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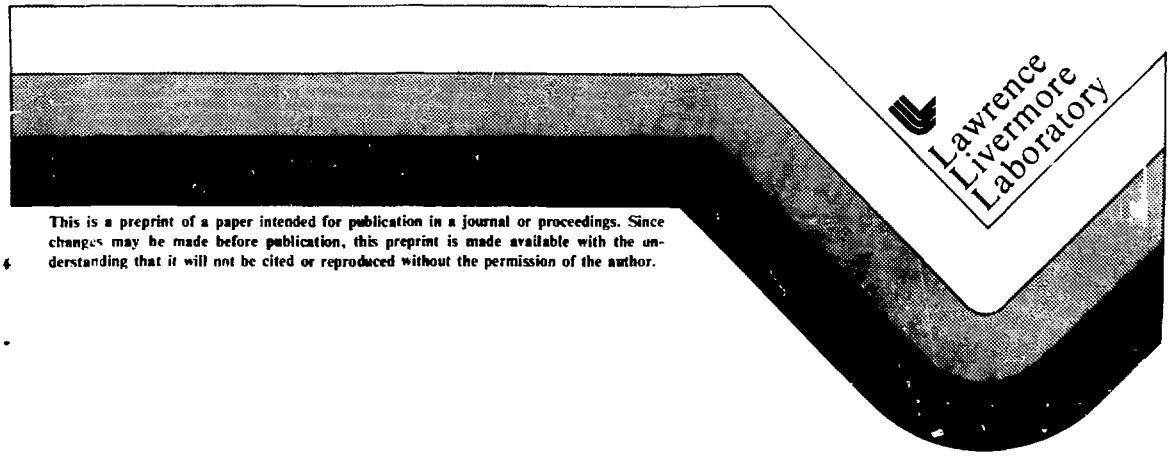

Time Resolved, Sub-keV X-Ray Measurements Using Filtered X-Ray Diodes*

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ABSTRACT

We describe filtered x-ray diode detectors used to measure absolute x-ray spectra below 1.5 keV at the Lawrence Livermore Laboratory Argus and Shiva laser facilities. We use K or L-edge filters in five and ten channel arrays to obtain energy resolution between 200 eV and 1.5 keV with channel FWHM's typically 200 eV. A channel with relatively uniform energy response is employed to independently measure the total x-ray energy up to 1.5 keV. Filter transmissions and detector sensitivities are measured absolutely to within ± 10% and ± 20% respectively at Lawrence Livermore Laboratory. With a FWHM time response that is less than 180 ps, the windowless diode detector developed for our experiments does not contribute significantly to system time response. Most of the fast oscilloscopes that we use for recording signals have a FWHM of 300 or 700 ps. We present, as examples, some ten channel x-ray spectral results obtained for disk irradiations at the Argus 1.06 micron laser facility.

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Introduction

A significant fraction of emission from laser irradiated targets is in the form of low energy x rays. Measuring these x rays with appropriate spectral and temporal resolution has become important for understanding the physics of laser target interactions. We have therefore developed an experimental arrangement consisting of sets of filtered, photoelectric, x-ray diodes to measure x-ray spectra below 1.5 keV at the Lawrence Livermore Laboratory Argus, Shiva, and Nova laser facilities. We use K or L edge filters to obtain energy resolution between 100 eV and 1.5 keV with channel FWHMs typically 200 eV. The energy response of each channel is determined mainly by the type and thickness of the filter and, to a lesser extent, the energy sensitivity of the metallic detector cathode selected for the channel. Over 15 filter-detector combinations have been developed for these systems including one with a flat response between 100 eV and 1.5 keV.[1] This channel with relatively uniform energy response is used to independently measure the total x-ray energy up to 1.5 keV. To obtain system channel energy responses, we calibrate filters and detectors separately. Filter transmissions and detector sensitivities are measured absolutely to within $\pm$ 20% as a function of x-ray energy using the facilities of the LLL x-ray calibration and standards laboratory.

The miniaturized, windowless diode detectors were developed for these experiments.[2] They feature interchangable cathodes and have FWHM response times that are less than 200 ps. Most of the fast oscilloscopes that we use for recording signals have a FWHM of either 300 or 700 ps. The detector, therefore, does not contribute significantly to system time response. A very fast detector (FWHM $\approx$ 50 ps) has been developed at LLL by Donald E. Campbell.[3] This detector is used with a Thompson TSN-660 oscilloscope (FWHM $\approx$ 90 ps) to provide a channel with FWHM less than 120 ps.

The main advantage of our diagnostic experiment is good absolute accuracy and reliability. For simplicity we do not use critically reflecting mirrors. This makes it easier to install and use two or three multichannel systems on evacuated flight tubes around the target chamber. For superior channel responses below 500 eV, we are, however, using a system of five reflector-filter-x-ray diode channels.[4] For comparison, we briefly mention other types of instruments used for low energy x-ray measurements. A three channel, low energy, x-ray streak camera has been developed at LLL featuring transmission filtering and grazing incidence mirror reflection for high energy cut off.[5] [6] This instrument has the advantage of 15 ps time resolution and large dynamic range. A second, very different, system providing complimentary soft x-ray information will utilize a crystal spectrometer combined with a grazing incidence reflector.[7] This instrument will have one eV energy resolution but no time resolution and the disadvantage that it is difficult to calibrate absolutely.

We will describe a ten channel system used at the Argus facility. The filters, detectors, and their respective calibrations will be discussed. Typical channel sensitivities as a function of x-ray energy will be shown as well as the response of these channels to a 160 eV temperature distribution. After further consideration of detector and system time responses, we present results for Argus laser excitation of disk targets.

