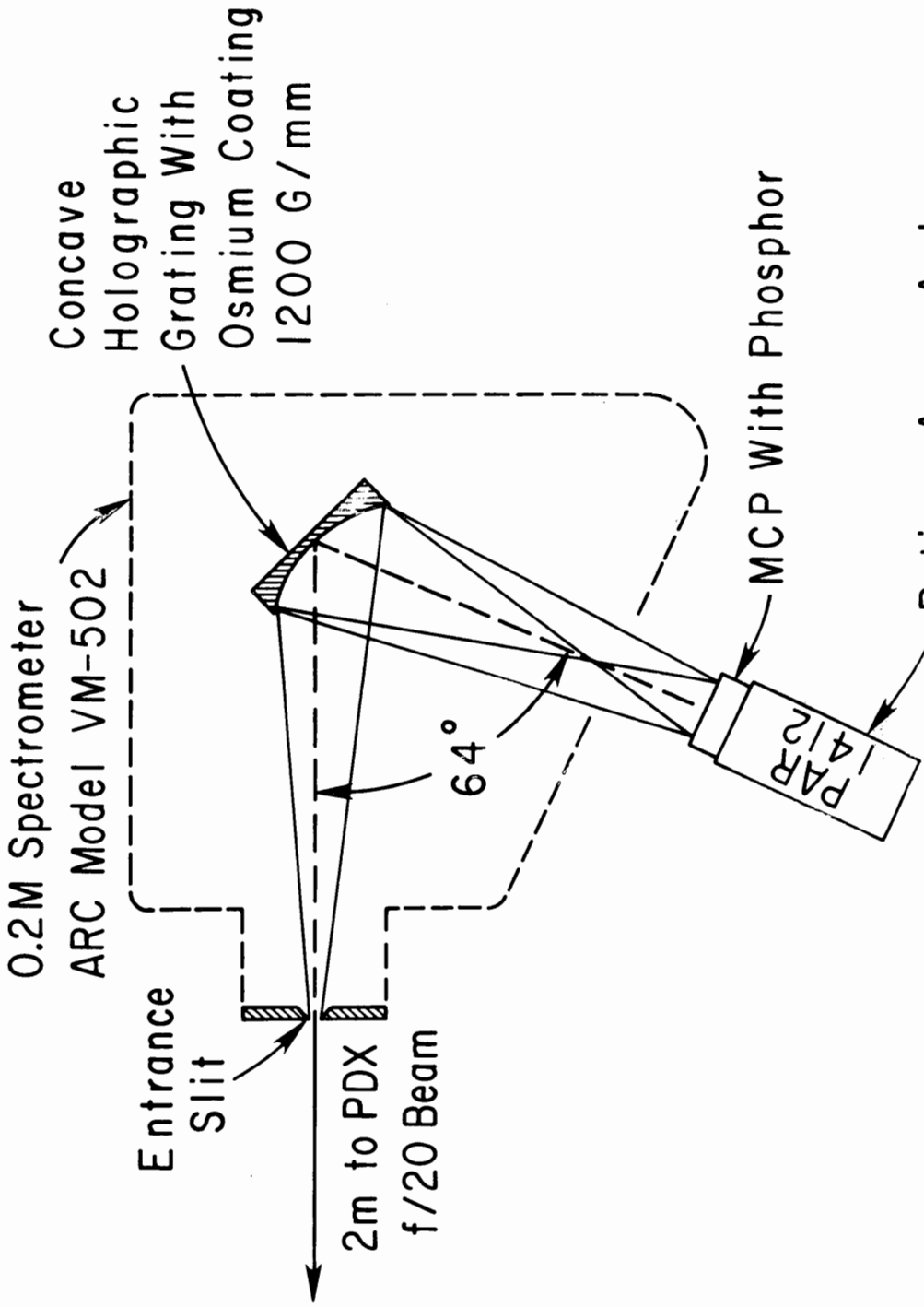

Fig. 10

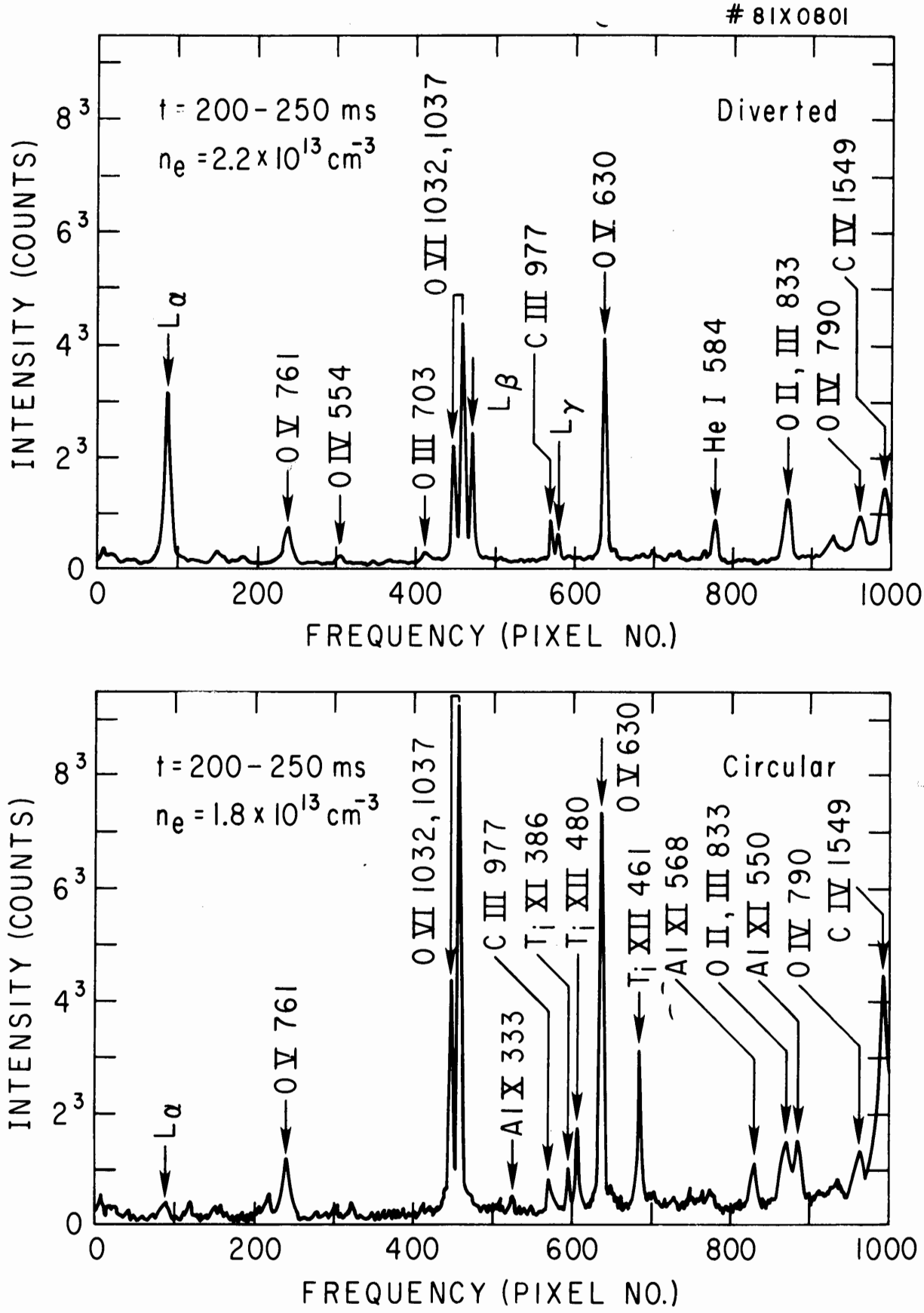
#81X0801
t = 200 - 250 ms
$n_e = 2.2 \times 10^{13}\ cm^{-3}$
Diverted
INTENSITY (COUNTS)
FREQUENCY (PIXEL NO.)
Lα
O V 761
O IV 554
O III 703
O VI 1032, 1037
Lβ
C III 977
Lγ
O V 630
He I 584
O II, III 833
O IV 790
C IV 1549
t = 200 - 250 ms
$n_e = 1.8 \times 10^{13}\ cm^{-3}$
Circular
Lα
O V 761
O VI 1032, 1037
C III 977
Ti XI 386
Ti XII 480
O V 630
Al X 333
Ti XII 461
Al XI 568
O II, III 833
Al XI 550
O IV 790
C IV 1549

