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UCRL - 75713
PREPRINT

CONF-740529-10

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INSTRUMENTATION FOR X-RAY DIAGNOSTICS OF PLASMAS

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October 21, 1974

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This paper was prepared for submittal to the
Denver X-Ray Conference on Applications of X-Ray Analysis
Denver, Colorado, August 7-9, 1974

MASTER

CONTRIBUTOR: THIS DOCUMENT IS UNCLASSIFIED

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INSTRUMENTATION FOR X-RAY DIAGNOSTICS OF PLASMAS*

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ABSTRACT

Measurements of x rays emitted by hot plasmas provide a powerful diagnostic method of determining important plasma parameters and suggest certain types of plasmas as possibly useful x-ray sources. Instrumentation to accomplish these measurements for various types of plasmas are reviewed. State-of-the-art x-ray spectrometers, calorimeters, and source-imaging devices, designed especially for plasmas generated by focused, nanosecond laser pulses are described. Possibilities of time-resolved measurements on such short-lived plasmas are discussed.

INTRODUCTION

Laboratory plasmas that attain temperatures high enough to radiate appreciable x rays are short-lived. X-ray times vary in accordance with various plasma-producing mechanisms. X-ray times of CTR plasmas can be as long as 10 ms, for plasma focus and exploding-wire plasmas, as long as 100 ns. Laser-produced plasmas exist, depending on the laser pulse length, from roughly 0.1 to tens of nanoseconds. Nearly all experiments that have been or are being done with plasma-focus, exploding-wire, and laser-produced plasma x rays are time-integrated experiments.

* Work performed under the auspices of the U. S. Atomic Energy Commission and the Defense Nuclear Agency.

However, x-ray instrumentation has now progressed to the point where resolution times of ≈ 1 ns or less are available. These kinds of experiments are referred to as "rate" experiments. There is still a second type of time-resolved experiment. This obtains when the x-ray photons incident on the detector are spaced in time equal to or longer than the resolution time of the detecting system. In this case, an x-ray counting experiment can be done. Of course, by appropriate electronic integration this experiment could be carried out as well as a rate experiment. In the following discussion various experiments classified on the basis of these three time domains, time-integrated, rate, and counting experiments, will be discussed.

X-ray diagnostic instrumentation will be discussed in the context of the experimental work being done at Lawrence Livermore Laboratory and other laboratories primarily in connection with laser-produced plasmas. This results from the fact that most of the current innovation in pulse x-ray instrumentation is occurring in conjunction with laser-produced plasmas. The various types of instrumentation can, of course, be used with high-temperature plasmas produced by any mechanism.

TIME-INTEGRATED EXPERIMENTS

Spectral Measurements

Up to the present time spectral measurements of plasma x-rays have been done using basically two techniques, crystal diffraction and absorption edge methods.

Crystal Diffraction Methods. Bragg crystal spectrometers were used by Boyer *et al.* (1) and Griem *et al.* (2) in 1958 to analyze x rays from a theta-pinch in hydrogen. These experiments showed a continuum x-ray spectrum up to several keV photon energy.

The possibility that plasmas produced by focused high-intensity laser pulses on high-Z targets would be efficient x-ray emitters was predicted by Kidder (3,4) in 1968 and confirmed experimentally by Mead *et al.* (5,6) in 1969. A Bragg spectrograph, which incorporates vertical focusing, used by Mead to analyze line spectra from laser-produced plasmas is shown in Fig. 1.

Two special-purpose Bragg crystal spectrometers currently being built at LLL are shown in Fig. 2. The purpose of these spectrometers is to measure line broadening of K α lines of specific dopants introduced into laser targets, e.g., neon or argon. The expected line broadening, assuming that the laser intensity

Fig. 1. Mead's Bragg spectrograph.

is high enough to compress these targets to 10 times liquid-hydrogen density, is also given in Fig. 2. The calculated resolution for these two instruments for two assumed source diameters is also indicated. The indicated x-ray energies are higher than the normally observed $K\alpha$ lines since most of the atoms in the plasma are completely stripped of electrons. In the Bragg crystal spectrometer of Kephart *et al.* (7) the data are read out with counters rather than film.

