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DEVELOPMENT OF A TEMPORALLY AND SPATIALLY RESOLVED GRAZING INCIDENCE SPECTROMETER*

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Abstract

In this report we present design considerations for a grazing incidence spectrometer which will resolve both temporally and spatially the emission from a wide variety of plasmas. The basis of the design involves use of microchannel plates (MCPs) which are curved to conform to the Rowland circle of the spectrometer. The spectra are obtained when the anode is properly gated. The use of multiple anodes allows gating and with appropriate delays results in sequential time resolution of a few nanoseconds. Simultaneous gating of the anodes with spatial resolution of <100μ for any given time frame can also be obtained. The efficiency of this spectrometer is also compared with conventional grazing incidence spectrometers.

Introduction

We have been using grazing incidence spectrometers (GIS) as diagnostic tools for studying a wide variety of plasmas, looking at both line and continuum radiation. These spectrometers offer excellent spectral resolution ($\Delta\lambda/\lambda = 10^{-3} - 10^{-4}$) and the grazing incidence geometry gives reflectivity in the 10-300Å range not attainable with any other instrument. The standard operating modes for this instrument are as a scanning monochromator, which uses time-dependent photon counting techniques, but integrated over a narrow wavelength range, and as a spectrograph which utilizes film to offer maximal resolution over a very broad spectral range but has decreased sensitivity and [illegible] integrated measurements. To incorporate the advantages of both of these modes of operation we are currently assembling a [illegible] meter GIS which will allow us to acquire spectra over a wide spectral range (10-300Å) with [illegible] resolution in a photon counting mode with [illegible] temporal and spatial resolution.

The system incorporates a [illegible] meter GIS and has a full complement of gratings with interchangeable mounts. The detection system [illegible] channel plate (MCP) which will have a [illegible] [illegible] the Rowland circle (see Fig. 1). The [illegible] channel width MCP will [illegible] with several [illegible] strips as shown in Fig. 2 which can be gated [illegible] simultaneously for increased sensitivity (with or without spatial resolution), or sequentially yielding time resolved spectra. Using a [illegible] risetime high voltage pulser feeding the anodes (which look like [illegible] Ω [illegible] in parallel or series we can vary the timing by changing the lengths of cable as shown in Fig. 3. The output electrons are then proximity focused onto a phosphor whose light output is guided by a fiber optic plate to a film plane where standard films can be used. An obvious

future development will be to replace the film with solid-state CCD's for increased sensitivity and direct on-line digital read out.

Sensitivity and Time Resolution

The pulsed spectrometer system works, in its most sensitive mode, by [illegible] individual photons incident on each channel of the MCP while its [illegible] positively. A bias voltage of 1kV across the MCP gives rise [illegible] electrons per detected photon. Pulsing the anode at 5kV gives [illegible] average energy at the phosphor of

$$[illegible] \times 10^{3} \frac{kV}{eV} \times 1.6 \times 10^{-12} \frac{ergs}{eV} / (1.6 \times [illegible])^{-6} \frac{cm^2}{ch} = \frac{25\ ergs}{(ph\text{-}cm^2)}$$

[illegible] efficiency [illegible] P-11 or P-20 phosphor is 10 percent [illegible] light emitted into the f/ aperture of the fibre [illegible] between .02 and .08 ergs/cm² at the film plane [illegible] Royal Pan-X film exposed to .15 erg/cm [illegible] normal processing and [illegible] w/push-processing. This [illegible] margin for [illegible] photon [illegible]

[illegible] M[illegible], the limiting factor in [illegible] The [illegible] MCPs [illegible] transfer [illegible] we get a large signal [illegible] detected [illegible]

[illegible] counts (in percent [illegible] counts we can compare this

sensitivity with our current system (film only). To get a minimally detectable density of .1 using the most sensitive film (Kodak 101) requires[1] ≈8 x 10^6 photons/cm^2. A typical resolution unit is approximately 10^{-2} cm x .5 cm or 5 x 10^{-3} cm^2, so 4 x 10^4 photons are needed per resolution unit for a minimum detectable signal. If the MCP detection efficiency is 1 percent we would get 400 counts (5 percent statistics) in the same resolution unit. A more reasonable MCP detection efficiency is 5 percent which implies an increase in detection sensitivity over 101 film of a factor of 100. In a given resolution unit there are 10^3 channels and each channel is capable of delivering [illegible] electrons[illegible] for detecting 20 photons before saturation. Thus, the instrument has at least three orders of magnitude dynamic range for a given resolution element.

In practical terms, this means that for an experiment involving a weakly emitting plasma that requires [illegible] counts to give a satisfactory time-integrated spectrum on film, time resolution by a factor of 10 is now possible [illegible]. [illegible] experience on x-ray framing[3] cameras [illegible] technology suggests a limit of a few [illegible] exposure times.