Experimental Arrangement

Figure one schematically shows the experimental arrangement used at the Argus laser facility. Ten filtered, windowless diodes are mounted on an evacuated flight tube attached to the Argus target chamber. Each detector is attached to a ceramic vacuum interface for electrical isolation. The arrangement of five rear detectors has been duplicated at two other locations around the Argus target chamber. A large 1.5 kG

ring magnet positioned in the target chamber is used to sweep electrons emitted from the source away from the detectors. The flight tube is evacuated to the 10^{-6} Torr range by means of a closely coupled cryostat pump. A separate roughing system including a turbomolecular pump is used to reduce the pump down time.

Figure two shows a detailed filtered-detector assembly. X rays enter the detector after passing through a tantalum collimator, a thin Parylene debris shield, and one or two filters. X rays passing through the front detector grid interact with the cathode producing electrons. The 80% optically transparent, wire mesh anode is biased to +5 kV. The cathode is tapered to match a high quality 50 ohm signal cable coupled through a vacuum feedthrough. The positive signal induced by electrons accelerated to the grid is recorded using fast oscilloscopes.

Filtered-Detector Energy Response

Filters

For each channel the filter transmission and absolute detector sensitivity are measured as a function of photon energy at two LLL x-ray facilities. A subkilovolt facility provides intense, nearly monoenergetic, proton-induced fluorescence lines from 183 to 932 ev.[8] Electron-induced x-ray lines with greater than 95% spectral purity are used to cover the 1.5 to 8 keV energy range.[9] Details of the calibration procedure are discussed in reference ten.

Figure three shows filter transmission results for a few representative cases. The theoretical filter transmission curves were obtained using the absorption cross section values adapted from the work of Henke et al.[11] Filter thickness values were adjusted to obtain best fits to the data.

Formvar measurements are in good agreement with the calculated transmission curve above and below the carbon and oxygen K edges. Note that these results verify the chemical composition that has been given for Formvar. The iron filter calibration is complicated by the presence of iron oxide and by a lack of available source energies in the critical region below the iron L edges. We obtained reasonable fits, however, by assuming a different iron oxide composition for each sample. The calculated nickel transmission curve gives a good fit to data obtained at the two separate x-ray facilties. The transmission observed at 902 ev suggests a small impurity in the nickel sample. The good fits to the aluminum and nickel data could be slightly improved above 1.5 keV by correcting for source impurities.

Our initial calibrations indicated that variations from sample to sample are not significant particularly in the case of Formvar and aluminum. Zinc was the only exception with thickness variations of 15 to 20%. We concluded that only the zinc filters needed to be individually calibrated and that the other filter batches were characterized to within 10%. Our further experience has shown that up to 20% thickness variations are present for certain types of filters ---iron, cobalt, and nickel. Thus, for best results, we need to calibrate every filter.

Detectors

In our first experimental arrangement we used several different elemental cathode materials including Si, Al, C, V, Fe, and Cu. The aluminum and copper cathodes were machined from very pure materials. The other elements were each vapor deposited on the front surface of a copper cathode. We selected these materials to take advantage of the decrease in response below their respective K or L absorption edges.

Practical considerations have led us to a system consisting of three cathode types - Al, Cr, and Ni. We found that the sensitivity of V, Fe, and Cu detectors decreased over a period of time probably due to oxidation. Besides these undesirable but gradual changes, we observed

abrupt changes in the absolute sensitivity of one of the Si detectors. In contrast, the Al detectors were relatively stable over a period of several months. Figure four shows absolute sensitivity measurements for the types of detectors used in the present system. Because of their stability, we are using aluminum cathodes exclusively for channels below 800 eV. To obtain more signal amplitude and to avoid the effects of the Al K-edge jump, we use chromium in the intermediate region shown in Figure four and nickel for channels above one keV. Note that the Ni detector response is well determined near its L-absorption edges by the copper L calibration source line. In general, interpolation between calibration energies is difficult near detector absorption edges because of sudden changes in response. With the discrete source energies presently used, calibration points in the region above their respective absorption edges are available for Ni and Cr but not available for iron and copper. Besides this calibration advantage, both Ni and Cr have thinner, more stable oxide layers than the cathodes that they have replaced.

One of our objectives, in addition to obtaining greater detector stability, has been to decrease the sensitivity variations between cathodes of a given type. In the case of Al, because of a variety of surface treatments the original detectors were found to vary in absolute sensitivity by a factor of two. (Response curve shape variations, however, were much less significant). The improved treatment consists of thorough cleaning of the detector followed by machining the front face to less than 25 microns surface roughness and then storing it in dry air for a month.

The measured absolute sensitivity values for 15 treated Al detectors are in a 20% band about the average from 185 eV to 4 keV. The success of this treatment is probably due to greater uniformity of the aluminum oxide layer as well as the uniformity in effective surface area.

Channel Response Functions

The characteristics of the ten channels used in the 0.2 to 1.5 keV range are summarized in Table one. Most of the practical filter materials have absorption edges between 1/2 and 1 keV. We have only one channel below 400 eV. Additional filters not listed include freestanding boron foils that have been developed at Lawrence Livermore Laboratory to provide a K edge at 185 eV. Also under consideration is a germanium filter with L edges near 1.3 keV. Brittleness is the basic problem with these two materials. We have also developed a relatively high energy channel consisting of an Al cathode and a Zr filter with L absorption edges near two keV. We have found that this channel is not practical, however, because of the low diode sensitivity at this energy and because of the low amplitude of all of the spectra in this energy range.

The dependence of the channel response on energy is determined in each case by folding the filter transmission and detector sensitivity calibration curves. The blast shield transmission vs energy is also taken into account. Representative results are shown in Figure five. The channel responses decrease sharply at filter absorption edges but are rather broad - generally 100 to 250 eV.

