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FACILITIES AND TECHNIQUES FOR X-RAY DIAGNOSTIC CALIBRATION IN THE 100-eV TO 100-keV ENERGY RANGE

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Facilities and techniques for x-ray diagnostic calibration in the 100-eV to 100-keV energy range

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Mail Stop 379, P.O. Box 808, Livermore, California 94550**MASTER**Abstract

The Lawrence Livermore National Laboratory (LLNL) has been a pioneer in the field of x-ray diagnostic calibration for more than 20 years. We have built steady state x-ray sources capable of supplying fluorescent lines of high spectral purity in the 100-eV to 100-keV energy range, and these sources have been used in the calibration of x-ray detectors, mirrors, crystals, filters, and film. This paper discusses our calibration philosophy and techniques, and describes some of our x-ray sources. Examples of actual calibration data are presented as well.

Introduction

The importance of x-ray diagnostics in so many areas of physics research led researchers at LLNL to assemble one of the most sophisticated, fully equipped x-ray calibration facilities in the country. The LLNL X-Ray Calibration and Standards Laboratory¹ is one of only a few such facilities in the world that can routinely perform x-ray calibrations throughout the 100-eV to 100-keV energy range.

Today's calibration laboratory is an outgrowth of a single x-ray facility that was built in the early 1960s in support of the LLNL nuclear weapons program. In the early stages of this program, weapons diagnosis was limited mostly to the measurement of prompt gamma and neutron emissions. But as the diagnostic value of x-ray measurements came to be recognized, we developed more complex x-ray detectors and diagnostic systems. Likewise, the x-ray calibration facilities also grew in sophistication and in number to our present 12 facilities, each of which is designed to perform particular functions in particular energy ranges.

Although our primary mission is still to support the weapons program, we also support the LLNL laser and magnetic fusion energy programs. This support involves detector and diagnostic systems calibration, along with x-ray measurements of filter and blast shield thicknesses.

Calibration philosophy

The basic philosophy at LLNL for the absolute calibration of detectors and diagnostic systems originated in the mid 1960s, when Ebert, Gaines, and Tepelt developed the Laboratory's first x-ray calibration facility.² We knew from the start that an x-ray source of known intensity and spectral purity would have to be developed, since for absolute calibration it is necessary to determine the detector output as a function of incident x-ray energy. The ideal calibration source would thus be a tuneable, monoenergetic x-ray source with enough intensity to produce an easily measurable output signal from the instrument being calibrated.

Such a source can be approximated with a combination of fluorescent radiation sources and absorption edge filters. We decided to determine the absolute intensity of the source by means of counting techniques. This was done using a detector of known efficiency and a source geometry where the x-ray intensity decreased in inverse proportion to the square of the distance over the region of interest. This arrangement allowed us to calibrate the field detector near enough (e.g., 20-30 cm) to the x-ray source to get a readable signal, and yet place the monitor detector somewhat further away (e.g., 200 cm). The monitor detector could thus operate in a counting mode and still measure the absolute x-ray flux at the location of the field detector.

Under these conditions the effective x-ray source diameter has to be made smaller than the diameter of the collimation in the x-ray beam line of sight (Figure 1). The monitor detector (not shown in the figure) views the entire source and thus measures the intensity in the umbra of the x-ray

Figure 1 LLNL calibration geometry. The detector to be calibrated (i.e., the field detector) is normally placed between 20-30 cm from the fluorescent target, and the monitor detector (not shown here) is roughly 200 cm away. The fluorescent beam umbra is of uniform intensity.

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beam. Either the field detector must intercept all of the x-rays coming through the defining collimator, or it must be collimated in such a way that the collimator is within the umbra of the x-ray beam. When either of these conditions is satisfied, the x-ray flux measured by the monitor detector can be correlated with the x-ray flux incident on the field detector.

Assuming a monoenergetic x-ray beam, the sensitivity of the detector can be calculated for a particular energy using the relation

$$S = (1/\epsilon A_2 T r_1^2) / (N A_1 E r_2^2) \quad \text{C/keV} \quad (1)$$

where

- I = current in A,
- ϵ = efficiency of monitor detector,
- A_2 = area of collimator on monitor detector,
- T = difference in x-ray beam transmission to the two detectors,
- r_1 = distance to the defining beam on the field detector,
- N = counts per second at the monitor detector,
- A_1 = area of the defining beam on the field detector,
- E = energy of (monoenergetic) fluorescent x-rays,
- r_2 = distance to the collimator on the monitor detector.