The use of bent-crystal spectrometers to measure x rays from high-temperature plasmas was pioneered by Birks (8) and Cohen *et al.* (9) in connection with CTR plasmas; Boster *et al.* (10) in connection with plasma-focus devices, and Chase *et al.* (11) in connection with laser-produced plasmas. Subsequent work using bent-crystal spectrometers with laser-produced plasmas has been done by a number of investigators (12-22).

^aCompression = 10 X liquid-hydrogen density.

Fig. 2. Two special-purpose Bragg spectrographs.

A bent KAP crystal spectrometer currently in use at LLL is shown in Fig. 3. The crystals are bent to a radius of only 2-3 cm, thereby providing a broad range of spectral coverage from approximately 0.5 to 7 keV. Data can be recorded on film or silicon surface-barrier detectors.

A bent-crystal spectrometer for measuring subkilovolt x rays (23) is shown in Fig. 4. A bent lead stearate crystal with 75 layers and a d spacing of 10 nm is used to cover the energy range of 0.25-1.1 keV. Recording is made with No-Screen or Kodak 101 film. A pinhole camera is used with this spectrometer for alignment purposes.

Fig. 3. Bent KAP crystal spectrometer.

Fig. 4. Sub-kilovolt bent-crystal spectrometer.

Absorption Edge Methods. The thick K-edge filter method is illustrated by the experimental arrangement due to Slivinsky *et al.* (24) shown in Fig. 5. The targets used for these experiments consisted of deuterated polyethylene (CD_2) disks, 0.31 cm thick. They were located at the center of an evacuated target chamber (<4 Pa). The plasmas for these studies were produced with the LLL Long Path Laser. The spectral energy band to which each detector responded was determined by a thick K-edge filter located in front of each detector. These filters transmitted x rays just below their K-edge and also x rays of energies greater than about twice the K-edge energy, as shown in Fig. 6a. If the spectrum under investigation falls off rapidly with photon energy, then the resulting transmission will look typically as shown in Fig. 6b. It was determined experimentally that the spectrum did indeed fall off rapidly, and that the x-ray energy in the tail was always $<20\%$ of the total energy measured for each channel. Thus, the four K-edge filters, in conjunction with detectors 1 through 4, provided a measurement of four K-edge notches of the spectrum, with the high-energy tails contributing small but accountable backgrounds.

Fig. 5. Slivinsky's experimental arrangement.

Fig. 6. X-ray transmission of thick K-edge filters.

The detectors used in channels 2, 3, and 4 were NaI(Tl) crystals coupled to 56 AVP photomultiplier tubes. The crystal thickness for each channel was chosen so that the K-notch x rays were totally absorbed, whereas the tail x rays were about 50% transmitted. This further reduced the fraction of the measured signals that was due to the high-energy tails. For channel 1, a 1.9-cm-thick Pilot B fluor was used instead of NaI(Tl). The notch-to-tail ratio for this channel was increased by a factor of 4 because of the x-ray response of the plastic fluor. Calibration for all detectors included measurements of the absolute dc sensitivities for x rays from 8 to 98 keV, the detector gain as a function of photomultiplier voltage, and detector linearity in the pulsed mode. A typical spectrum measurement, normalized in this way, is shown in Fig. 7. Its shape is noteworthy, since it appears to be inconsistent with a single-temperature Maxwellian electron distribution.

The Ross filter technique has been used in connection with laser-produced plasmas by Johnson (25) and Cuderman (26). A Ross filter system consists of two identical detectors placed behind two x-ray absorbing foils with nearly the same atomic number and with thickness adjusted to achieve matched transmission curves except in the energy range between their K edges. The difference in detector output signals for such a system is proportional to the energy detected between the K edges of the foils. The products of the foil-transmission and detector-sensitivity curves for two Ross filter silicon diode detector systems using iron-nickel and molybdenum-silver filter pairs are shown in Fig. 8. The corresponding difference-response curves are shown in Fig. 9. These curves illustrate the sharp response function that can be obtained with Ross filters. The optimum detection sensitivity is achieved when the difference between the filter detector-response curves between the K edges

Fig. 7. X-ray spectrum from laser-produced plasmas on a CD_2 target.

