LA-UR- 95-2439

CONF-950750--8

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Author(s): Roger J. Bartlett
Robert G. Hockaday
Cenobio H. Gallegos
Joseph M. Gonzales
Vance Mitton

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A TRANSMISSION GRATING SPECTROMETER FOR PLASMA DIAGNOSTICS

Roger J. Bartlett and Robert G. Hockaday
Los Alamos National Laboratory
Los Alamos, NM 87545

Cenobio H. Gallegos, Joseph M. Gonzales and Vance Mitton
EG&G Energy Measurements
Los Alamos, NM 87544

Radiation temperature is an important parameter in characterizing the properties of hot plasmas. In most cases this temperature is time varying caused by the short lived and / or time dependent nature of the plasma. Thus, a measurement of the radiation flux as a function of time is quite valuable. To this end we have developed a spectrometer that can acquire spectra with a time resolution of less than 1 ns and covers the spectral energy range from ~ 60 to 1000 eV. The spectrometer consists of an entrance slit placed relatively near the plasma, a thin gold film transmission grating with aperture, a micro channel plate (MCP) detector with a gold cathode placed at the dispersion plane and an electron lens to focus the electrons from the MCP onto a phosphor coated fiber optic plug. The phosphor (In:CdS) has a response time of ~ 500 ps. This detector system, including the fast phosphor is similar to one that has been previously described (1). The spectrometer is in a vacuum chamber that is turbo pumped to a base pressure of ~ 5 x 10^{-7} torr. The light from the phosphor is coupled to two streak cameras through 100 m long fiber optic cables. The streak cameras with their CCD readouts provide the time resolution of the spectrum. The spectrometer has a build in alignment system that uses an alignment telescope and retractable prism.

Introduction

Pulse power driven implosions of materials can produce copious amounts of x-rays in a relatively short time period. This radiation in turn can be used in a variety of experiments. Characterizing these implosions is important for their use as radiation sources. Knowing the spectrum is important and is usually determined by measuring the intensity of the x-rays in several wavelength bands using filtered x-ray diodes. From these data an equivalent black body temperature is derived and is often used as a figure of merit for the source. The time response of the source is also determined by the diodes. Often it is desirable to have more detailed spectral information about the source than can be provided by the filtered diodes. This can be obtained by using a spectrometer. In the soft x-ray region this usually mandates a grating dispersing element. Both reflection and transmission gratings can be used; however, the transmission gratings are affected less by carbon and other surface contaminants than are the reflection gratings. There have been a number of papers describing transmission grating spectrometers. References 2-7 and the references therein show the many uses for these instruments.

We have built and fielded a transmission grating spectrometer (TGS) for the purpose of diagnosing radiation from pulse power sources. The TGS consists of a gold transmission grating

with a 130 μm aperture, a microchannel plate (MCP) intensifier with a gold cathode, and an electrostatic electron lens to focus the electrons from the MCP onto a fast phosphor. Light from the phosphor is coupled through a fiber optic plug forming the vacuum interface to 100 m fiber optic cables leading to streak cameras with CCD read outs. The spectrometer has been used to measure the relative spectra of several pulsed sources but has not been absolutely calibrated. The spectrometer is further described below.

Spectrometer Design

The basic requirements of the spectrometer are dictated by the source characteristics and the desired spectral and temporal information. For the pulse power sources of interest here, the radiation pulse has a duration greater than 15 to 20 ns and in some cases approaches 100 ns. The spectral emission from these sources peaks in the region between 60 and 300 eV and falls off above and below the peak in a manner characteristic of black body radiation. The temporal resolution for our system is limited to approximately 500 ps by the phosphor light converter in the system. This resolution gives adequate information about the source time response.

The spectral resolution is limited by several elements in the system and is also a trade-off with the signal to noise ratio. In some cases spectral line information is desired while in other cases the general shape of the spectrum is adequate. These two conditions require different resolving powers and must be considered in the design. Sometimes the two conditions can be addressed by having more than one detector system, a low resolution system that provides adequate temporal resolution and a high resolution detector that may be time integrated or provide a snap shot of the spectrum at a particular time.