Folds of total response functions with a 160 eV temperature x-ray distribution are also shown in Figure five. The main reason that we do not need mirrors for high energy cut off is that nearly all of the spectra that we measure decrease rapidly at higher energies similiar to the 160 eV thermal spectrum chosen as an example. The contribution to the detector signal above the absorption edge is negligible in every case except the first channel. The energy dependence of the Formvar filter and the increase in the incident spectrum above the carbon K edge result in a large signal contribution above 300 eV. It is thus difficult to measure the initial rising part of this spectrum. To improve measurements below 500 eV, a filtered x-ray diode system has been built with the addition of a grazing incidence reflector for each of five different channels. The carbon channel, for example, has a high energy cut-off at 300 eV.

Table 1

Filtered X-Ray Diode Channel Characteristics

	Cathode Type	Filter[a,b]			Channel Width eV
		Absorption Edge	Thickness mg/cm	Edge Energy keV	
1	Al	Carbon-K[c] Oxygen-K	0.15	0.28	110
2	Al	Vanadium - L	0.33	0.52	125
3	Al	Chromium - L	0.43	0.58	110
4	Al	Iron - L	0.31 (Fe) 0.06 (Fe_2O_3)	0.71	270
5	Al	Cobalt - L	0.98	0.79	240
6	Al, Cr	Nickel - L	0.62	0.86	160
7	Cr	Copper - L	0.89	0.94	170
8	Cr, Ni	Zinc - L	1.0	1.03	180
9	Ni	Aluminum - K	2.5	1.56	470
10	Ni	Aluminum - K	5.0	1.56	250

[a] A ten $\mu g/cm^2$ Parylene filter was also used for each channel.

[b] Except for Formvar and Al, the filter foils were provided by the Lebow Co., Santa Barbara, Ca.

[c] Formvar ($C_{10}H_{16}O_5$) was used for this filter.

Time Response

We have made preliminary x-ray diode time response measurements. Data were recorded using a Thompson TSN-660 oscilloscope with a 90 ps FWHM time response. We obtained a FWHM value less than 260 ps for the response of this system to x rays from a 165 ps laser pulse incident on a gold disk target. A soft x-ray streak camera on the same shot gave a reasonably symmetric x-ray pulse with a FWHM of about 190 ps. Unfolding the x-ray and oscilloscope time response yields a detector FWHM of $\tilde{\sim}$ 150 ps. This value is larger than we expected. The detector pulse does not return to the baseline as rapidly and smoothly as is predicted. Figure six shows our expected detector time responses calculated for two different anode to cathode spacings.[12] We have reduced the spacing from 5mm to the optimum value suggested by the calculation. The observed slower return to the baseline may be due to mismatch at the cathode-vacuum feedthrough interface and inductance effects not taken into account in the calculation. Measurements to more accurately determine the detector time response are in progress.

Although the Thompson oscilloscope is available for one or two channels, the oscilloscope recording system consists primarily of direct access and amplified Tektronix R7903 oscilloscopes. The measured FHWM values are 300 and 700 ps for these systems respectively. Thus the x-ray diode FWHM does not significantly increase the time response of most channels.

Typical Results

Figure seven shows representative x-ray spectra measured for 1.06 μm irradiations of aluminum and gold disk targets at the Argus facility. The laser parameters and experimental geometry are also shown in the figure. The points were determined using the total charge measured for each channel, the channel response functions, and an iterative unfolding code.[13] The UNSPEC code takes a trial spectrum and, using all the input information simultaneously, converges to a best fit spectrum.

We have found that the Al and gold spectral shape variations have not been significant from shot to shot. Gold spectral amplitudes were found to depend significantly on the laser intensity decreasing by roughly a factor of three when the intensity is increased a decade to $3x10^{15}$ W/cm^2. We made the measurements at only one angle, therefore, some of the spectral amplitude variations may be due to variations in the emitted x-ray angular distributions.

The Au spectrum is much flatter partly due to unresolved N series lines in the 500 to 800 eV range. The Al spectrum drops rapidly with increasing energy. From these spectra we determine that, compared to Al, gold emits over eight times as much x-ray energy integrated between 200 eV and 1.5 keV. According to the crystal spectrometer measurements of Koppel, most of the Al K line emission is shifted up above 1.5 keV out of our highest energy channel. The low amplitude observed in our highest channel is consistent with the crystal spectrometer spectrum that shows a low level of cold Al K emission.

As a second example we show, in Figure eight, spectra measured with the Argus ten channel system. These experiments involved a Ta disk and several gold disks norminally 600 to 700 μm in diameter and 14 to 25 μm thick each rotated 30° from the beam axis and irradiated from both sides with gaussian pulses of 600 ps FWHM. The ten channel system viewed the disk face at an angle of 60° with respect to the disk normal. Spectral values were normalized to the total laser energy in the south beam incident on the front face.

Spectral emission from the three gold disk targets irradiated at $3X10^{14}$ W/cm^2 was relatively consistent both in amplitude and in spectral shape. These spectra were within a 15% band over the measurement range.

The most striking feature of these results is the decrease in normalized disk emission amplitude with an increase in laser irradiance. The magnitude of emission from the gold disk with the greatest incident irradiance, for

example, was nearly a decade below that of the disks at $3X10^{14}$ W/cm^2. We observed anomalously narrow pulse widths on this shot. Note also that this spectrum is relatively flat and the 500 eV dip rather shallow.

The Ta disk spectral shape generally resembled that of the gold disks. This spectrum dropped a decade from 200 to 1100 eV as in the case of the gold disks at $3X10^{14}$ W/cm^2; however, for Ta both the 500 eV dip and the amplitude of the second peak were relatively weak.

Discussion

We now consider the question of uncertainties in the absolute x-ray spectra measured using Dante systems. Are there significant systematic differences between the real and measured spectra?

The most significant source of systematic error is due to detector calibration uncertainties that vary from 20 to 30% across the calibration energy range. The uncertainties are less above 550 eV and in the neighborhood of the carbon calibration line at 277 eV. Uncertainties are definitely greater below 200 eV as indicated by fluctuations in the boron (185 eV) calibration values. The energy region in the vicinity of the oxygen K-edge (531 eV) is perhaps the most difficult to calibrate due to the effects of small amounts of oxygen contamination in both the source and the detector.