Fig. 8. Response curves for two Ross filter detector systems.

Figure 5. Difference Response Curves at Fe-Ni, Mo-Ag (150, 51)

Fig. 9. Difference-response curves for the detector system of Fig. 8.

is adjusted at ~60% of the unfiltered, detector-response curve. This yields a response difference outside the K edges which is generally <1% of the unfiltered response. The curves in Fig. 9 also show how the thickness ratios must be adjusted so that the difference in response immediately below the K edges is balanced by the difference above the K edges. When Ross filters are used to measure spectra with strong line-radiation components, the thickness ratios must be adjusted to give identical transmission at the energy of the line radiation if small errors are to be realized.

The major disadvantages of the Ross filter technique is that two detectors with similar response characteristics are required for every energy band covered. This can be overcome to some degree by matching the foils in triplet sets so that only three detectors are required for two energy bands. There is also difficulty in covering all energies with narrow-band systems because nonmetallic elements and noble gases cannot be readily formed into suitable x-ray absorbers and some metals are highly reactive with the atmosphere. Ross filters with bandwidths of 50%

of the mean band energy have response differences of 10% outside the K edges of the foils, introducing considerable measurement error in addition to the loss of energy resolution. A third disadvantage is the lower and upper energy limits for which Ross filters can be made. The foils must be so thin that they are difficult to fabricate for energies below 4 keV and the highest K edge is that of uranium at 115.6 keV.

With the thick K-edge filter method the x-ray spectrum is obtained by applying an unfold code to the data. The presumed advantages of the Ross filter method is the simple interpretation of the data. However, if a large spectral range is to be covered, the Ross channels will be of lower quality and one would again have to resort to an unfold code to obtain the x-ray spectrum.

X-Ray Stacked Diode

An x-ray stacked diode developed by Gaines et al. (27) is shown in Fig. 10. Each section consists of three beryllium foils and a prefilter. The center foil or cathode of each section is plated with certain metals. In this array the prefilter is 0.025-mm beryllium and the first center foil is plated with aluminum. The beryllium prefilter "stops" essentially all of the x radiation below the aluminum K edge and the signal is nearly proportional to the x-ray fluence in the region of the aluminum K edge, i.e., ≈ 1.5 keV. The second stage has a chlorine (Saran) prefilter and an aluminum cathode. The Saran prefilter is thick enough so that x radiation at or somewhat above the chlorine K edge (2.8 keV) is strongly attenuated. Therefore, the aluminum cathode of the second stage

Fig. 10. X-ray stacked diode.

responds mainly to incident x rays with energies of nearly 2.8 keV (shown as 3.0 keV in Fig. 10). The third stage has a 0.025-mm scandium prefilter and a gold cathode. The sensitivity resulting from this combination is primarily to 4.5-keV x rays. The fourth stage has no prefilter and a chromium cathode which responds primarily to 6-keV x rays.

The stacked x-ray diode is a relatively insensitive x-ray detector and hence can be used for high x-ray fluences. It also has the advantage of recording several x-ray energy channels simultaneously.

Nuclear Emulsions. A third technique of measuring x-ray spectra is the conversion in nuclear emulsion of x-ray photons into electrons. Knowledge of the electron energy and initial direction with respect to the incident x-ray direction then gives the x-ray energy. A diagram of such an experiment carried out by Lee et al. (28) is shown in Fig. 11. A filter is used in front of the emulsion to "stop" low-energy x rays ≤ 50 keV that would only fog the emulsion surface.

Experiments were carried out to determine the spectral distribution of electron tracks produced in the emulsion by either photoelectric or Compton effect of x rays from the plasma focus. The 600- μm -thick Ilford emulsions, stacked behind a 1.5-mm-thick lead absorber, were placed at a distance of 90 cm from the source of the axis of the electrode. The electron ranges were measured with Leitz scanning microscopes equipped with an 18- μm reticle grid. The tracks due to ≈ 100 -keV electrons in nuclear emulsion are shown in Fig. 12.

