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FLAT-RESPONSE X-RAY-DIODE-DETECTOR DEVELOPMENT

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ABSTRACT

In this report we discuss the design of an improved sub-nanosecond flat response x-ray diode detector needed for ICF diagnostics. This device consists of a high Z cathode and a complex filter tailored to flatten the response so that the total x-ray energy below 1.5 keV can be measured using a single detector. Three major problems have become evident as a result of our work with the original LLNL design including deviation from flatness due to a peak in the response below 200 eV, saturation at relatively low x-ray fluences, and long term gold cathode instability. We are investigating grazing incidence reflection to reduce the response below 200 eV, new high Z cathode materials for long term stability, and a new complex filter for improved flatness. Better saturation performance will require a modified XRD detector under development with reduced anode to cathode spacing and increased anode bias voltage.

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INTRODUCTION

The need for a subnanosecond x-ray detector with a flat response below 1.5 keV has been long recognized. For such a device, the detector signal is proportional to the low energy x-ray energy regardless of the spectral shape. Because most of the x-ray energy emitted in laser-plasma interactions is below 1.5 keV, the total x-ray energy can be measured using a single detector.

In this memo we review our flat response x-ray diode development. We then discuss problems that have become evident as the result of our experience with the original design. We describe a new detector and compound filter that should give better performance and propose a developmental program leading to the improved diagnostic device.

The original flat response x-ray detector consisted of a relatively large EG&G XRD-30 with a gold cathode and a complex filter tailored to flatten the response below 1.5 keV[1]. The compound filter was constructed to over 20% of the XRD cathode surface with 800A of Parylene N and 80% with 3 microns of aluminum. We adapted this design to the XRD-31 (15 mm diam. cathode), our standard XRD used in most broadband spectrometers for laser interaction diagnostics. We then improved the mechanical construction of the new smaller filter[2], attempted to upgrade the detector surface quality, and calibrated each of the filter components and detector responses separately at the LLNL Ionac facility[3]. To achieve more uniform cathode performance, we first diamond-turned the copper substrates and later coated them with nickel to reduce copper migration through the vapor deposited gold surface layer. Two of the best Au/Ni/Cu detectors with similar response shapes were selected and used for several months on a long series of Argus gold disk irradiations[4]. We have had problems with variability of new gold cathode response versus energy and instability of cathode sensitivity with time. These problems will be discussed more fully in another report[5]. We emphasize that cathode stability is one of the major problems that remains to be solved in developing a more practical flat response detector.

When gold XRD calibration results below 200 eV became available, a problem with our present design in this energy region became evident. Figure 1 shows the composite flat response obtained for our best gold cathode used at Argus with the low energy NBS gold response data of Day et al.[6] normalized at 185 eV, our lowest Ionac calibration value. The peak response below 200 eV is greater than the average by at least a factor of three. Fig. 2 compares our composite gold cathode response with that of the simple model based on the first order relationship of the sensitivity (C/keV) to the photoionization cross section, $\mu(E)$[7]. The $\mu(E)$ curve is from the recent evaluation of Henke et al[8] and has been normalized to the experimental data. The good agreement between the model and the data suggests that Day's detector response is similar to that of our detector and that our normalization is reasonable. More importantly the model confirms the significant deviation from flatness below 200 eV.

NEW FLAT RESPONSE DESIGN

One of the main problems in the new design is to preferentially flatten the response below 300 eV without degrading the general flat performance elsewhere.

Filters

We have not yet found suitable thin filters to flatten the very low energy response peak without producing bad side effects such as excessive roll off. For example, as shown in Fig. 1, increasing the Parylene thickness does not greatly improve the performance. The composite response decreases as rapidly above the carbon edge as it does in the region below 200 eV where a larger decrease is needed. Fig. 3 shows the calculated x-ray transmission through 80A pure gold based on recent data[8] and using optical constants from Hagemann et al[9]. The gold transmission roll off below 150 eV is similar to that of 800A Parylene, and the gold does not have the carbon edge discontinuity. The gold filter, however, does not adequately suppress the low energy response peak, and furthermore requires an additional 150-200 A carbon backing for support.

Grazing Incidence

We next consider decreasing the response below 200 eV by small angle scattering from the diode surface. To first order the energy deposited in the diode is proportional to 1-R(E), where R is the energy dependent reflectivity. Assuming this, we calculated the gold reflectivity energy dependence using the REFLECT2 computer code[10] and determined that grazing angles between 10 and 20 degrees were suitable for further investigation. Fig. 4 shows 1-R versus energy for 10 and 15 degree angles taken from the work of Rehn and Choyke[11,9] and related data from the recent compilation of Henke[8]. These data are in better agreement at 15°, the preliminary angle we have selected for the new flat response design. Until we obtain XRD calibration data at suitable grazing incidence angles, we will use the 1-R curve at 15° for gold-based designs.

New Compound Filtered Flat Response

The flat response curve shown in Fig. 5 was obtained using our best composite gold cathode response discussed above consisting of LLNL data down to 185 eV and Day's normalized data below 185 eV. Ideal deposition at 15 degrees was assumed. The compound filter covers three different areas of the gold cathode consisting of 100A of gold (14%), 3 μm Al (64%), and 9 μm Al (22%). In Fig. 5, contributions to the response from the three different cathode areas are overlayed. Nearly all the response below 600 eV comes from the cathode region filtered by the thin gold. Above 700 eV the response is shaped with filter components that can be fabricated and calibrated with much greater accuracy. In this region, the physical effects contributing to the response do not cause such rapid variations with energy.

For a more practical design, we replace the 100A gold with an 80A gold layer deposited on a free standing 150A carbon foil[12]. Construction details will be discussed later. The resulting calculated response is shown in Fig. 6. Deviations from flatness are less than 10% above 250 eV. The importance of calibration work particularly below 200 eV cannot be overemphasized due to the significant assumptions made in calculating the composite response.

FLAT RESPONSE DETECTOR SATURATION

Saturation is a major problem with the flat response detector because the portion of the detector filtered by thin gold or Parylene is very sensitive. We have therefore calculated maximum flux levels for the most sensitive part of our flat response design consisting of a typical gold XRD filtered with 100A of gold (or nearly equivalently 800A Parylene).

Our assumption is that detector output pulse amplitudes are still reasonably linear up to 20% of the dc saturation current limit. To provide a frame of reference, we assumed a 1 ns pulse from a 400 micron diameter disk and determined the uniform disk emission temperature corresponding to 20% peak volts/cm^2 for various detector parameters. In addition, we assumed that the incident flux was at a 15-degree glancing angle with respect to the XRD surface as discussed previously. It should be noted that above 200 eV there is very little decrease in specific saturation obtained by using grazing incidence because the increase in projected area on the detector is nearly cancelled by an increase in detector sensitivity[13].

The dc saturation current for a planar diode, I_{dc}, is given by

$$I_{dc} = 7.37\ (V)^{3/2}\ A\ d^{-2}\quad \text{(Amps)} \qquad (1)$$

where the bias voltage V is in kV, the anode to cathode spacing d is in mm, and the surface area A is in cm^2.