It should be noted that the statistical uncertainties in the detector calibrations are much better than 20-30%. For example the spread in all the calibration values for the six diamond turned aluminum cathodes is less than 8%.

Filter transmission uncertainties are less than 10% and are thus usually not significant. Preliminary data obtained using uncalibrated filters, however, has resulted in discrepancies as high as 25% particularly in the case of cobalt, iron, and nickel as verified later by

calibrations. In some cases fragile filters have been broken in use prior to calibration. Except for filters such as Formvar and aluminum with low thickness variations, the corresponding measurement uncertainties are substantially increased.

The combined absolute uncertainties due to filter and detector calibration errors thus vary from 20% for a known filter in a well calibrated detector energy region to 40% for an uncalibrated filter in a relatively uncertain detector energy region. A conservative absolute uncertainity for the total x-ray energy obtained by integrating the unfolded spectrum is 25-30%.

Our present knowledge indicates no significant uncertainties due to problems in the following areas: blast shield transmission corrections, recording system calibrations, spurious background including EMP, high energy x-rays, electrons, or ions and finally instrumental effects such as incorrect detector solid angles or partially blocked lines of sight.

Uncertainties in recording x-ray detector signals generally are not significant. Disk shot data quality is usually good. High frequency trace baseline noise is not a serious problem as has been the case for other types of targets. The time and amplitude axes of all oscilloscopes have been calibrated; and appropriate corrections, generally less than 5%, have been made. Interchanging oscilloscopes between channels has resulted in no significant changes in results.

We also feel that spurious background contributions are not present due to EMP, high energy x rays, electrons or ions. We have some evidence that EMP induced signal components are not significant. We observe relatively low signals with the Dante system viewing the back of a thick disk target. EMP effects, which should be present during these shots, are apparently delayed. Perhaps a delayed ringing that we observe is due to EMP.

Signal components due to nigh energy x rays are insignificant due to the very rapid decrease in detector sensitivity with increasing photon energy.

The question has been raised; however, does the broad low component of the channel response from two to three times the filter K edge energy distort the unfolded spectra? Our conclusion is that this distortion is not significant except in the case of the first channel. From the 160 eV temperature case shown in Figure five, we see that the first channel is the only one with a significant response above the filter absorption edge. Using any of the unfold gold disk spectra in Figure eight and the channel response functions, we find that the signal contribution below the filter absorption edge is about 50% for the Formvar channel but is greater than 92% for all the others.

Electrons up to very high energies (less than 10 MeV) are removed from the beam by the sweeping magnet located more than a meter in front of the detectors. Direct electron backgrounds are thus not a problem. We feel; however, that electron fluorescence of the forward section has been a major contributor to background signals observed in some shots prior to the installation of suitable forward collinator near the sweeping section.

The percentage contribution of this background source is directly related to the high energy electron to low energy x-ray intensity ratio. Compared to other targets, this ratio is lowest for disk shots. This background has been removed by suitable forward collimation reducing the detector view of the target to a one cm. diam. circle completely excluding the target positioning assembly and including only about five mm of the glass target stalk.

Ions, on the other hand, are definitely not a source of background due to their much greater time of flight to the detector.

We have examined the unfolding code in detail and have determined that it is operating correctly. The problems involved in deriving the x-ray spectrum above 500 eV are due mainly to relatively broad channel resolution and the presence of spectral lines. The unfolded results are relatively insensitive to the shape of the trial spectrum used to begin the first iteration. Below 500 eV, however, the shape of the unfolded spectrum is significantly more dependent on the trial spectrum. In this region the spectrum is determined only by the first channel. Because this channel has an additional broad response around 500 eV above the 277 eV carbon filter K-edge, there is uncertainty concerning the fraction of the signal to be assigned to the lower energy region. Our procedure, though consistent, may result in spectra differing systematically from reality below 500 eV. It should be noted; however, that the integrals of the unfolded spectra are relatively insensitive to initial assumptions. One of the main purposes of the new mirror system on Shiva, therefore, is to provide more and better low energy channels to more accurately determine the spectra below 500 eV.

There is some experimental confirmation of our experimental results. We have recently observed a strong channel by channel correlation between three channel x-ray streak camera intensities and our own results.[14] If our measured spectra differ from the emitted spectra, at least the systematic differences have not been changing significantly from shot to shot.

The flat response, filtered x-ray diode mounted on a rear position on the ten channel system has given important experimental confirmation of the multichannel system results. This instrument has given values for the total x-ray emission that are consistently 80% of the spectral integrals for nearly all disk targets within the experimental uncertainties of both instruments. We are continuing to investigate the 20% systematic difference. Since we have had extensive experience with only one flat response detector, we need to assemble, calibrate, and use a double or triple array.

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Figure Captions

1. Experimental arrangement of ten filtered, sub-keV x-ray diodes at the Argus laser facility. This type of diagnostic experiment is locally called a Dante system.

2. Filtered, windowless, x-ray diode assembly.

3. Representative filter transmission calibration results. Transmission curves were fit to the calibration points using absorption cross section values adapted from the work of Henke et al.[11]

4. Absolute sensitivity measurements of x-ray diode types used in our experiments.

5. Energy dependence of the response functions for representative channels. Each of the dashed curves shows the channel response to a 160 eV thermal x-ray spectrum normalized at the peak amplitude.

6. Detector response vs time calculated for two different anode to cathode spacings. The original spacing was five mm. The 2.1 mm spacing theoretically minimizes the FWHM time response.

7. X-ray spectra measured for 1.06 μm irradiations of aluminum and gold disks using the ten channel system at the Argus facility.