The spectral energy range and resolving power, $\lambda/\Delta\lambda$, of the TGS can be examined using the grating equation:

$$m\lambda = d\,(\sin\alpha + \sin\beta)\qquad\qquad 1$$

where λ is the wavelength of the radiation, m is the diffraction order, d is the period of the grating, α is the incidence angle of the incoming radiation relative to the normal to the grating and β is the diffraction angle. For normal incident radiation, $\alpha = 0$, and for first order diffraction, m =1, then in the small angle approximation Eq. 1 can be written as

$$\lambda = xd/l\qquad\qquad 2$$

where x is the distance along the diffraction plane from the zero order position and l is the distance from the grating to the diffraction plane. Eq. 2, with a given set of parameters, sets the wavelength range of the spectrometer. The linear dispersion of the grating is obtained from Eq. 2 and is

$$d\lambda/dx = d/ml\qquad\qquad 3$$

In the range where the small angle approximation holds (for our system between zero order and ~ 200 Å), the dispersion is approximately linear and equal to 5 Å/mm in first order for d = 2000 Å and l = 400 mm. Thus with an effective detector discrimination size of 0.1 mm the spectral width is 0.5 Å, giving a $\lambda/\Delta\lambda$ = 10x where x is in mm.

For this resolving power to be achieved the image of the source must be equal to or less than the detector size. The resolving power based on the image size can be derived from Eq. 1 and in the small angle approximation is

$$\lambda/\Delta\lambda = x/[(\Delta x + w) + (l/L)(s+w)]\qquad\qquad 4$$

where Δx is the effective detector width, w is the exposed width of the grating (0.13 mm here), s

is the effective source size and L is the distance from the source to the grating. In most cases where we have fielded the spectrometer the second term in the denominator is small relative to the first and can be neglected. Under these conditions the image size dominates the resolving power and limits it to 4.3x where x is in mm. It can be seen that the resolving power is linear and increasing with increasing x; i.e., for longer wavelengths.

A third factor, the number of grating bars illuminated by the source can limit the resolving power. For the aperture size of 0.13 mm and the 5000 line per mm grating, this limit is 650, well above the other limits involved here.

It is interesting to note that if the second term in the denominator is small relative to the first and can be neglected then the resolving power is constant for constant x. Thus by placing the dispersion plane at a fixed x value, the spectrum will be dispersed along a line perpendicular to the grating and the dispersion will be linear in photon energy and proportional to l; i.e.,

$$h\nu = hc/\lambda = hcl/xd \qquad\qquad 5$$

where h is Planck's constant, c is the speed of light and hν is the photon energy. For the spectrometer described here l is fixed and the dispersion is along x. In a second generation spectrometer that is under construction we have fixed x and dispersed the photon energy along l.

The microchannel plate detector is approximately 50 mm long. Using Eq. 2, the parameters listed above and placing zero order approximately 10 mm in from the end of the MCP gives an energy range from zero order down to approximately 62 eV. The usable upper energy limit is around 1.5 keV caused by other factors in the system and the fact that the resolving power is becoming quite small at the higher energies.

Grating, Detector and data acquisition system

A schematic diagram of the gold grating and the associated parameters are shown in Fig. 1. The gratings were purchased from X-OPT, Inc. in Gainesville, FL. The gratings are more fully described by Ceglio et al.(8) and by Hawryluk et al.(9). The 5000 bars per mm grating was covered with an aperture of dimensions 0.13 x 10 mm^2. This slit size was such that only one set of dispersing bars between the support structure was illuminated. Its size also affects the resolving power as seen from Eq. 4.