Fig. 11. Nuclear emulsion measurement of an x-ray spectrum.

Fig. 12. Electron tracks in nuclear emulsion.

The histogram in Fig. 13 is a result of electron range measurements with 3807 tracks (longer than $18\text{ }\mu\text{m}$) observed over background. A few tracks extended more than $600\text{ }\mu\text{m}$, indicating electron energies of greater than 500 keV . The dotted curves represent the expected electron track distributions, arbitrarily normalized, for three different models of the source. The curves were obtained by taking account of the attenuation through the lead absorber and the efficiency of nuclear emulsion.

X-RAY PULSE CALORIMETRY

The detectors discussed here have a flat energy response over a wide range of x-ray energy. They also have long time constants relative to the incident x-ray pulse.

The pioneering work on conversion of laser energy to soft x rays done by Chase *et al.* (11) and Mallozzi *et al.* (29-31) indicated that the conversion efficiency for iron-target, laser-produced plasmas was relatively high ($\approx 27\%$ for x-ray energies $\geq 200\text{ eV}$). X-ray pulse calorimetry was the primary diagnostic for these experiments. Subsequent measurements by Violet

Fig. 13. X-ray spectrum from a plasma focus.

et al., (32-36) Richards et al., (37) and Whitlock et al (38) confirmed these early results and demonstrated a conversion efficiency dependence on the target atomic number.

X-ray pulse calorimeters currently being used at various laboratories are described below:

Silicon Surface-Barrier Detector. A silicon surface-barrier detector system has been used at LLL as a sensitive x-ray calorimeter, Fig. 14. This detector can be used for x-ray fluences between 10^{-11} and 10^{-5} cal/cm². This detection system has been described by McQuaid *et al.* (39) and Violet *et al.* (36).

Fig. 14. Silicon surface-barrier calorimeter detector.

Thin-Film Thermopile. A thermopile matrix detector used at LLL (37) was vacuum-deposited onto a glass substrate, as shown in Fig. 15. Copper and nickel were used as the junction materials. Gold was used as an absorbing button. The pure metals were used for the evaporated materials in this device because they are far more convenient to evaporate than the usual thermocouple alloys. Both the copper and the nickel films are 350 nm thick. A 1700-nm gold button was evaporated on every hot junction to absorb the incident pulsed radiation.

All reference junctions are shielded from the radiation by a 0.05-cm gold shield; 0.08-cm-diam openings in this shield allow the radiation to reach the absorbers. There are a total of 400 junctions in an area 2.2×2.2 cm, giving a junction density of approximately 82 junctions/cm². The total series resistance of the device is 85 Ω . Three pads are provided for the external leads. Much of the electrical noise is eliminated by using the three signal leads and a differential amplifier. This detector measures x-ray fluences as low as 10^{-6} cal/cm².

Thermocouple. A thermocouple calorimeter has been developed by the Lockheed group (11). The absorbing element is a thin (0.025-mm) tantalum foil, and the temperature increase of the foil is detected by a chromel-alumel thermocouple junction.

Fig. 15. Thermopile matrix calorimeter detector.

Figure 16 shows the design of the calorimeter housing, which was fabricated from Delrin. The tantalum foil absorber and support ring are illustrated in Fig. 17. The foil is held in place by two 0.127-mm-diam constantan wires which are spot-welded to the foil and the support ring as shown in Fig. 17 to give firm mechanical support to the foil. When the calorimeter is operated in vacuum, the thermal insulation of the foil from the surrounding housing is sufficiently good to give a time constant of a few seconds for recovery from a thermal signal. The electrical noise accompanying the input pulse occurs on a much shorter time scale, and thus does not disturb the measurement. The two thermocouple wires are soldered to the leads from a twisted shielded-pair cable which pass through two holes in the back of the Delrin housing and are held in place with a tapered dowel. The solder joints are protected from the x-ray beam by a 0.183-mm lead shield. The rf shield from the cable is continued over the calorimeter housing by soldering it to the brass support that fits over the back of the Delrin housing (not shown in Fig. 16) and wrapping the assembly with copper tape. The calorimeter is thus completely shielded except for the front surface of the tantalum absorber.