The calculations shown in Table 1 were done for our standard XRD-31, our 50 ps XRD, and a proposed new detector with high bias and small anode to cathode spacing. In addition, to quantify a minimum operating level, we calculated the disk temperature corresponding to 50 mV•ns generated by the new flat response detector using a 12 mm^2 collimator at two different practical target-to-detector distances. (A 50 mV, 1 ns pulse can be accurately recorded using a Tektronics amplified 7912 oscilloscope. This minimum output level is thus very conservatively high.

DISCUSSION

We have assumed that output detector charge does not significantly decrease due to space charge effects up to 20% of the dc limit. This needs to be verified experimentally on Novette or any other facility producing adequately intense x-ray pulses. Perhaps this level is too conservative and detectors can be operated closer to the dc limit. Spielman and Anthes concluded, in one of the few XRD saturation studies[14], that pulse degradation effects are very distinct and occur at exactly the Child-Langmuir space charge limit of Eq. 1.

Unfortunately, the 20% saturation x-ray flux level is much too low at 3 meters for the present XRD-31 geometry and is not increased enough by reducing the anode to cathode spacing to 1 mm. It is clear that we have to reduce the spacing as much as possible in our new model and, therefore, need to be even more concerned about standing off the detector bias voltage. As will be discussed later, however, a spacing of at least one mm is required to permit grazing angle incidence on the cathode surface. The proposed new detector, therefore, requires raising the bias level to 20 kV to obtain adequate dynamic range for operating a flat response detector at 3 meters.

The XRD-32 has been designed by EG&G, Las Vegas, with a 20 kV bias voltage, but with much greater anode to cathode spacing. Twenty kV at 1 mm should be attainable, however, since studies show that carefully designed structures can stand off up to 80 kV at 1 mm[15]. With an optimized anode and cathode structure, the performance may then be limited by detector vacuum conditions at shot time. The gold-based flat response detector can only be operated conservatively at 5 kV after reducing the spacing to 1 mm provided that very long flight tubes are used such as that of the 7-meter FFLEX system.

Screen Shielding

The use of low transparency mesh screens to reduce the incident flux has been suggested to combat the effects of saturation[14]. Tests at Sandia using a 24% transmitting copper mesh gave only a very limited improvement over the unshielded case due most probably to the local nature of saturation. It should be noted that local saturation is very sensitive to the position of the mesh between the source and the cathode. There are two limiting cases. If the screen is located at the cathode, some portions of the cathode see all of the source. Local saturation is therefore not reduced. If the screen is at the source, then ideally the local saturation is reduced by the screen transmission factor. Consider the case of an ideal screen consisting of 4 micron diam holes located regularly every 8 microns yielding a transmission of 20%. Fig. 7 shows the fractional area of the source viewed by a point on the detector as a function of the screen to source distance. This analysis suggests local saturation is not significantly reduced unless the screen is reasonably close to the source. It would be interesting to test this concept as part of a series of diode saturation experiments.

XRD STABILITY

Vapor deposited gold XRD stability has not been satisfactory to date[5]. Most of the problem appears to be due to their affinity for water vapor. We have indirect evidence that diode responses have remained reasonably stable for long periods of time while they were kept under vacuum, but that abrupt changes in response occurred when the systems were let up to air. One of the keys to stability, therefore, is better operating procedures to minimize the exposure of cathodes to air. More frequent XRD calibrations and recycling of the diodes will certainly improve the experimental accuracy. Operation of cathode surfaces at elevated temperatures should also be thoroughly investigated. We need to try diamond-turned cathode surfaces in order to decrease surface porosity. The development of more stable surfaces, of course, will require periodic calibration measurements at a facility such as the LLNL IONAC.

New Flat Response Cathode Materials

Among the elemental cathode materials that should be considered for flat response designs besides gold, include platinum,tungsten, iridium, and tantalum in roughly decreasing order of priority. Figure 8 shows a comparison of calculated responses for all of these cathode materials based on the $\mu(E)$ model. Note that all of these high Z response curves are very similar to each other. Moreover the gold response excursions below 300 eV are significantly greater than any of the others; therefore, these new materials may yield even better response designs below 300 eV. Platinum has been used for synchrotron radiation mirrors and may have better long term stability. Including inert materials such as tungsten and tantalum in the experimental study of response versus glancing angle will certainly improve our prospects for developing a stable flat design.

FLAT RESPONSE DETECTOR CONSTRUCTION

We now outline suggestions for constructing the new flat response detector.

Detector

Modifying a suitable XRD detector for grazing incidence as shown in Fig. 9 seems to be the most practical approach to the new design. The XRD-32 is an XRD-31 modified to provide 20 kV bias voltage. It has a reasonably sized 15 mm diameter cathode but the same mirror time response problems as the XRD-31[16]. An upgraded XRD is presently under development at EG&G, Las Vegas, that should have very good time response, better than 15 kV bias, and improved construction[17]. It features a two piece cathode similar to that of Figure 9 with tolerances necessary for grazing incidence operation. Material costs will be significantly reduced by using a thin disk for the active part of the cathode, an important consideration for materials like gold and platinum. The thin disk may be stored and replaced more conveniently and may lead to more efficient automated calibration procedures. Both the cathode and anode need to be designed for very high voltage standoff capability and therefore should have no sharp edges. The proposed anode shown in Fig. 9 is constructed of solid stainless steel and supported with good tolerances with respect to the cathode.

Compound Filter

There are advantages in using a slit as a detector aperture and in constructing the composite filter, as suggested in Fig. 10, with symmetry along the long axis of the slit. By centering the thinest filtered region on the slit axis, the high flux is projected onto the detector where the anode to cathode spacing can be made the smallest. The anode can be angled away from cathode in regions not effected by saturation, thus providing better clearance for incident and reflected x-rays. A 1×12 mm^2 blade beam is shown in Fig. 10 passing between the anode and cathode and striking the cathode surface at a 15^0 grazing angle. By making the compound filter symmetric along the slit axis, the amplitude of the detector signal can be adjusted by appropriately reducing the slit length without modifying the shape of the response.

CONCLUSIONS

There are three major problems with the present flat response XRD detector. They include deviation from flatness due to a peak in the response below 200 eV, saturation at low x-ray flux levels, and long term stability. We propose to improve the flatness by using grazing incidence reflection to reduce the response below 200 eV. We have calculated a new design based on 15 degree grazing incidence on a gold cathode that shows significantly improved performance.

To make the flat response detector a practical device at 3 meters from Novette targets (at the rear positions of the present XRD spectrometer), we need to modify the detector to greatly increase its space charge saturation current limit. We have shown that the desired performance can be obtained by reducing the anode to cathode spacing to 1 mm and increasing the anode bias to 20 kV. Present information suggests that this modification is practical. Saturation measurements need to be made on Novette or any facility producing adequately intense x-ray pulses. The main purpose is to measure the saturation level of our XRDs and to compare these results with the calculated space charge limit. The use of low transparency screens to reduce the incident x-ray flux might be tested as a secondary objective of the XRD saturation series.

To improve the long term stability of the detector, operational procedures need to be upgraded most importantly to greatly reduce exposure of cathode surfaces to water vapor. New cathode surfaces need to be made. Diamond-turned surfaces should perform better than vapor-deposited cathodes used heretofor. Among the elemental cathode materials that should be considered besides gold, include platinum, tungsten, iridium, and tantalum. Long term stability tests of the new cathodes need to be conducted at the LLNL Ionac calibration facility. To complete the design, we need absolute cathode response measurements for a range of grazing incidence angles from 8 to 20 degrees first at the LLNL Ionac and then below 500 eV at one of the synchrotron radiation facilities. The emphasis should be on Pt, W, Au, Ir and Ta in that order. Final flat response compound filter designs will be developed with the aid of this information.