[illegible]

The response of the system can now be calculated for typical plasmas. In [illegible], I_{plasma}, the plasma source spectral photon radiance, is related to N, the number of counts/resolution unit by

$$[illegible]\ \Omega$$

obtainable only if a mirror is not used, and is approximately 1×10^{-3} cm^2 sr. If Ω_S calculated without a mirror is greater than Ω_- calculated with a mirror, one would not use a mirror. Typical values for the other parameters that determine n are

$\delta t = 2 \times 10^{-9}$ sec - 2×10^{-2} sec,

$\delta\lambda$ = .6Å (1m spectrometer, 300 ℓ/mm grating)

ϵ_{det} = .01

R_G = .1

which gives $n = N_{plasma} \times \delta t \times 6 \times 10^{-13}$ Å cm^2 sec sr for a system which uses imaging optics.

Plasma sources can often be described as being optically thick blackbody radiators or optically thin line radiators. If we focus a blackbody radiator on the entrance slit of the spectrometer, N_{plasma} will be given by the Planck formula

$$N_{plasma}(\lambda) = \frac{2c}{\lambda^4 (e^{hc/\lambda kT} - 1)} \quad \frac{\text{photons}}{\text{cm}^2 \text{ Å sec sr}}$$

The maximum number of photons detected in a wavelength dispersive device will occur at a wavelength of

$$\lambda_{max} = 3.9 \times 10^3 / kT$$

and the spectral photon radiance at this peak is given by (kT in eV)

$$N_{plasma}(\lambda_{max}) = 1.2 \times 10^{19} (kT)^4 \quad \frac{\text{photons}}{\text{cm}^2 \text{ Å sec sr}}$$

Assuming that such a source remains at a temperature T for a framing time of 10 nsec,

[illegible]

[illegible] statistics could be obtained on a keV, 10 nsec emitter.

[illegible] for spatially resolved spectroscopy. To do this we use [illegible] and reduce the width of the slit from the .5 cm used [illegible]. The magnification is the ratio of object to image [illegible] wavelength dependent.

[illegible] the number of counts/resolution unit detected in the portion [illegible] which images a given volume of plasma, n_v, one uses [illegible] non-spatially resolved case with a modified Ω (Fig. 3) [illegible]

$$\Omega = \Omega_{sr} \; w \left(\frac{[illegible]}{[illegible]_{ss}} \right) A_{sv}$$

where [illegible] the width of the entrance slit

[illegible] = the spatially resolving slit width

[illegible] = source to spatial resolution slit distance

r_{es} = source to entrance slit distance

A_{sv} = the surface area of the volume of plasma being imaged visible to the entrance slit.

Consider as an example, a 100μ diameter, 100eV, 10 nsec blackbody emitter, spatially resolved with a 10μ image defining slit placed 5 cm from the source and 40 cm from the spectrometer entrance slit. Using the same values at R_g, ε_{det}, and $\delta\lambda$ as before, we get for the number of counts at the blackbody peak/resolution unit,

$$n_v = 7.2 \times 10^{15}\Omega$$

assuming an entrance slit width w of 10^{-3}cm

$$\Omega_{sr} = 1.4 \times 10^{-12}cm^2sr$$

and $n_v = 1 \times 10^3$ counts/resolution unit imaged at the peak of the blackbody spectrum (≈75Å). The spatial resolution at the source is limited to ≈10μ (the diffraction limit is 5μ at 25Å) which for the above geometry gives a magnification of 16x at the microchannel plate (assuming a 3600ℓ/mm grating at 88 degree incidence). The spatial resolution limit is the 2×10^4 elements that make up the vertical dimensions of the MCP for large objects, and the imaging optics or slit size (keeping in mind the diffraction limit for longer wavelengths) for small objects magnified on the exit plane. A practical limit is probably 10μ.

An alternative mentioned above to the use of a cross slit for position sensitive information is a cylindrical mirror which would focus in the non-analyzing plane. This case gives much higher sensitivity at wavelengths above 500Å and could be used if necessary in this region.

For an optically thin line radiator, approximately 10 counts are necessary to detect a line peak. Taking into account the 1 percent quantum efficiency of the MCP and 10 percent diffraction efficiency of the grating, this requires 10^4 photons incident on the grating. To resolve one millisec this requires 10^7 photons/sec incident on the grating. The number of ions viewed, N_{ion}, is given by

$$N_{ion} = R^2 \int n_i d\ell$$

where Ω = the acceptance angle of the spectrometer, R is the entrance slit to plasma distance, and $\int n_i d\ell$ is the integral of the ion density along the line of sight of the spectrometer. On the average, each ion will emit $\frac{\Omega}{4\pi}$ photon into the grating, where A_{slit} is the entrance slit area and R is again the plasma to entrance slit distance.