Fig. 16. Thermocouple calorimeter detector.

Thermocouple signal was led into a low-noise dc amplifier and line driver with a gain of 1000 whose output was used to drive oscillograph chart recorder. The smallest thermocouple signal that could be detected with this arrangement was about $2 \mu\text{V}$, corresponding to a fluence of $7.2 \times 10^{-5} \text{ cal/cm}^2$. A mercury battery and resistor network capable of providing voltage levels from $20 \mu\text{V}$ to 1 mV was also incorporated into the electronics

package to provide calibration signals. Calibration of these calorimeters is accomplished using the pulsed particle beam from the Lockheed 3-MeV Van de Graaff accelerator as an energy source.

These devices are simple, compact, and rugged, can be easily calibrated, and are insensitive to mechanical shock or electrical noise. The range of sensitivity for soft x rays (e. g.,

Tantalum absorbing foil
(Back side)

Fig. 17. Tantalum foil absorber and support ring.

a 0.5-keV blackbody spectrum) extends from fluence levels of $1.7 \times 10^{-2} \text{ cal cm}^{-2}$ (the spill limit) to levels of $7.2 \times 10^{-5} \text{ cal cm}^{-2}$, at which point the thermocouple signal is comparable to the noise.

Thermoluminescent Dosimeters. Thermoluminescent dosimeters (TLD's) have a linear response with respect to absorbed x-ray energy, a large dynamic range (10^7), insensitivity to visible and infrared light, and small size. When used for

x-ray diagnostics of plasmas, TLD's have the advantage of not responding to spurious rf noise as may x-ray diodes or photomultipliers. Also, the TLD's do not outgas and can be easily used inside vacuum chambers. The two most widely used TLD crystals are LiF and $\text{CaF}_2(\text{Dy})$. The light output of these crystals when plotted against x-ray dose is nearly linear up to about 1000 rad.

The response of the $\text{CaF}_2(\text{Dy})$ TLD material has been measured (40) in the soft x-ray region using line sources at 1.49 (Al), 5.9 (^{55}Fe), 14.5 (^{238}Pu) keV and also at the 662-keV line of ^{137}Cs . The 0.889-mm-thick TLD-200 is completely absorbing for the soft x-ray sources, but mostly transparent to the ^{137}Cs x ray (calculated absorption $\sim 2.1\%$). Figure 18 is a plot of the measured sensitivity as a function of absorbed x-ray energy. A least-squares best-fit constant sensitivity is indicated by the straight line. $\text{CaF}_2(\text{Dy})$ is about 30 times more sensitive to x rays than LiF. A typical size for these crystals is 3.2 mm square $\times$ 0.889 mm thick. Since these crystals are thin to high-energy x radiation, they can be used in conjunction with appropriate filters as x-ray spectral measuring devices. For example, a 1-mm-thick LiF chip used with a 0.013-mm aluminum filter is sensitive to an x-ray energy interval of 5-13 keV.

X-Ray Imaging Devices. The x-ray pinhole camera has the following properties: (1) It can record high-energy x-rays; because there is no energy cutoff as in the x-ray microscope (to be described), protons of all energies can be recorded. (2) It can be used to record faint diffuse features of the x-ray emitting regions. By use of a large pinhole, the camera sensitivity can be increased greatly with a consequent loss of resolution.

Fig. 18. Sensitivity of $\text{CaF}_2(\text{Dy})$ thermoluminescent dosimeter.

The resolution of a pinhole camera (41) can be obtained from Fig. 19. A point source at the object distance, u , will produce on a screen at the image distance, v , a disk of light of diameter d . If the pinhole diameter is a , then

$$d = a(1 + M).$$

where the magnification M is:

$$M = \frac{u}{v}.$$

Thus the illuminated disk or circle of confusion is proportional to the aperture a and increases with increasing magnification. The "blurring" of the image depends on the ratio of d to a given dimension of the image, i.e., upon d/D_i . From Fig. 19 we have

$$\frac{d}{D_i} = \frac{a}{D_0} \left(1 + \frac{1}{M}\right).$$

Thus, the blurring like d , varies directly with a ; but unlike d , it becomes less as the magnification increases.