8. X-ray spectra measured for irradiations of a tantalum disk and several gold disks at the Argus facility.

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TEN CHANNEL FILTERED SUB-keV X-RAY DIODE ARRANGEMENT AT ARGUS AND SHIVA

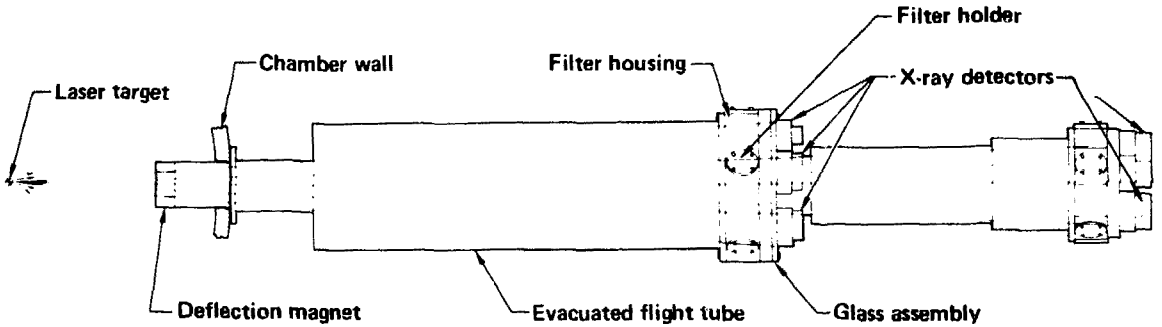

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Figure 1

TYPICAL FILTERED, X-RAY DIODE "DANTE" CHANNEL

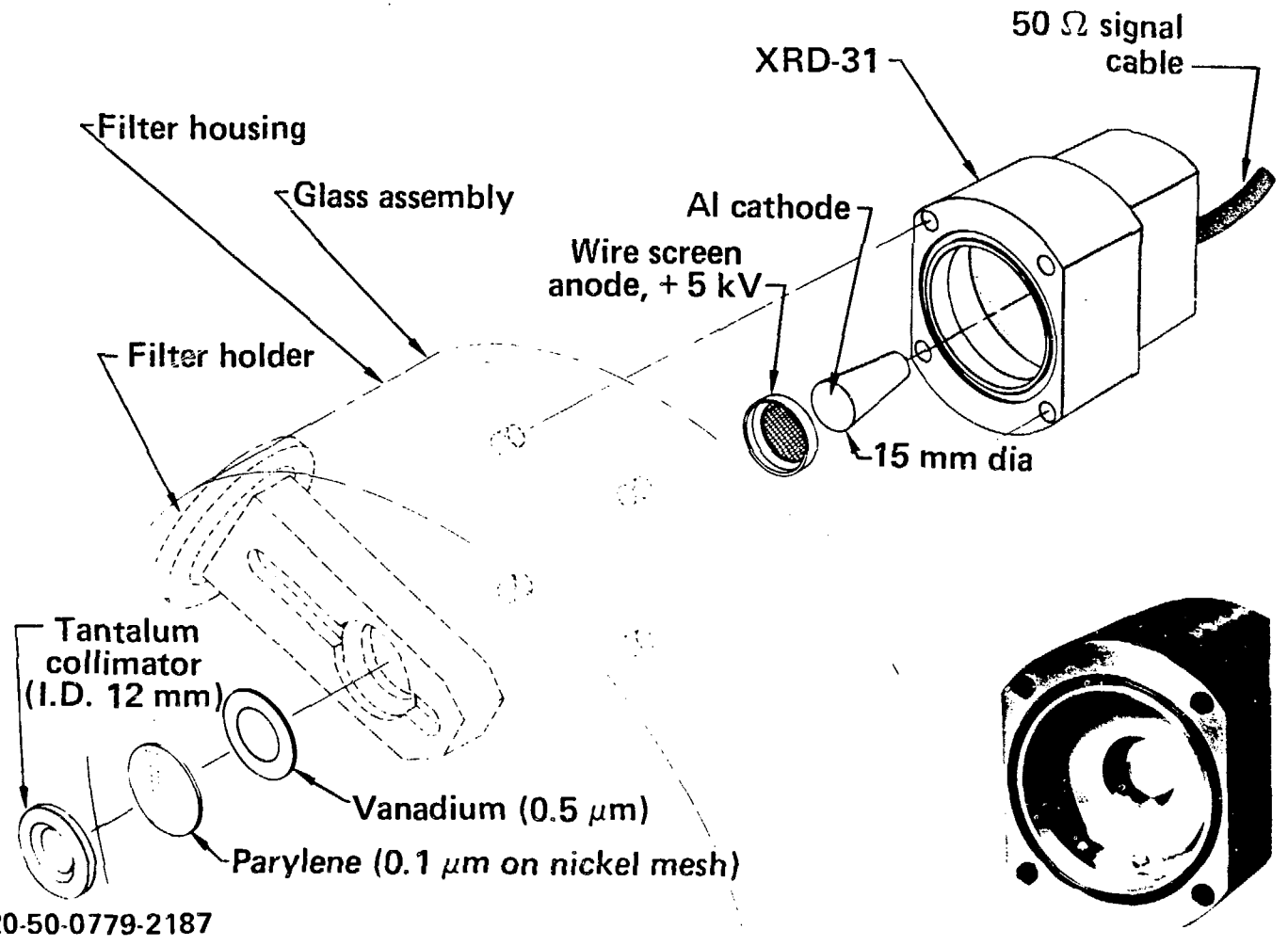

Figure 2

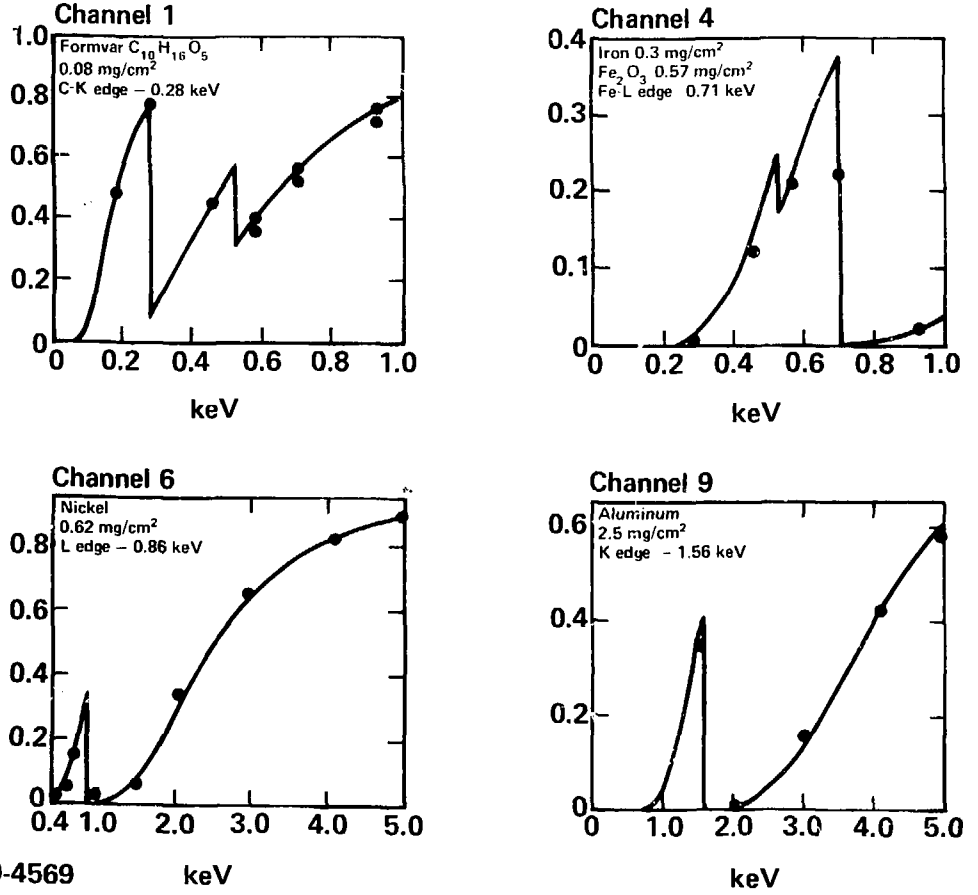

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Figure 3

FILTERED-DIODE CALIBRATION MEASUREMENTS (DETECTORS)