The brightness of a source minimally detectable with a 1 millisec exposure time is then given by

$$\text{brightness} = N_{ion} \frac{A_{slit}}{4\pi R^2} = 1 \times 10^7 \frac{\text{photons}}{\text{sec}} \cdot \frac{\Omega A_{slit}}{4\pi} \int n_i d\ell$$

$$\frac{\text{brightness}}{\int n_i d\ell} = .04 \text{ photons/sec/sr}$$

where $\Omega = 10^{-1}$ sr and $A_{slit} = 10^{-3}$ cm^2. This for application to plasmas like the Tandem Mirror experiment at Livermore most of the common impurities could easily be resolved on a millisec time scale.

Conclusion

We have shown that time resolved (high resolution) spectroscopy is possible in the 10 to 1000Å region using a grazing incidence spectrometer and pulsed channel plates. The system places very modest requirements on plasma brightness for efficient detection, and can be used in many different plasma regimes with lifetimes between 10^{-9} and 10^{-2} sec.

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Figure captions

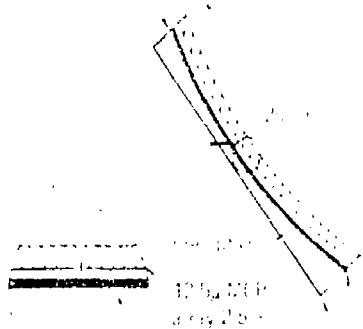
Fig. 1. Schematic of the 1 meter dia fitted with a microchannel plate.

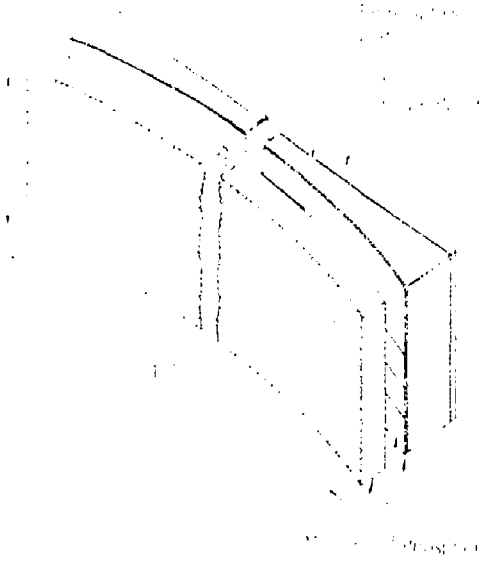
Fig. 2. Enlarged cross section of the detector showing the five anode strips.

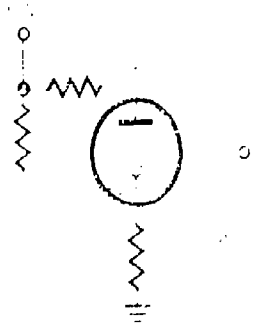
Fig. 3. Anode pulse diagram; delays and pulse widths are determined by cable lengths.

Fig. 4. Spectrometer solid angles: a) with mirror to fill two optics, b) without mirror, c) with a position defining slit.

500 cm







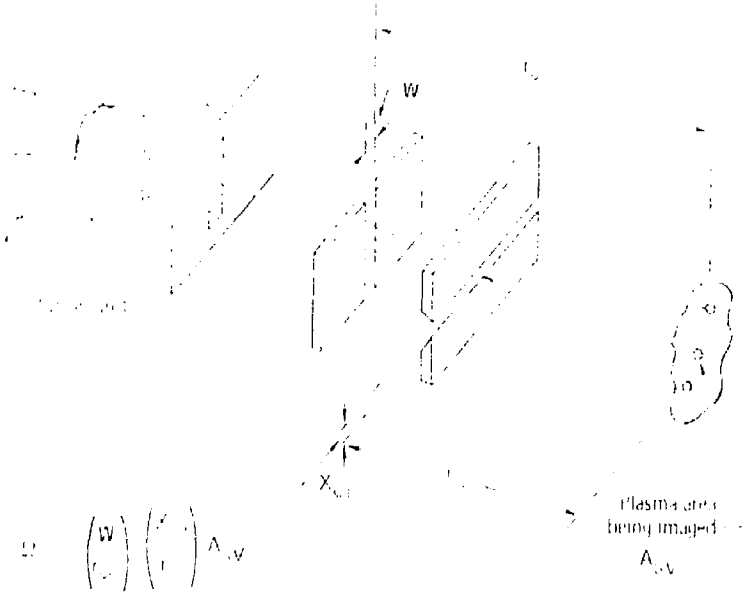


Figure 5