The detector system is shown in Fig 2. Radiation from the source is dispersed by the grating along the length of the MCP detector. The photons strike the gold cathode of the microchannel plate and produce electrons in proportion to their intensity which are then amplified by the MCP. An electrostatic lens focuses the electrons from the MCP in one dimension onto an In:CdS phosphor electron to light converter. Light from the phosphor is couple to two streak cameras through two 49 fiber optical cables. Because the spatial relationship of the dispersed photons along the MCP is maintained, each fiber represents a separate photon energy channel and these channels are swept in time across the streak cameras and recorded on CCD cameras. The main limit to the time resolution is the phosphor which has a time response of approximately 500 ps.

The spatial resolution of the detector, as discussed above is the limiting factor in the energy resolution of the spectrometer. Several factors contribute to this resolution limit. Among these are the ballooning of the electron pulse from the MCP and in the phosphor, but in our system it is the finite size of the optical fibers that is the major factor. The fibers used here have an outer diameter of 0.125 mm and an active core diameter of 0.085 mm. Estimates of the combined effects is 0.1 mm spatial resolution. Because of the limit on the packing density and the

Transmission Grating Geometry

Transmission Grating Parameters

$P = 2000$ Å
$A = 800$ Å
$Z = 4700$ Å

Support Structure

$p1 = 150$ μm
$a_1 = 116$ μm
$p_2 = 3.8$ μm
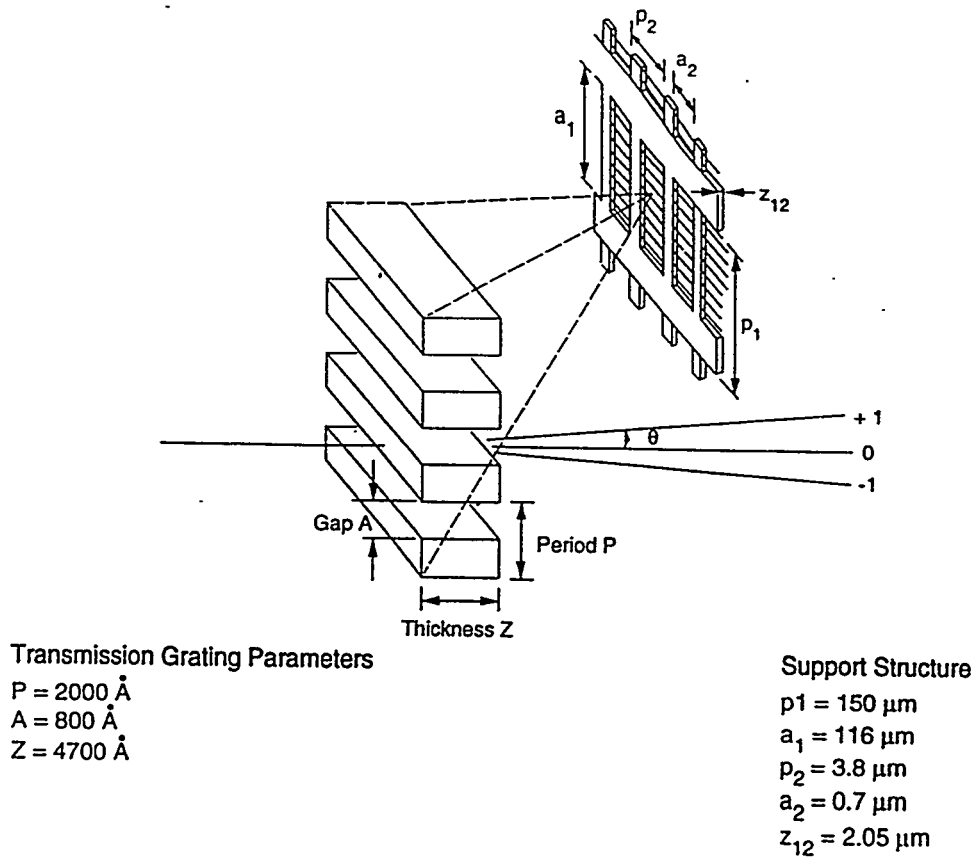$a_2 = 0.7$ μm
$z_{12} = 2.05$ μm