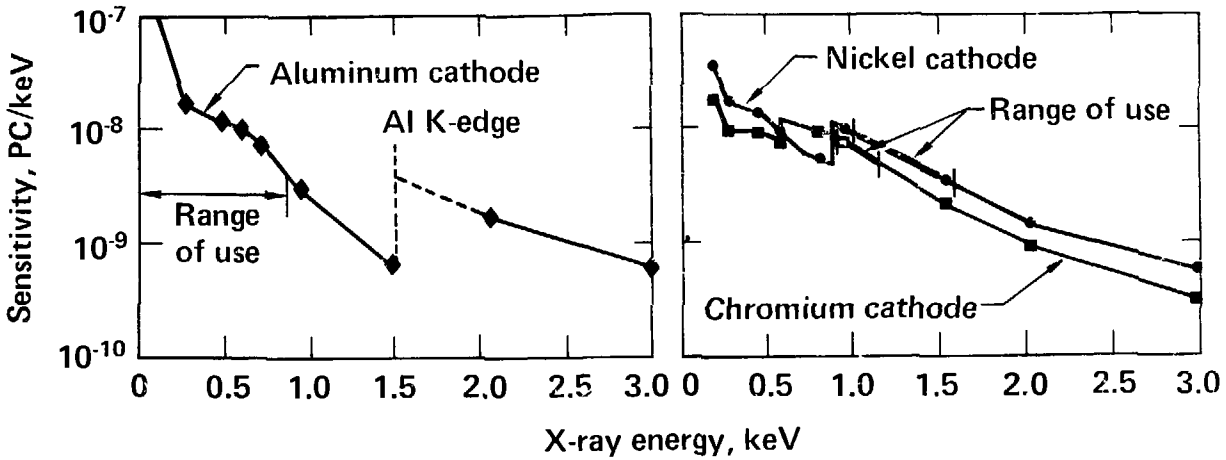

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Figure 4

DANTE CHANNEL SENSITIVITIES AND CHANNEL RESPONSES TO 160 eV TEMPERATURE SPECTRUM

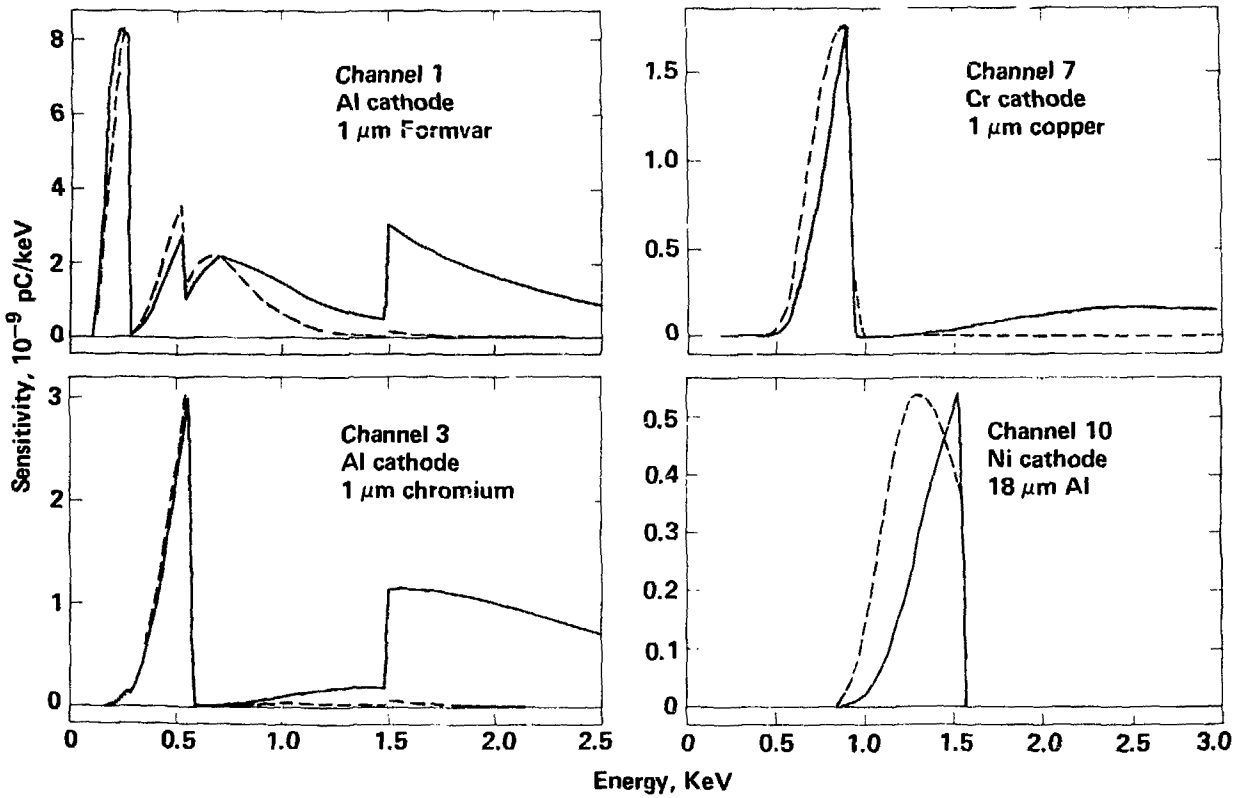