In theory, reiterated use of this equation will yield a calibration curve showing the absolute detector response as a function of x-ray energy at several energy points. In actual fact, however, the x-ray sources are not truly monoenergetic, so that Equation (1) gives only an approximate sensitivity value. A determination of the true sensitivity needs to account for the actual x-ray spectrum associated with each fluorescent energy source, and this involves using either a Si(Li) or intrinsic germanium detector to measure the actual spectra from the various fluorescent x-ray sources after they have been filtered. This information is then coded for use in a computer program which is capable of both analyzing the data and correcting Equation (1) for the effect of the spectral contaminants. For most of our detectors, these corrections amount to only a few percent.

X-ray sources

Although we presently have 12 x-ray facilities in the Calibration and Standards Laboratory, we shall only describe 3 of them in this paper. These are the most heavily used facilities, designed to calibrate detectors in the energy range of 109 eV to 100-keV. They all employ fluorescent radiation sources and absorption filters, and a geometry that is similar to the one described in Figure 1.

The age of the facilities is inversely related to the energy range, with the oldest covering the highest energy range and the newest covering the lowest. The complexity of each facility also increases with decreasing x-ray energy. This is due partly to the fact that low energy x-rays are easily attenuated. It is difficult, moreover, to produce intense monoenergetic sources of these x-rays.

Photographs of the three facilities to be described are shown in Figures 2-4.

High-energy facility

The first and oldest facility to be described is shown in Figure 2. Using primary x-rays from a radiographic x-ray tube, this facility excites fluorescent radiation in the range of 8-100 keV from thin metal, elliptically shaped targets. The targets are placed at 45-deg angles with respect to the primary and the fluorescent x-ray beam line of sight (see Figure 1).

The elliptical shape of the fluorescent sources makes them appear circular when viewed through the line of sight. Their apparent diameter of 1.27 cm is smaller than the collimation in the line of sight, which allows for the correlation of the monitor and field detector fluxes (this is discussed above, under the heading "Calibration philosophy").

The metal fluorescers are viewed from the side opposite the incident primary beam. Such a source target geometry can make the beam more monoenergetic by providing some filtration and reducing the scattered primary beam. Further filtration is achieved by passing the beam through absorption edge filters as it exits the shielded enclosure housing the radiographic x-ray tube. The resulting x-ray beam has about 95% of its photons in the K α peaks and the remaining 5% in the rest of the spectrum (i.e., the beam has a spectral purity of 95%).

A typical spectrum from this facility is shown in Figure 5; the fluorescers, filters, and available energies are listed in Table 1. Also shown in this table is the typical x-ray intensity at the normal experimental location about 20 cm from the source. The monitor detector for determining the intensity is a 2.54-cm-thick by 2.54-cm-diameter sodium iodide detector attached to the end of a 1.5-m long evacuated pipe with thin mylar windows. It is collimated with a 0.07714-cm diameter pinhole located about 200 cm from the source. The detectors to be calibrated are inserted in the path of the x-ray beam at a location about 20 cm from the source, between the front of the vacuum pipe and the shielded enclosure.

Low-energy facility

The second facility to be described covers the energy range of 1.5- to 8-keV (Reference 3). It utilizes an electron beam generated by an EMI electron gun to excite one of nine available water-cooled targets.⁴

This facility is shown in Figure 3. It produces an x-ray beam of fluorescent radiation as well as some bremsstrahlung when electrons from the gun strike the target. The linear x-ray target geometry was designed to reduce bremsstrahlung, since, as can be seen in Figure 6, x-rays are observed in the rearward direction, and bremsstrahlung is preferentially produced in a forward direction.

Figure 2. The high-energy x-ray facility, showing the shielded enclosure and vacuum line of sight pipe

Table 1. High-Energy X-Ray Facility

Fluorescer	Filter	K α Energy (keV)	Intensity at Experiment ^a (x rays/cm ² ·s)	Spectral Purity
Copper	Nickel	8.047	$8.81 \cdot 10^6$	0.94
Selenium	Selenium	11.221	$1.70 \cdot 10^7$	0.89
Molybdenum	Niobium	17.478	$5.35 \cdot 10^6$	0.93
Tin	Silver	25.270	$7.81 \cdot 10^6$	0.96
Praseodymium	Lanthanum	36.023	$4.26 \cdot 10^6$	0.96
Dysprosium	Samarium	45.985	$3.09 \cdot 10^6$	0.98
Hafnium	Erbium	55.757	$2.11 \cdot 10^6$	0.98
Platinum	Tantalum	66.820	$3.60 \cdot 10^6$	0.98
Lead	Platinum	74.957	$2.74 \cdot 10^6$	0.98
Uranium	Thorium	98.428	$7.69 \cdot 10^6$	0.97

^a The monitor detector location is about 20 cm from the target.