The optimum pinhole diameter (41) is illustrated in Fig. 20. The aperture is divided into Fresnel zones as shown. The illumination at P is clearly a maximum when the aperture subtends only the first Fresnel zone, $a = a_0$, is given by:

$$a_0 = 2 \sqrt{\frac{0.9 \lambda v}{(1 + M)}}.$$

Fig. 19. Pinhole camera resolution.

Thus for a 1-keV x ray with an image distance of 10 cm and a magnification of unity, the optimum pinhole diameter is $\approx 14 \mu\text{m}$.

Seward (42) has used an array of 16 pinholes, ranging in diameters from 6 to $75 \mu\text{m}$, in a 0.025-mm gold foil, which produces simultaneous pictures at different sensitivities and resolutions as shown in Fig. 21. Several filters are also used to eliminate varying amounts of soft x rays. These are images of a spherical-shell laser target $\approx 250 \mu\text{m}$ in diameter.

The resolution limitations of an x-ray pinhole camera can be significantly improved by using an x-ray microscope. An x-ray microscope to take high-resolution photographs of laser-produced plasmas has been developed by Seward and Palmieri (43).

Fig. 20. Optimum pinhole diameter.

Since x rays can be reflected through small angles from highly polished surfaces, it is possible to construct an x-ray imaging arrangement, or lens, using this reflection property. Seward and Palmieri use a two-element grazing incidence x-ray lens having a focal length of about 250-mm. When this lens is placed 355 mm from the x-ray source, it forms an image with a magnification of 3 at a distance of about 1065 mm from the lens. Therefore, it functions as an x-ray microscope suitable for examining the geometrical features of a laser-produced plasma viewed as an x-ray source.

The x-ray lens consists of two cylindrically ground glass surfaces as shown in Fig. 22. Each cylindrical surface produces a line focus in the image plane. The two surfaces are oriented at 90° with respect to one another and are placed so that a small

Fig. 21. Pinhole photograph of a spherical-shell laser target.

fraction of the incident x-ray beam is reflected from both surfaces. The combination of the two perpendicular line foci produces a true image.

Using the plasma X laser and the Long Path Laser at LLL on a variety of targets, the properties of this device were investigated in early 1973 (44). From these studies it was found that (1) the system is sensitive enough so that film can be used to record the x-ray image from most targets; (2) the resolution is $\approx 5 \mu\text{m}$; and (3) focal conditions are not critical. The above resolution exceeds significantly that obtainable from a pinhole

Fig. 22. X-ray microscope lens.

camera in the soft x-ray region. A comparison of the resolution of a x-ray pinhole camera and a x-ray microscope is shown in Fig. 23. Both instruments looked at a laser-produced plasma on an iron slab target. A wire mesh was placed in front of each device. The thick wires were spaced at 4 lines mm and the five wires at 40 lines mm. The resulting images are shown for the pinhole camera, Fig. 23a, and the microscope, Fig. 23b.

Fig. 23. Comparison of pinhole camera and x-ray microscope resolution.

The potential advantage of an x-ray microscope for x-ray diagnostics of plasma are: (1) spatial resolution is good; $5\text{-}\mu\text{m}$ resolution is easy to achieve with a simple system; (2) the lens can be placed far from the target, keeping this region free for other diagnostics; and (3) the high-energy cutoff makes absolute measurement of soft x-ray fluxes easier.

Figure 24 shows a photograph of a Long Path Laser plasma produced on an ion target obtained with the x-ray microscope. The x-ray source diameter is about $100\text{ }\mu\text{m}$.