Fig. 11

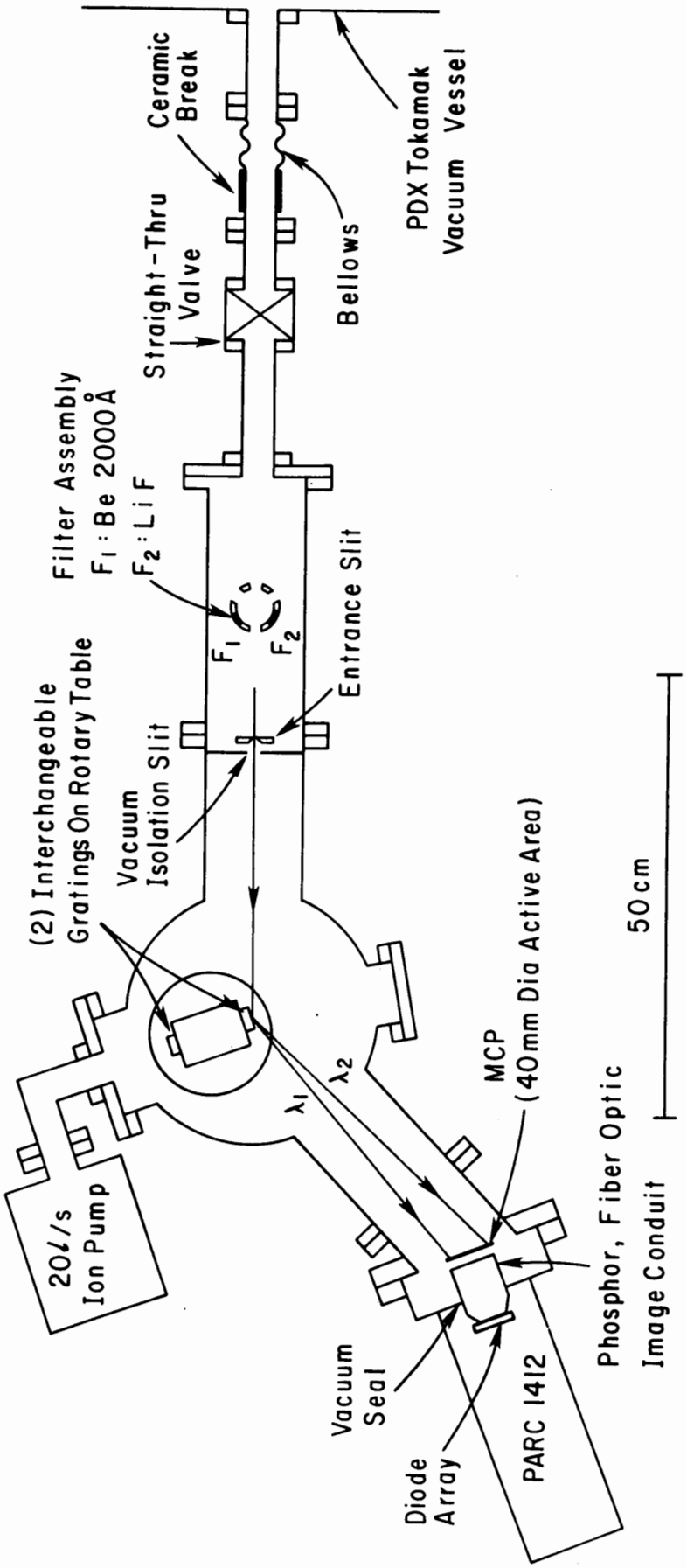

Fig. 12

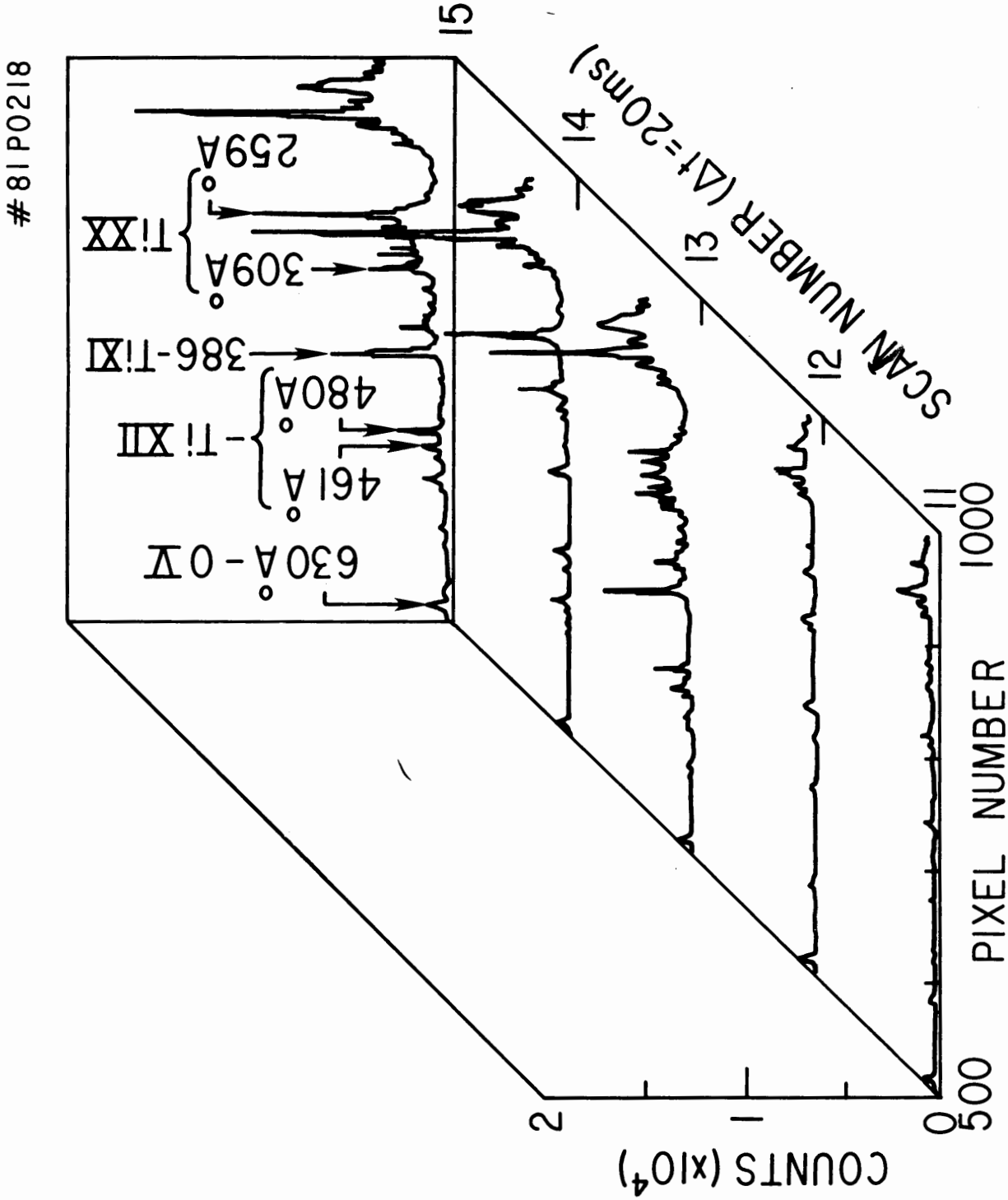
#81P0218
COUNTS (x10⁴)
2
1
0
500
PIXEL NUMBER
1000
11
12
13
14
15
SCAN NUMBER (Δt=20ms)
630Å - OI
461Å
480Å
- Ti XII
386-TiXII
309Å
259Å
TiXX