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FIGURE CAPTIONS

1. Composite flat response obtained using the original filter design, LLNL calibration data for our best gold cathode (XAU-61), and NBS gold XRD response data of Day *et al.*[6] The low energy calibration data were normalized at 185 eV, our lowest LLNL calibration value. The effect of increasing the Parylene filter thickness from 800 to 1000A is also shown.
2. Experimental gold XRD calibration values compared to the theoretical model. The low energy LASL (NBS) data are from reference 6. LLNL values are from the X-ray Calibration and Standards Laboratory. The gold photo absorption cross section curve from Henke *et al.*[8] has been arbitrarily normalized.
3. Flat response filters for the low energy region. Calculated x-ray transmission through 80A of pure gold compared to that through 800A of Parylene N. The absorption data are from reference 8.
4. Values of 1-R(E) for selected grazing incidence angles from pure gold. The curves, taken from reference 11, are based on the optical constants from reference 9. Data from the compilation of Henke *et al.*[8] are shown for comparison.
5. New composite flat response calculated assuming 15 degree grazing incidence on a typical gold cathode. Contributions from the three different areas on the cathode are overlayed. The composite filter consisted of 100A of gold (14%), 3 μm Al (64%), and 9 μm Al (22%).
6. Composite flat response of a proposed design obtained by replacing the 100A of gold in Fig. 5 with an 80A gold layer deposited on a free-standing 150A carbon foil.[12]

7. Fractional area of a source viewed by a point on the detector as a function of the screen to source distance. An ideal thin screen with 4 μm diam. holes located every 8 μm is assumed corresponding to a 20% optical transmission.
8. Calculated relative detector sensitivity versus energy for high Z elements suitable for the new flat response design. The curves are based on the photoemission cross sections of Henke _et al_.[8]
9. Suggested construction method for the new flat response channel based on 15^{o} grazing incidence on a high Z cathode, an XRD-32 detector with 20 kV bias capability, and 1 x 12 mm^2 slit collimation. Note that this model may be replaced by the improved XRD-57.
10. Preferred construction method for the new flat response, compound filter with symmetry along the entrance slit axis. The projected beam on the cathode is shown after passing through a compound filter with 14% (80A Au), 22% (10 μm Al), and 64% (3 μm Al).

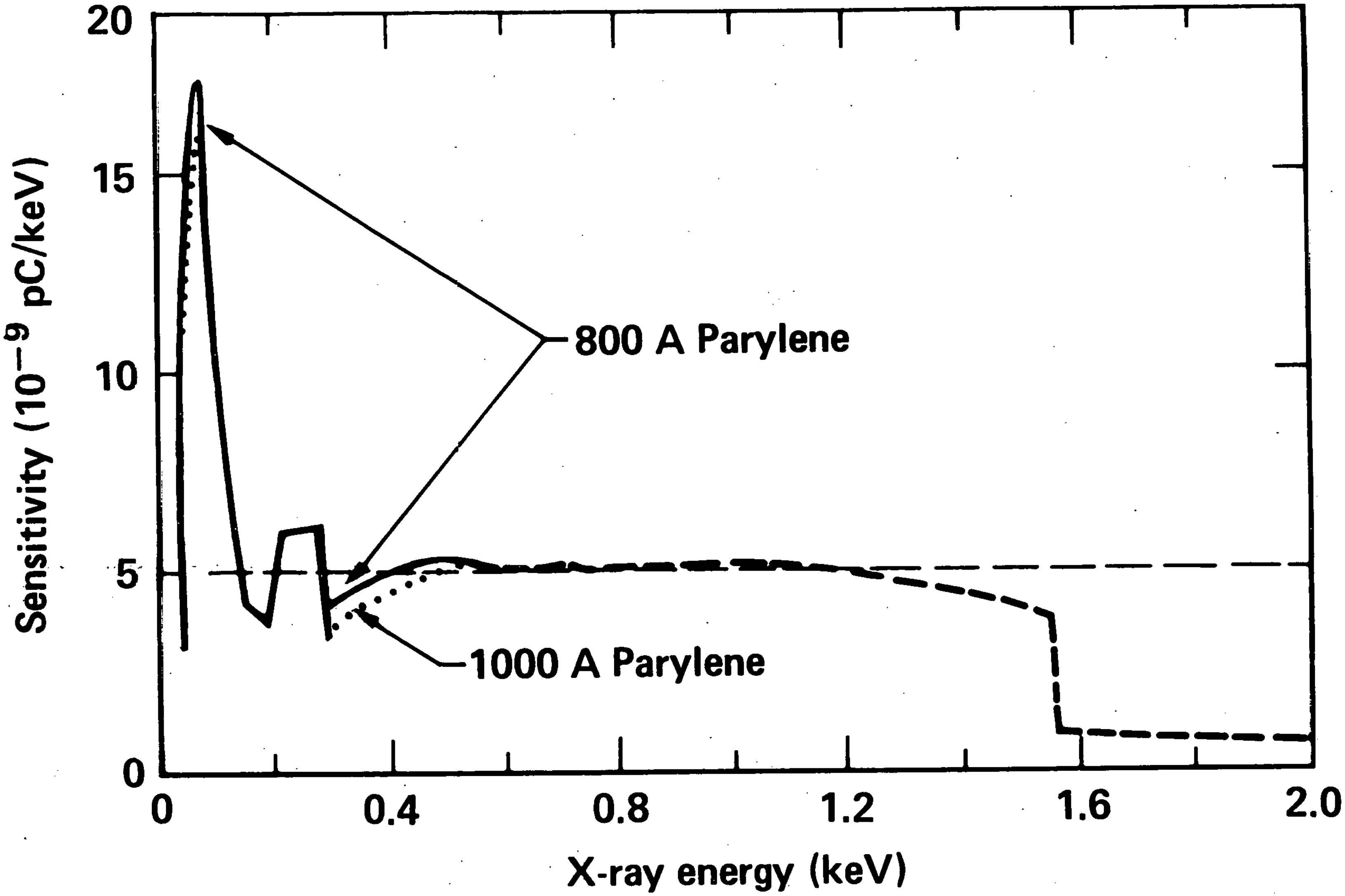
Table 1. NEW FLAT RESPONSE DETECTOR DESIGN PARAMETERS

Detector	Location	R (m)	Spacing (mm)	Bias Volts (kV)	Saturation Current (A/cm^2)	400 Micron Disk Temp Min[a] (ev)	400 Micron Disk Temp Max[b] (ev)
Standard XRD-31	Dante H (rear)	∿ 3	2.3	5	15.6	30	81
	FFLEX	∿ 7				46	123
50 ps XRD	Dante H	3	1.0	5	82	30	122
	FFLEX	7				46	196
Proposed XRD-32	Dante H	3	1.0	20	659	30	220
	FFLEX	7				46	>250

[a] X-ray temperature from a 400 μm diameter disk corresponding to 50 mV•ns generated by the flat response detector using a 1 x 12 mm^2 collimating slit at the distance R.