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Figure 5

CALCULATED X-RAY DIODE TEMPORAL RESPONSE

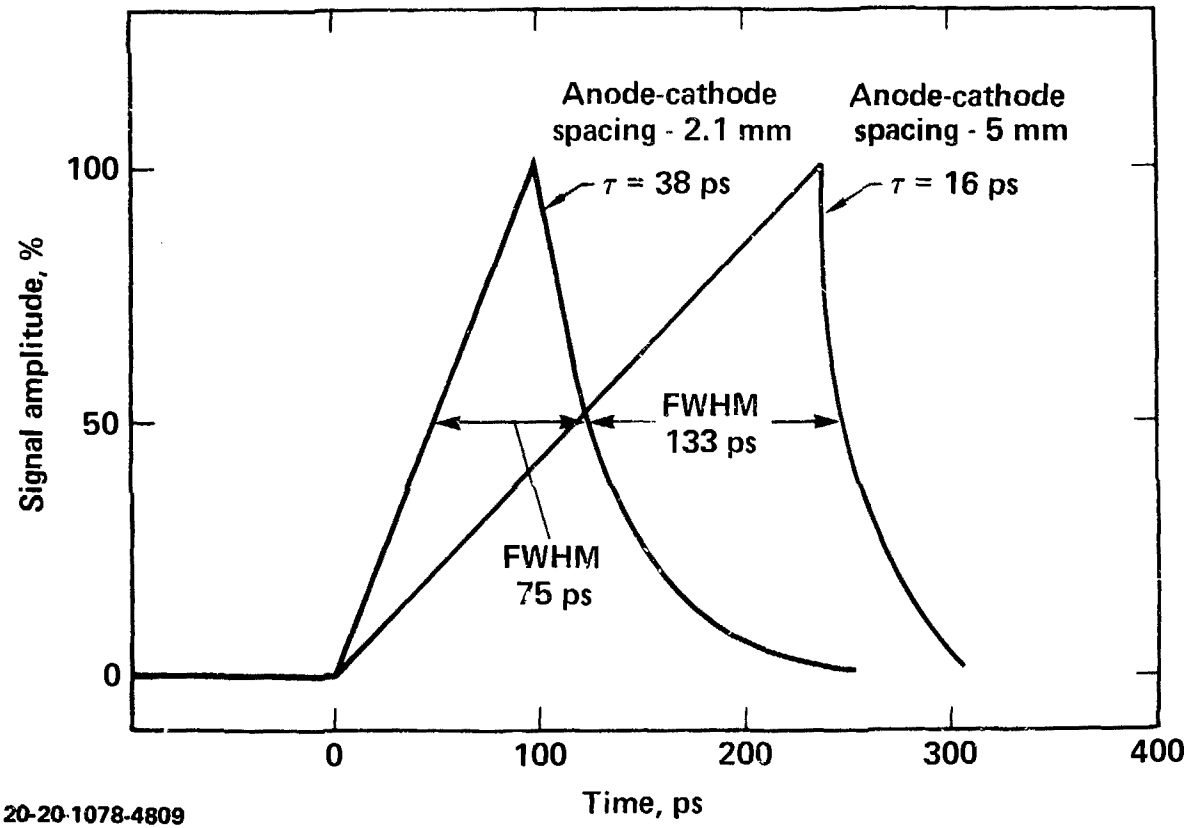
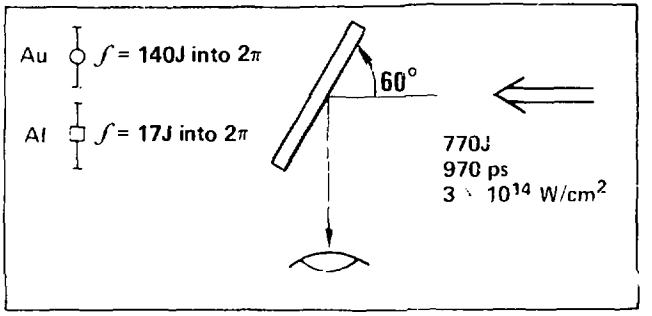