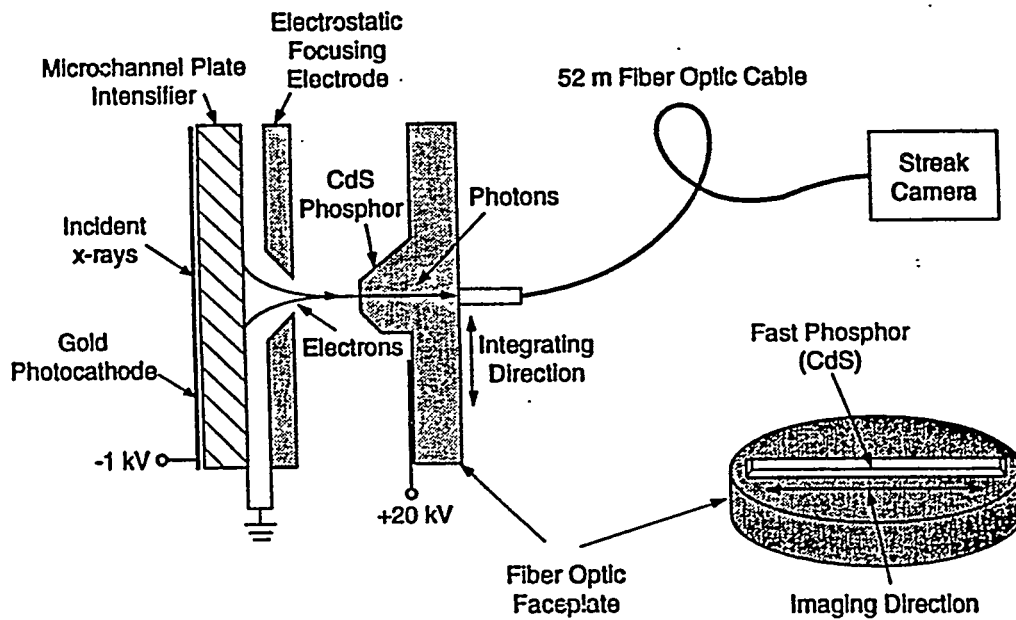Fig. 1. Schematic diagram of gold transmission grating.

Fig. 2. Schematic diagram of the microchannel plate intensified detector system.

finite number of fibers we do not have continuous energy coverage across the spectrum but rather 98 discrete energy bins. An optical patch panel allows us to arrange the 98 fibers along the dispersion plane.

Alignment, mechanical and vacuum systems

The spectrometer is directly coupled through a line of sight pipe to the pulse power source. The source is in a vacuum environment with a pressure of ~1E-5 torr. This requires that the spectrometer be contained in a vacuum enclosure that can maintain at least this vacuum level. The microchannel plate performs better if the pressure in below 1E-6 torr. Based of these criteria, we designed a vacuum chamber that was evacuated with a 50 liter per second turbo pump and had a volume of approximately 5000 cu cm. The aluminum chamber could be pumped down to a base pressure of ~ 1E-7. The system had two valves in the line of sight. One was a fast value that was used to reduce the amount of debris reaching the spectrometer from the pulse power implosion. The other was a high-vacuum gate valve with a window in the gate. This valve is used so that the spectrometer can be maintained under vacuum while the source is at atmospheric pressure and still perform alignment procedures.

The main body of the chamber was milled from a block of aluminum. The MCP detector was mounted on one end of the chamber but was electrically isolated from the chamber. The grating was mounted to the other end of the chamber on a rotary vacuum feed through. The chamber, the fast valve and the window valve were all mounted and aligned on an aluminum channel approximately 1 m long. The channel in turn was mounted to a heavy duty tripod that provided the mechanical degrees of freedom for alignment.

An optical telescope (alignment scope) was used to align the system to the pulse power source. The scope was mounted on a window port on the chamber near the detector end. Directly below the port was a prism that directed the view of the scope along the zero order axis of the spectrometer toward the source. The prism was mounted on a linear feed through and was directly in line with the zero order axis during the alignment procedure. After the alignment was complete, the prism was removed from the optical axis. The alignment procedure consists of aligning the scope to the zero order axis of the spectrometer by adjustments on the scope mount. Then the spectrometer was aligned to the source by observing the source with the scope and adjusting the spectrometer mount until the zero order axis was pointing directly at the source.