[b] X-ray temperature emitted corresponding to 20% of specific saturation current from the most sensitive part of the flat response detector.

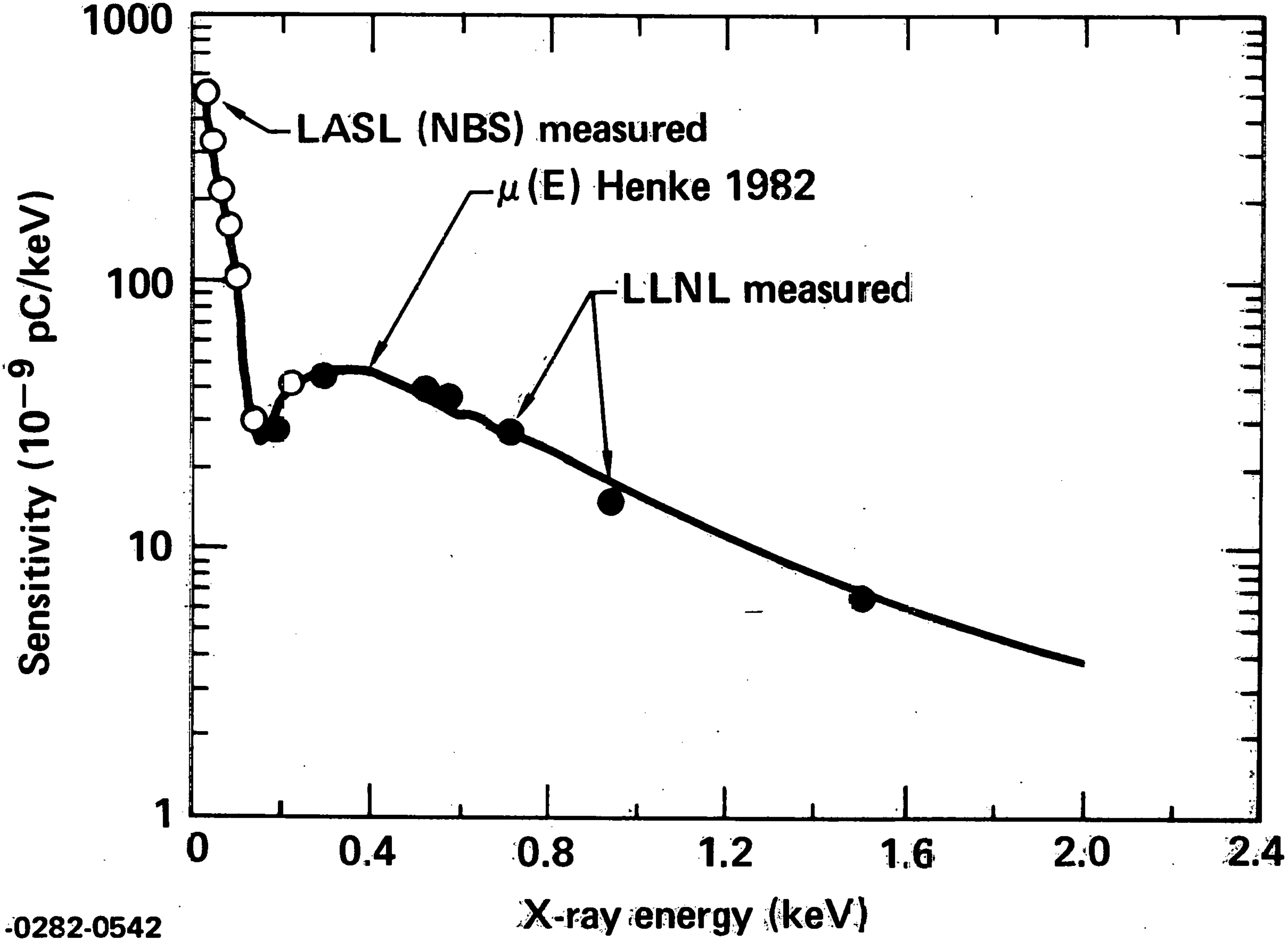
COMPOSITE FLAT RESPONSE OF ORIGINAL DESIGN SHOWING THE DEPENDENCE ON PARYLENE THICKNESSES



20-01-0282-0541

Fig. 1

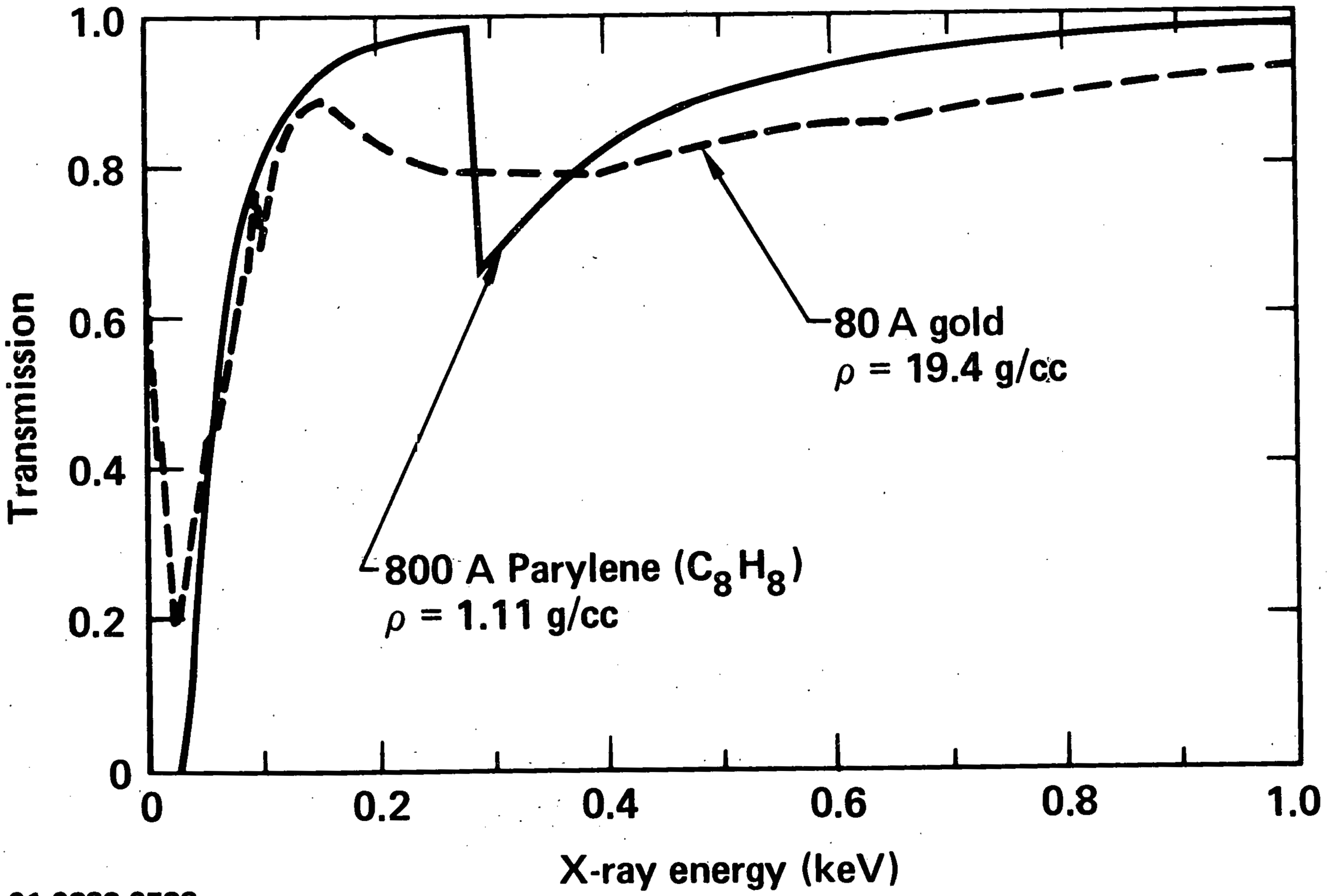
MEASURED GOLD XRD SENSITIVITY VS NORMALIZED PHOTOABSORPTION CROSS SECTION, $\mu(E)$