Figure 3. The low-energy x-ray facility.

Only those x-rays which pass back through the electron gun are used. The x-rays from each particular target are filtered by a selected absorption edge filter which for most targets gives a roughly 95% spectrally pure x-ray beam. Two targets giving an 88% pure beam are used to produce L-shell characteristic x-rays while the other, higher purity targets produce K-shell x-rays.

Since this facility produces x-rays which are easily attenuated by air, the x-ray beam is confined to a vacuum system. This system consists of a detector calibration chamber, a spectrometer chamber, and a monitor detector. The monitor, which is located at the end of a long line-of-sight pipe 8 m from the source, is a windowless lithium-drifted silicon detector 3-mm-thick and 10 mm² in area. It has been collimated by a 0.02366-cm-diameter collimator.

Table 2 lists the various targets and energies available for this facility, as well as the filters used for cleaning up the spectra. Also listed are the typical x-ray intensities at the normal experimental location of about 60 cm.

Ion-accelerator subkilovolt facility (Ionac)

The last facility to be described, one that is designed to provide absolute calibrations in the 109- to 932-eV x-ray energy range,⁵ is shown in Figure 4. This facility utilizes protons to excite fluorescent x-rays from various selectable targets. The advantage of this technique is that the mass of the proton is much larger than that of an electron and therefore the bremsstrahlung production is greatly reduced. The source of the protons is an ion accelerator capable of providing a 2-mA beam current on the target at 300 kV. Normal operating parameters, however, are now limited by the target cooling capacity to 250 kV with a 0.5- to 1.0-mA beam current.

The x-ray beam from the various selectable targets can be observed at two locations, each at a 45-deg angle with respect to the target. Depending on the target material, this beam is then filtered by either a thin beryllium, thin carbon, or thin boron foil. The primary purpose of the foil is to stop the backscattered protons and neutral particles which are produced when protons strike the target. In some cases (e.g., for the beryllium, boron, and carbon targets), these foils can also help to clean up the spectra by selectively attenuating any low and high energy contamination relative to the fluorescent peaks.

The monitor detector for determining the x-ray intensity is a gas flow proportional counter. It is collimated by a 0.0256-cm-diameter pinhole located in the detector calibration chamber about 112 cm from the x-ray source (see Figure 6). A spectrometer chamber for calibrating crystals and mirrors is available for measuring the spectral purity of the x-ray beam. A windowless Si(Li) detector is also available for spectral examinations. Table 3 lists the targets and their average energies, the fluorescers, filters, and the beam intensities that are routinely available for this facility.

Figure 4. The ion-accelerator subkilovolt x-ray facility.

Figure 5. A typical spectrum for a copper fluorescer, seen through a nickel filter at the high-energy facility.

Figure 6. The geometric relationship of the electron gun and the target for the low-energy facility.

Table 2. Low Energy X-Ray Facility

Fluorescer	Filter	K α Energy (keV)	Intensity at Experiment ^a (x-rays/cm ² ·s)	Spectral Purity
Aluminum	Aluminum	1.487	1.49×10^8	0.95
Zirconium	Yttrium	2.042 ^b	1.33×10^8	0.87
Silver	Rhodium	2.984 ^b	2.54×10^8	0.89
Scandium	Antimony	4.090	1.49×10^8	0.94
Vanadium	Titanium	4.952	1.03×10^8	0.98
Manganese	Chromium	3.898	6.98×10^7	0.97
Cobalt	Iron	6.930	8.01×10^7	0.98
Copper	Nickel	8.047	1.73×10^8	0.98

^a The experimental location is about 65 cm from the target.

^b L α energy.

Table 3. Ion Accelerator Subkilovolt X-Ray Facility^a

Fluorescer	Filter	Energy ^b (eV)	Intensity at Experiment ^c (x-rays/cm ² ·s)
Beryllium	Beryllium	109	9.00×10^8
Boron	Boron	183	1.35×10^8
Carbon	Carbon	277	8.78×10^8
Vanadium	Beryllium	510	1.00×10^8
Chromium	Beryllium	574	1.57×10^8
Iron	Beryllium	704	3.73×10^8
Copper	Beryllium	928	8.19×10^8

^a The spectral purity has been measured to be greater than 0.98 when all the fluorescent lines are included.

^b The x-rays from beryllium, boron, and carbon are K-shell x-rays while the rest are L-shell x-rays.

^c The experimental location is about 90 cm from the target.