Figure 6

LOW ENERGY X-RAY EMISSION – Au AND Al DISKS



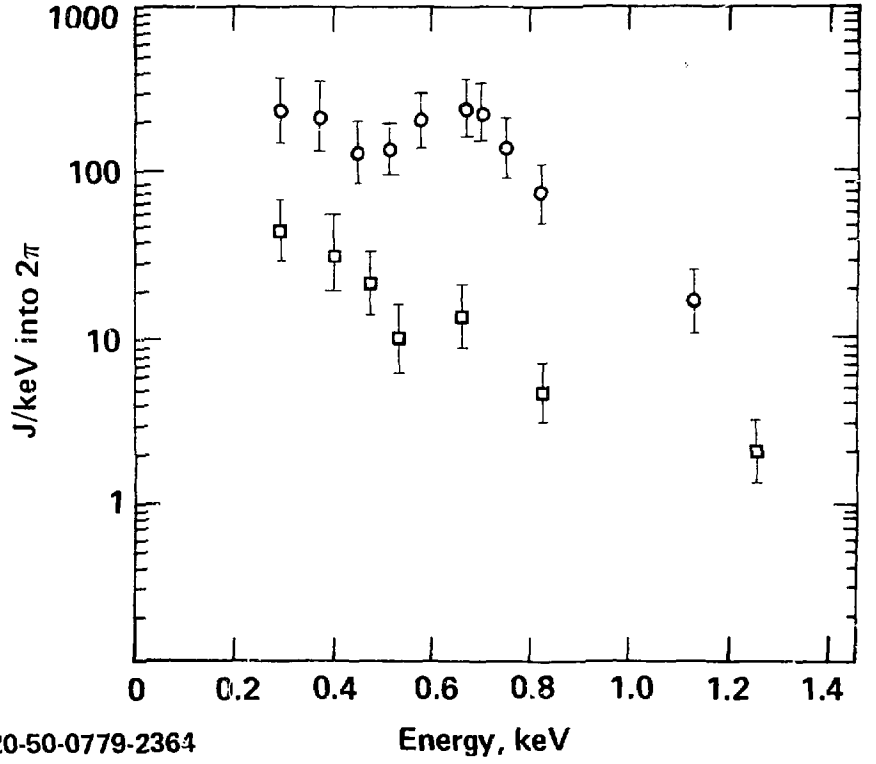


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Figure 7

LOW ENERGY X-RAY EMISSION - Ta AND Au DISKS

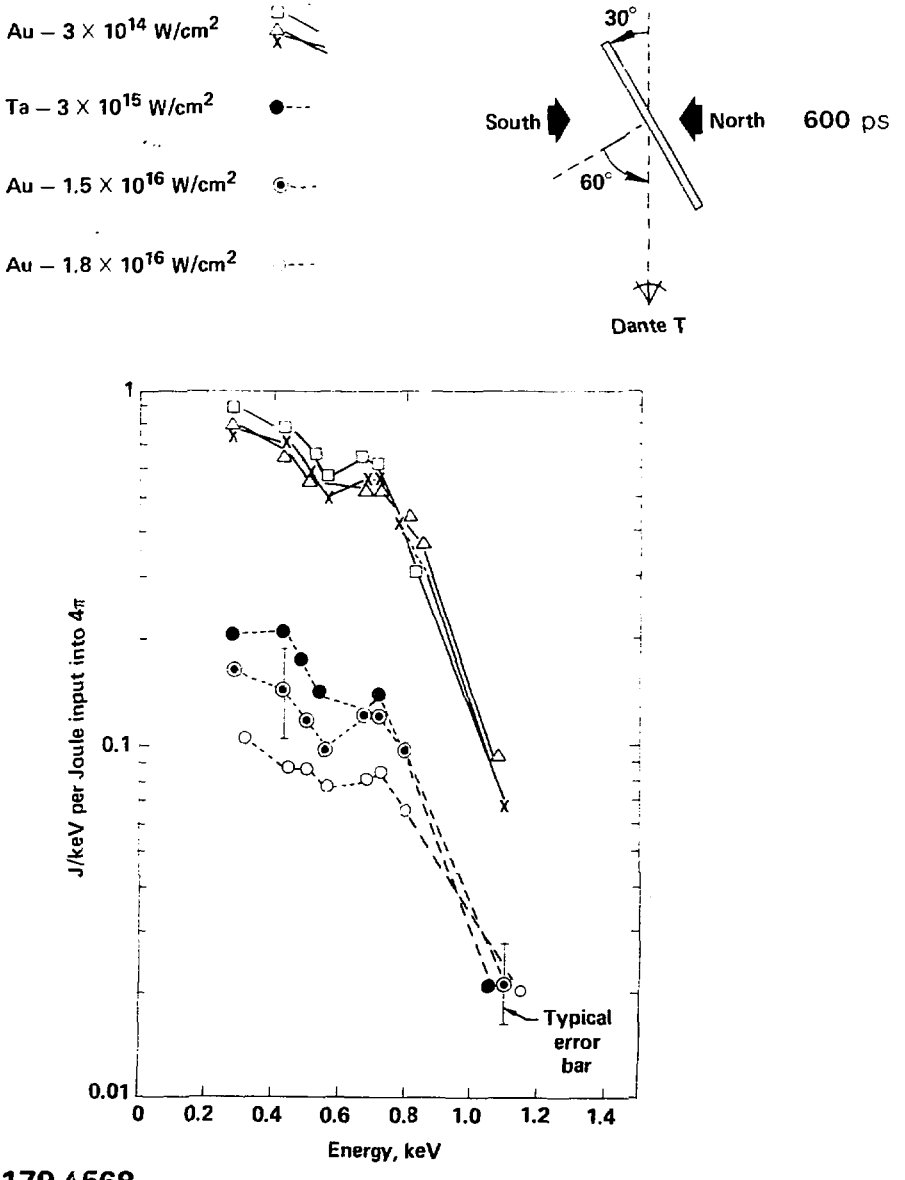

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Figure 8