20-01-0282-0542

Fig. 2

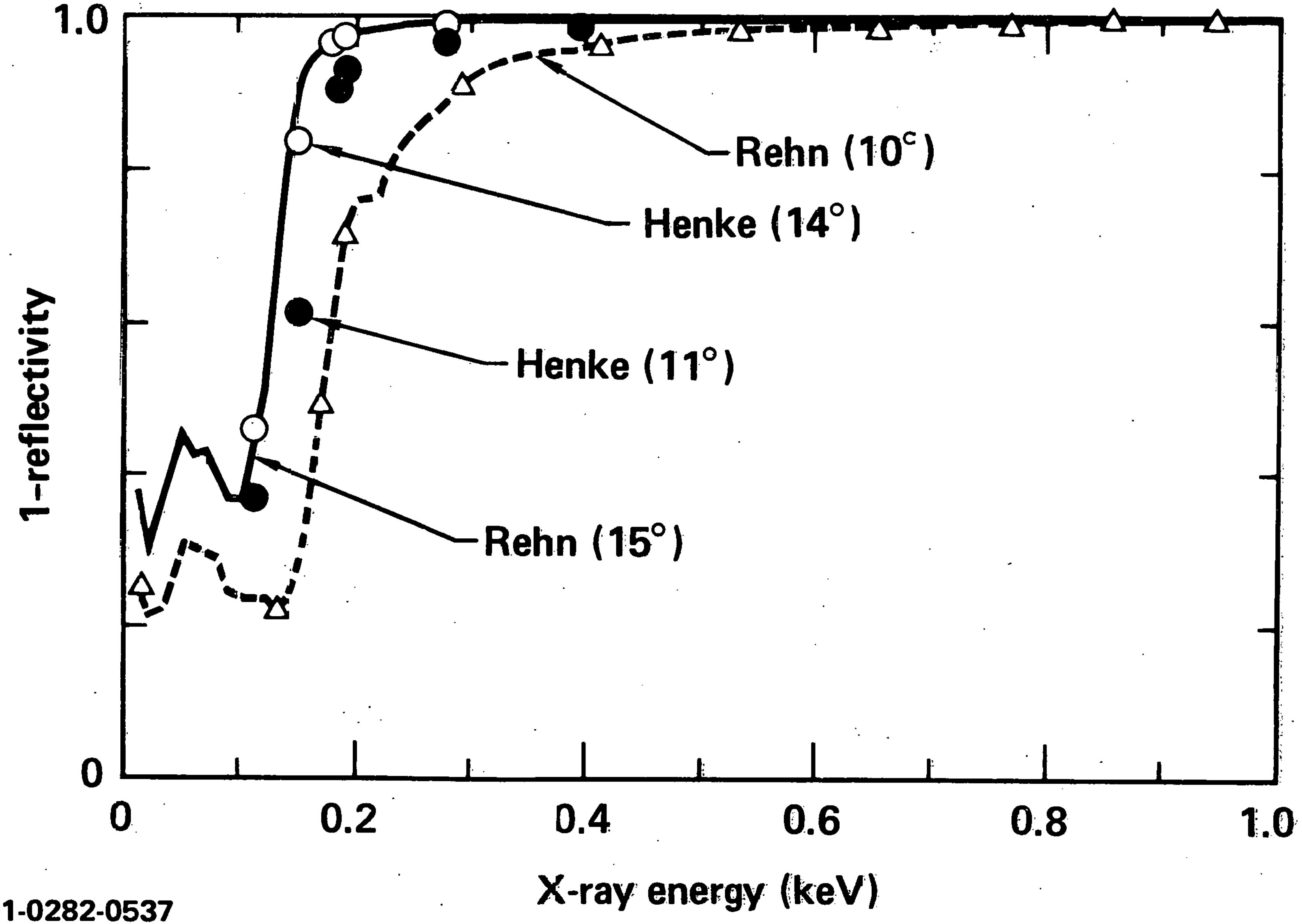
FLAT RESPONSE FILTER TRANSMISSION
TWO CHOICES FOR USE BELOW 500 eV



20-01-0282-0538

Fig. 3

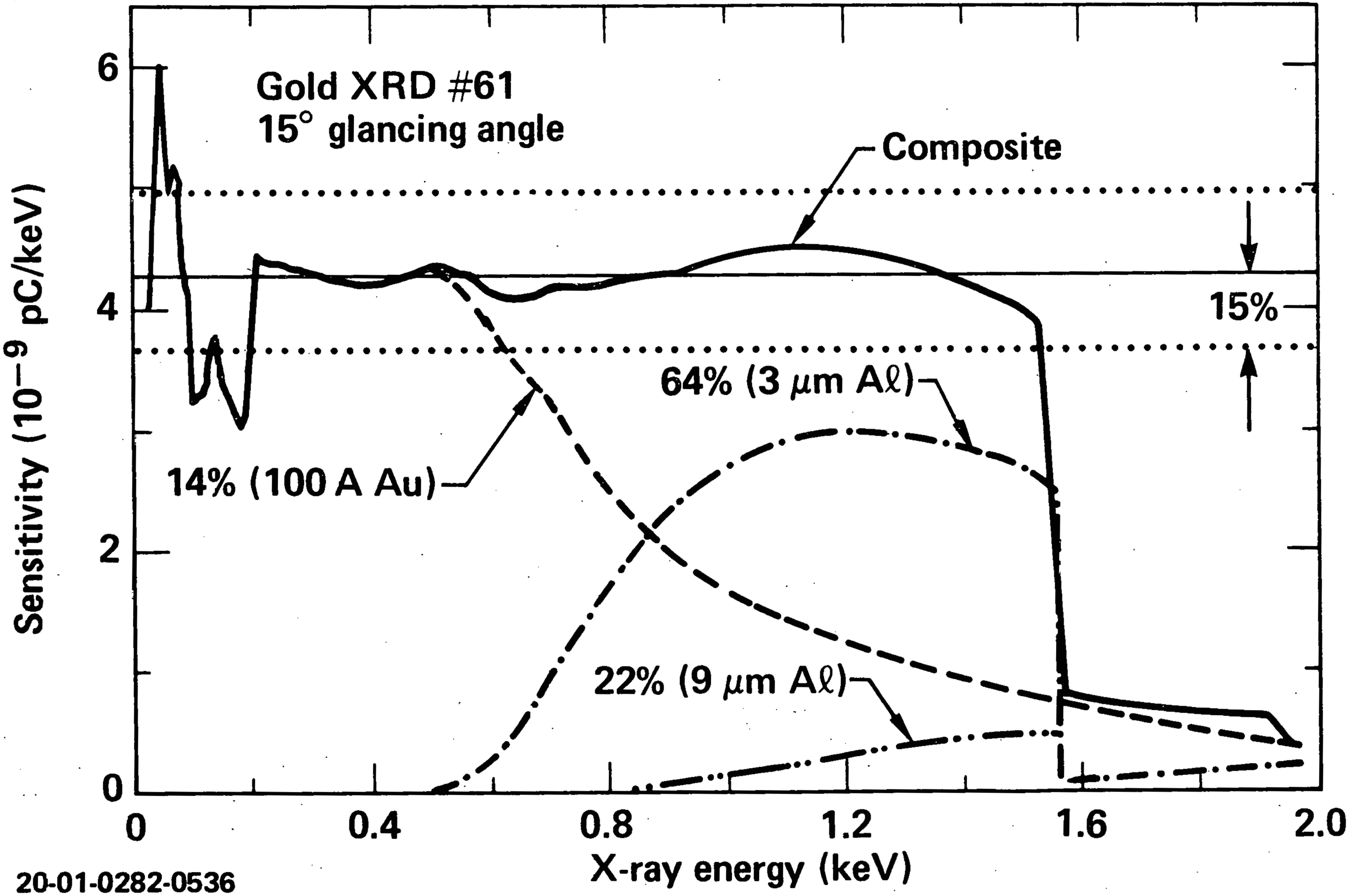
VALUES OF 1-REFLECTIVITY FOR PURE GOLD FOR DIFFERENT GRAZING INCIDENCE ANGLES