RATE EXPERIMENTS

X-Ray Diode (LLL)

A windowless x-ray diode (Fig. 25) has been designed and built at LLL and will soon be used in laser plasma experiments. The cathode at the base of a cone-like structure is plated with gold. The anode is an 80% open screen. The cathode structure tapers to the diameter of the output cable, where its impedance is $50\text{ }\Omega$ to match the impedance of the cable. The measured time response of this detector is also shown in Fig. 25. This was measured by exposing the detector to an electron burst with a 25-ps risetime. This detector promises to be a useful rate detector for plasmas with x-ray times as short as $\approx 1\text{ ns}$. The signal from this detector can be read out using the fast sampling system to be described or a 5-GHz oscilloscope.

Fig. 24. Photograph of a laser-produced plasma on an iron target taken with an x-ray microscope.

Fast X-Ray Diode (Lockheed)

Another approach to a fast x-ray diode is that taken by the Lockheed group (11). Their fast x-ray diode is shown in Fig. 26. The anode is a 50% screen across a 3-mm diam aperture. The impedance at the aperture is 5Ω . The anode has ten parallel output arms constructed by plating metal on a dielectric plate. The impedance at the end of an arm is 50Ω to match the signal cable. The signal fanout then consists of ten pulses that are then fed to a fast sampling system.

Fig. 25. Windowless x-ray diode.

Fig. 26. Fast x-ray diode.

Fast Sampling System (Lockheed)

A fast sampling system capable of reading out the signals of the two previously described fast x-ray diodes has been developed by the Lockheed group (11) and is shown in Fig. 27. For example, the ten signals from the Lockheed fast x-ray diode are fed to ten sampling heads with delays independently adjustable within a 5-ns range. The common trigger delay is adjustable within a 10-ns range. The outputs of the sampling heads are then fed to a multiplexer and from there to a histogram scope display indicated in Fig. 27.

X-Ray Streak Camera

The x-ray streak camera tube is being designed at LLL (44) to work in the x-ray energy range of 1 to 10 keV. This camera is used to temporarily resolve x-ray events occurring in the time regime of 100 ps or less. The camera concept is identical to that used in the 10-ps streak camera currently employed for temporarily resolving 1.06- μ m laser pulses; however, the photocathode has been replaced with an x-ray photocathode.

Gold makes a photocathode with about the highest quantum efficiency for this low-energy x-ray range. The gold is presently being evaporated on the thinnest beryllium substrate (0.0076 mm) that we have found will support a vacuum.

The x-ray sensitive streak tube was made by installing an x-ray sensitive photocathode and a new extraction grid in a standard commercially available image-converter streak tube (RCA C73435 series). The cathode is a 10-nm-thick gold layer supported on a 0.0084-mm beryllium vacuum window.

In the initial experiments with the x-ray streak camera, which is shown schematically in Fig. 28, a 0.33-mm diam aperture was placed in front of the x-ray photocathode. This aperture fixes the spatial resolution by limiting the usable photocathode area. The resultant streak is a straight line of varying intensity. The camera depicted in Fig. 29 uses components that were easily available. Because of the lens coupling and the characteristics of the image intensifier, the overall optical gain of the system is low, about 20. Nevertheless, the sensitivity of the camera is quite good.

The streak speed of the x-ray camera has been determined by observing the x-ray emission from an iron target during irradiation by two 0.5-J, 130-ps laser pulses separated by 300 ps. The streak photograph obtained, and the corresponding densitometer scan of the streaks are shown in Fig. 30. The ripples in the densitometer scan are noise due to low incident flux and low film

Fig. 27. Fast sampling system.

exposure. The resolution determined from Fig. 30 is consistent with the original estimate of 50 ps for the camera's time resolution.

COUNTING EXPERIMENTS

CRT plasmas have x-ray times long enough for the spectrum to be determined by counting experiments. For a Tokamak device hard x rays of 100 keV to 1 MeV energy are produced in the walls due to accelerated nonthermal electrons. A soft x-ray component corresponding to a temperature of ≈ 1 keV is produced from the thermal plasma itself. Both hard and soft components are measured in order to understand Tokamak processes. X-ray times for both components are about 10 ms. With a fast counting system in which energy resolution is not a critical requirement, an input counting rate of 500,000 counts/s is possible with a corresponding output counting rate of perhaps 100,000 counts/s. Thus, for a single Tokamak pulse, there would be the order of 10^3 counts in the x-ray spectrum. Landis et al. (45) have pointed out the possibilities of a fast counting system for soft x rays as shown in Fig. 31. The lower graph shows the variation of energy resolution with input counting rate measured on the manganese x rays from a ^{55}Fe source. Gaussian pulse shaping was used with various peaking times as indicated on the

Fig. 28. Phototube for x-ray streak camera.