Fig. 13

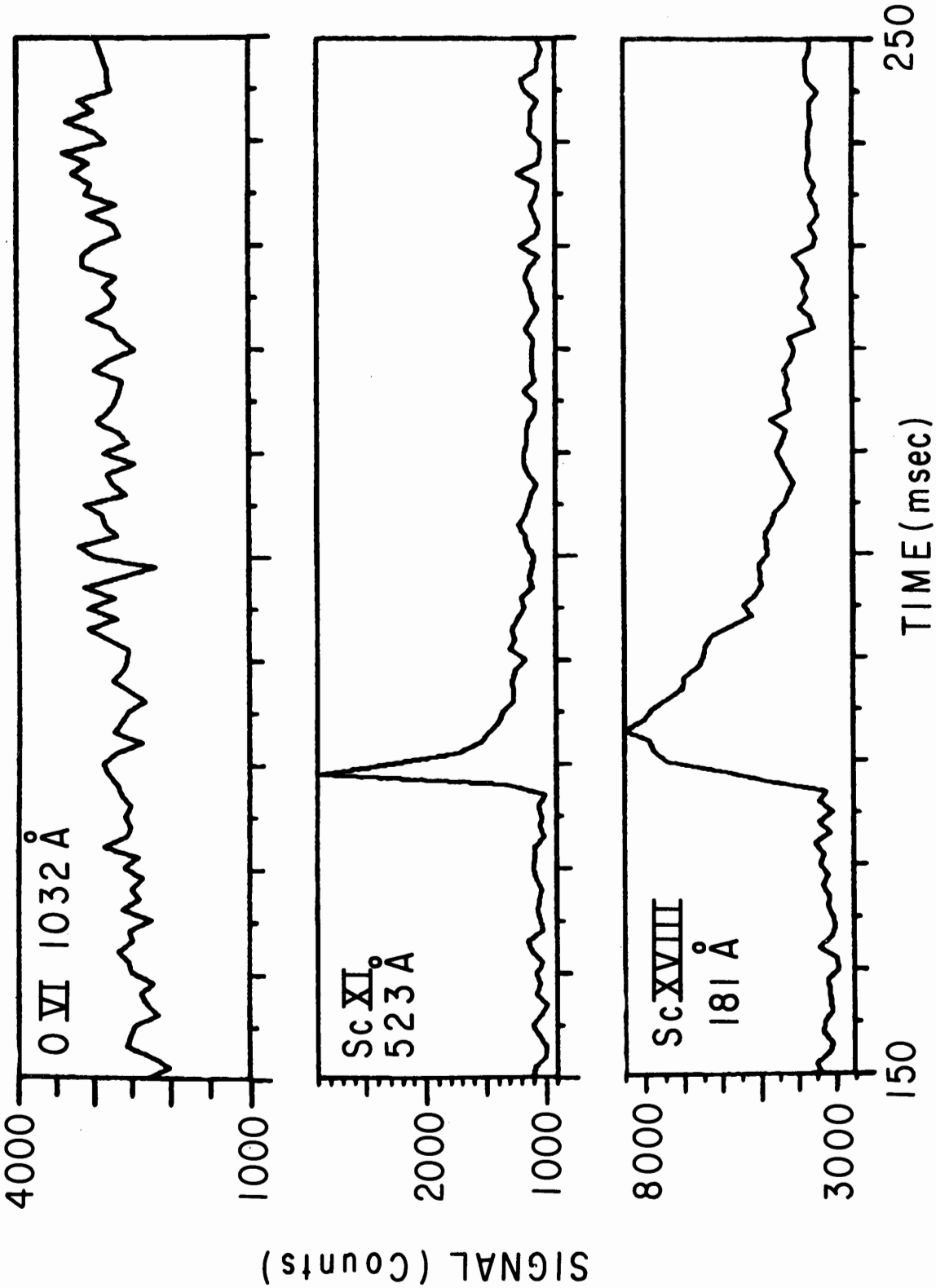
#82X0038
O VI 1032 Å
Sc XI 523 Å
Sc XVIII 181 Å
4000
1000
2000
1000
8000
3000
150
250
TIME (msec)
SIGNAL (Counts)

Fig. 14

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