20-01-0282-0537

Fig. 4

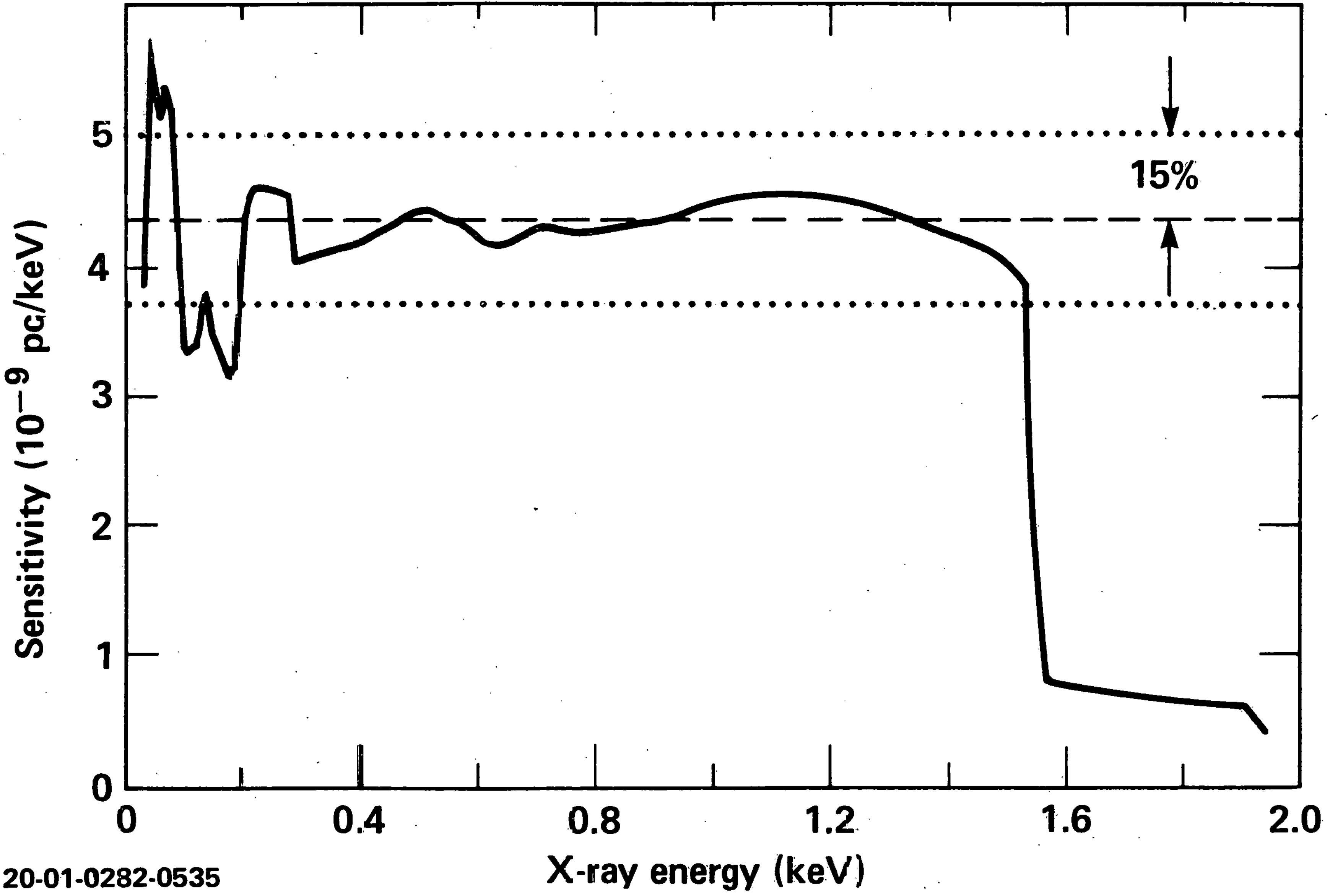
COMPOSITE RESPONSE OF NEW DESIGN USING GRAZING INCIDENCE



20-01-0282-0536

Fig. 5

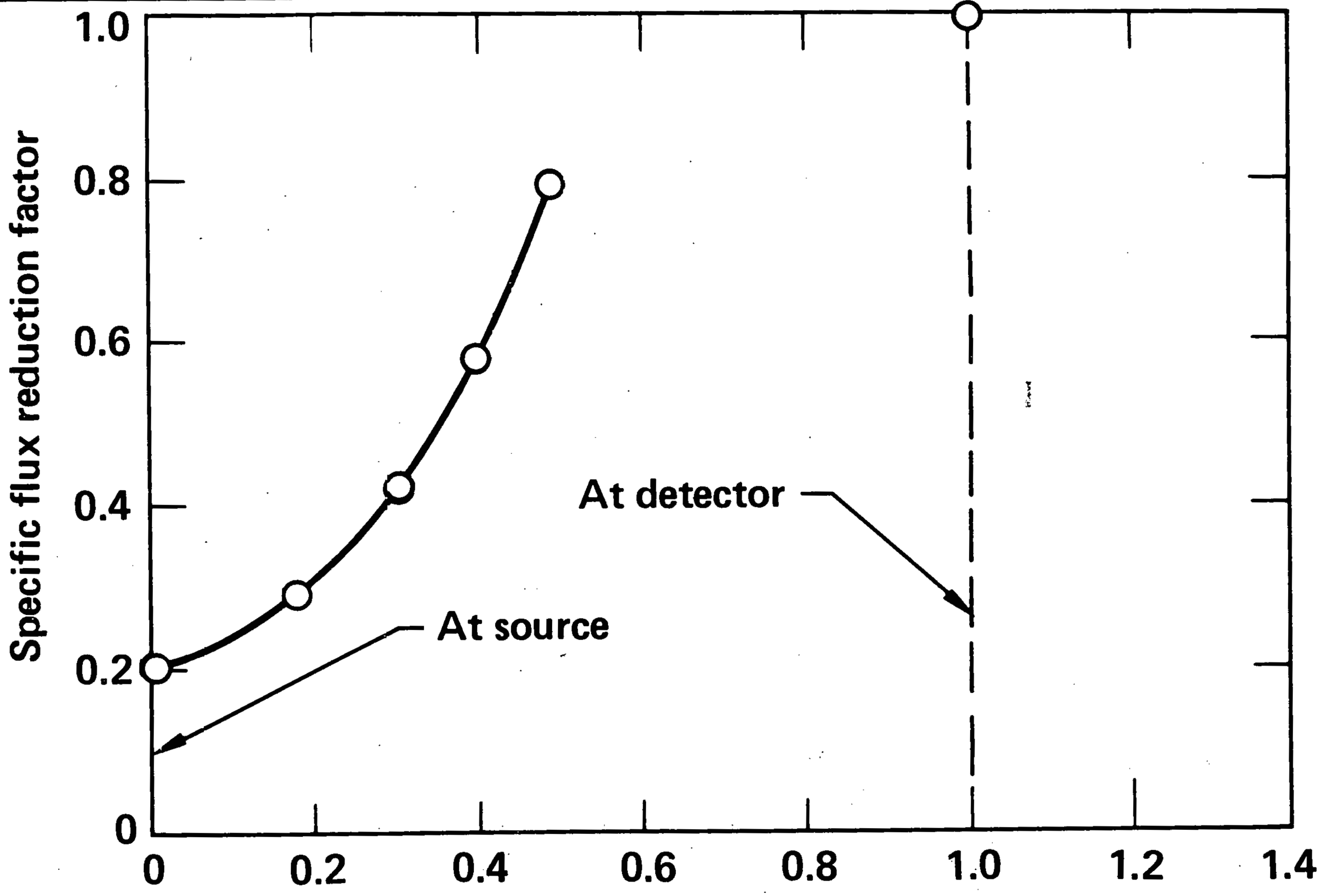