Fig. 29. X-ray streak camera.

Fig. 30. Streak photograph of x-ray streak camera.

curves. (The peaking time is measured from the base line to the maximum of the Gaussian pulse.) The upper graph shows the output rate variation which differs from the input rate due to pileup rejection. These data refer to a cooled silicon detector system which would be most suitable for the soft x-ray region. Fast counting rate systems have also been designed for use with hard x rays (up to 1 MeV) (46). The detectors most suited for such systems would be cooled germanium, NaI crystal-photomultiplier tube combinations, or proportional counters.

CALIBRATION

High-intensity sources of x-ray fluorescent line radiation are most useful for calibrating x-ray detectors. X-ray lines of various target materials can be excited by bremsstrahlung, electron, or proton irradiation. The background of continuum radiation that is present in bremsstrahlung and electron irradiation is nearly absent for proton sources. X-ray lines in the region of about 15 to 100 keV are available from the irradiation of fluorescer targets.

Below 1.5 keV, K α x-ray lines can be generated by irradiation of various targets by protons — say protons of 200-300 keV from a Cockcroft-Walton generator. Above 100 keV, strong radionuclide sources can be used that provide lines up to 1 MeV or higher. The strength of these various sources can be determined and monitored with calibrated counters. LLNL has a number of calibrated x-ray sources as listed in Fig. 32.

Fig. 31. Fast counting system.

These are monitored with calibrated NaI detectors for energies greater than ≈ 8 keV and with cooled silicon detectors between 1.5 and 8 keV.

CONCLUSION

This survey attempts to point out the principal types of instrumentation currently being applied to the x-ray diagnostics of high-temperature plasmas. X-ray spectra are measured by means of Bragg-crystal and bent-crystal spectrometers. Both film and active detectors are used to detect the scattered x rays.

Fig. 32. Calibrated x-ray sources at LLL.

Source	Source strength	Energy range
Radiographic x-ray machine – fluorescent x rays	10^{10} – 10^{11} protons/s	5–98 keV
Electron-gun generator – fluorescent x rays	10^8 – 10^9 keV cm ² ·sr	1.5–8 keV
Neutron-activation sources		
¹⁴⁷ Ce	30 Ci	145 keV
⁵¹ Cr	1000 Ci	320 keV
Long-lived radioisotope		
⁶⁰ Co	2000 Ci	0.25–1.3 MeV

K-edge absorption methods are also used to measure x-ray spectra. This includes three variants, thick K-edge filters, Ross filters, and the stacked diode. A third method of x-ray spectral measurements is the use of the electron-sensitive nuclear emulsion as a combined converter and energy sensor.

X-ray calorimetry is performed principally with four types of calorimeters, the silicon surface-barrier detector, thin-film thermopiles, thermocouples, and thermoluminescent detectors.

X-ray source imaging is accomplished by means of the pinhole camera and the x-ray microscope. Better resolution is possible with the latter.

Time-dependent or rate measurements of time-varying x-ray fluences are measured with fast x-ray diodes and recorded with fast sampling systems or fast oscilloscopes. The best time resolution (≈ 50 ps) is currently available with the x-ray streak camera.

In the case of CTR plasmas it would appear that the x-ray spectrum of a single pulse can be measured using already existing fast counting systems. Of course, time-integrated or rate measurements can also be performed with these types of plasmas.

X-ray detecting systems are best calibrated using well-characterized monochromatic sources. These are obtainable by means of radioactive sources or particle accelerators.

ACKNOWLEDGMENTS

The assistance of the following individuals in the preparation of this paper is gratefully acknowledged, H. G. Ahlstrom, P. J. Ebert, D. E. Jones, J. H. McQuaid, S. W. Mead, F. D. Seward, and V. W. Slivinsky.

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