Results and discussion

Fig. 3 shows the peak spectral response of a pulse power shot on the Sandia Saturn machine. The spectrum shows the general black body shape with a maximum near 150 eV indicating a radiation temperature of approximately 50 eV. There is considerable structure in the low energy part of the spectrum. This probably is caused by noise in the system but also may in part be caused by the radiation from the source. Calculations of the radiation from a gold source of this temperature show considerable line structure below ~ 300 eV with smoother output above that energy. The calculations were not directly comparable to the spectrometer results because of the finite band pass of the instrument; however, there was surpassing similarities in the peak structure between the two spectra.
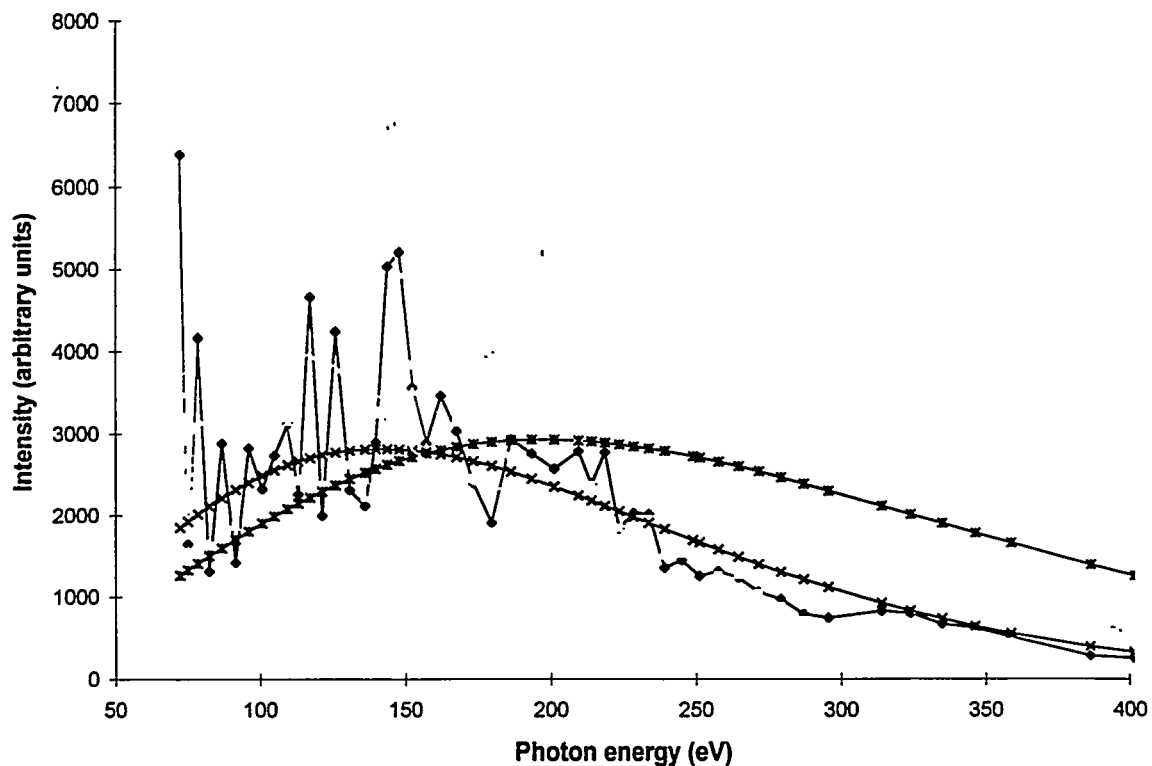
Fig. 3. Peak, relative output spectrum of pulse power source. The two smooth curves are calculated black body responses for 50 and 70 eV temperatures. Magnitudes have been adjusted for approximate agreement with the spectra

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