COMPOSITE RESPONSE OF NEW DESIGN WITH PROPOSED 80 A GOLD ON 150 A CARBON FILTER



20-01-0282-0535

Fig. 6

DETECTOR LOCAL SATURATION VS SCREEN POSITION USING A 20% TRANSMITTING X-RAY SCREEN

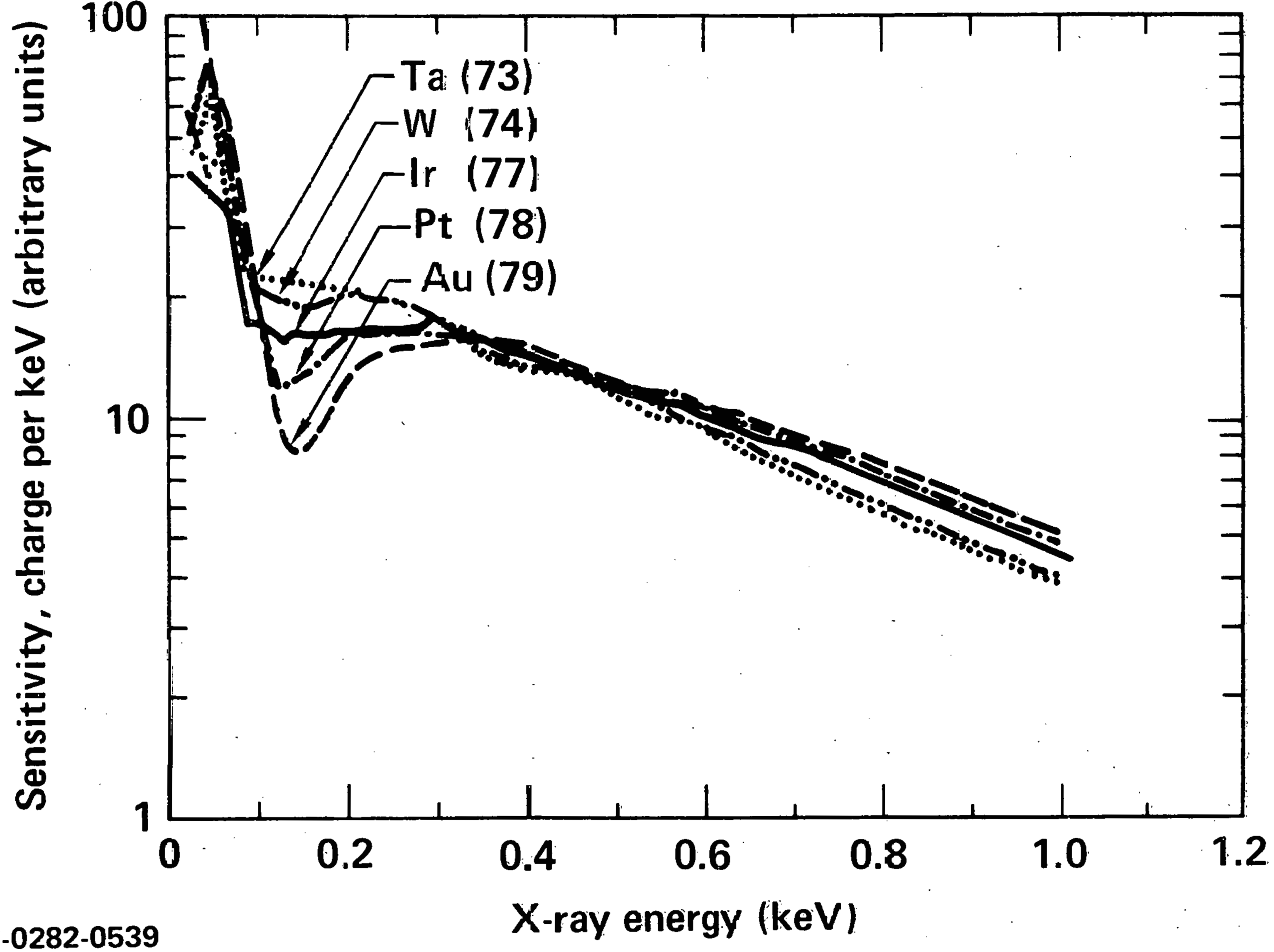


20-01-0282-0540

Source to screen distance (normalized)

Fig. 7

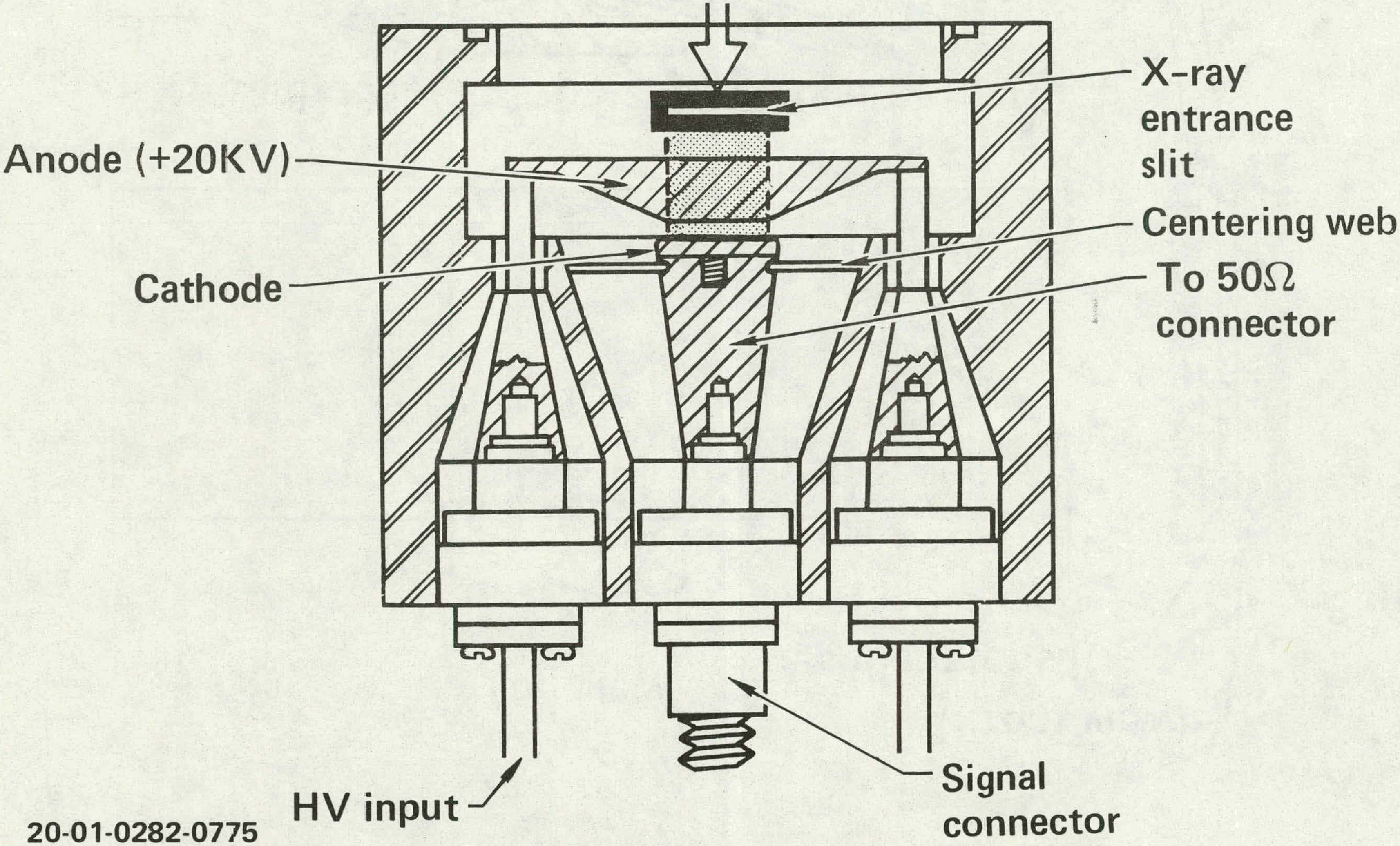
RELATIVE XRD DETECTOR SENSITIVITY FOR HIGH Z METALS FROM μ(E) MODEL



20-01-0282-0539

Fig. 8

NEW FLAT RESPONSE DETECTOR WITH GLANCING INCIDENCE XRD-32 (ENTRANCE VIEW)



20-01-0282-0775

Fig. 9

NEW FLAT RESPONSE COMPOUND FILTER

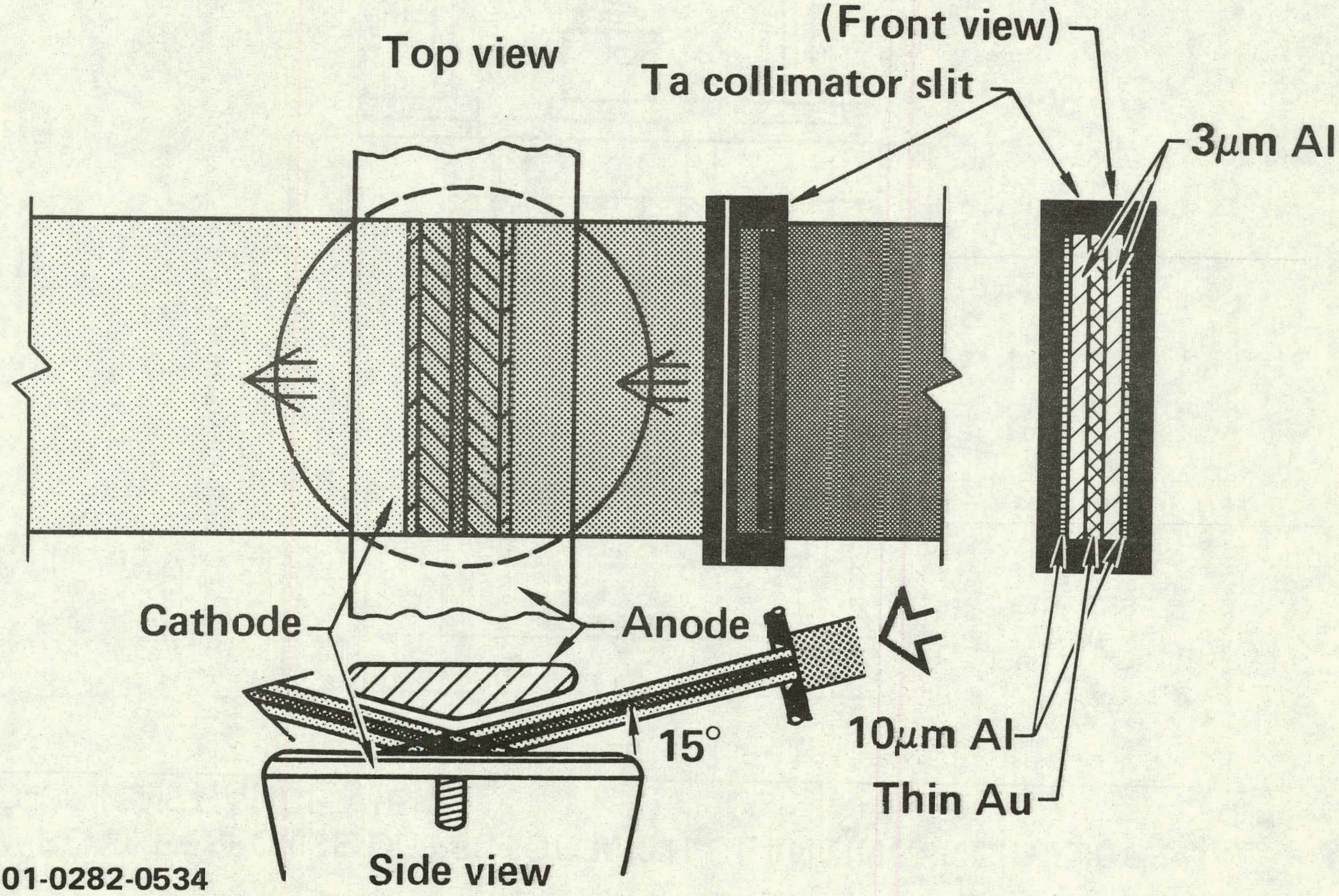


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Fig. 10

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