Spectral measurements

As was mentioned earlier, the ideal x-ray source for calibration purposes would be an intense monoenergetic source with variable energy and a high intensity output. Unfortunately, sources with these characteristics do not abound. One must therefore approximate this ideal as closely as possible, and then accurately measure the resulting spectra. By noting the discrepancy between the two spectra, measured and ideal, one is able to account for the spectral contaminants.

For measuring spectral purity in the 8- to 100-keV range we have used an intrinsic germanium detector whose efficiency has been determined by comparison to a sodium iodide detector. This efficiency compares very well with what can be calculated when all the attenuating materials between the germanium crystal and the source are taken into account. Detector effects such as escape peaks and Compton scattering must also be considered even though they are not usually very large. The results are then stored in a computer file and used to correct the calibration data for the effects of spectral contamination in this energy range.

The windowless Si(Li) monitor detector at the low energy (1.5- to 8-keV) facility is also used to examine the spectral purity associated with each energy point. In calculating this detector's efficiency, we have taken into account the thin gold layer over the crystal as well as the silicon dead layer. These calculations have been confirmed by measurements at a few energy points. Again, effects due to the detector itself such as escape peaks, Compton scattering, etc., are considered when evaluating the spectra. As with the 8- to 100-keV spectra, the spectra obtained for this lower energy range is also stored in a computer file and used to correct for spectra which are not truly monoenergetic. In addition to the Si(Li) detector, a crystal spectrometer can be used to examine the spectra in much greater detail if necessary.

The spectra from the 109- to 932-eV facility are fairly pure if we treat all the fluorescent lines from each target as one energy peak. For most calibration purposes, this is usually a fair assumption. If a more detailed knowledge of the spectra is desired it can be obtained from a crystal spectrometer, which is an integral part of the system.

Since the spectra for this ultra-low-energy facility are very pure, we are not now making any spectral corrections. In addition to the crystal spectrometer, a high resolution windowless Si(Li) detector is attached to the system and can be used to examine the spectra of the targets down to and including carbon.

Absolute intensity measurements

The key to making absolute calibrations is in determining the absolute intensity of the x-ray beam striking the instrument to be calibrated. We believe that the easiest way to do this is to actually count all the photons striking the device being calibrated, and then to use the measured spectral distribution in determining the number of photons at each energy. Such a procedure requires a monitor detector of known efficiency, preferably a detector that is 100% efficient for all x-rays observed.

As described previously, for the 8- to 100-keV facility, a 2.54-cm-thick by 2.54-cm-diameter Na(I) detector counts the individual photons in the x-ray beam. This detector is 100% efficient for the x-rays of interest (i.e., it absorbs all incident x-rays), and needs only to be corrected for the effects of the 0.0127-cm-thick beryllium and the 0.0001-cm-thick aluminum entrance window. The escape peak is not a problem since it gets counted along with all the other x-rays in the spectrum.

A 3-mm-thick windowless Li detector monitors the x-ray beam on the 1.5- to 8-keV facility. In the range of interest this detector is also 100% efficient, and the only necessary corrections are for the 150-Å gold layer on the crystal and the 100-Å silicon dead layer. Since we are counting all the x-rays in the beam the escape peak presents no problems.

The beam monitor on the ion accelerator subkilovolt facility is not 100% efficient for all x-ray energies. Since the x-ray beam is so nearly monoenergetic, however, we do not make spectral corrections for this facility. All we have to know is the efficiency of the detector at the energy of interest in order to count the number of photons in the x-ray beam. The monitor for this facility is a 2.54-cm-diameter gas flow proportional detector that is collimated with a 0.0253-cm-diameter pinhole. The gas (96% helium, 4% isobutane) is maintained at a pressure of 760 torr. We have measured the efficiency of this gas compared to P-10 gas for comparison with a calculated value. Agreement is quite good when the measured transmission of the 10 000-Å-thick polyethylene window is taken into account.

Calibration techniques

The techniques used in calibrating various detectors and diagnostic systems may vary to some degree but in general follow the same pattern. Obtaining reliable and repeatable results usually requires a facility operator who is knowledgeable, experienced, and very careful in setting up and conducting the calibration. The following paragraphs describe a typical sequence of events in the calibration process.

Before the actual calibration can be done, the x-ray source must be energized and allowed to stabilize. For the x-ray energy desired, the proper target and filter are selected. The detector to be calibrated is now positioned with respect to the beam geometry by means of a remotely controlled mechanical positioner. Positioning the detector in the x-ray beam must be done with some care and the various geometric parameters must be measured accurately to insure that the geometry conditions described earlier (under "Calibration philosophy") are satisfied.

After allowing a short time for the detector to stabilize, its dark current is measured. The shutter on the x-ray source is then opened and the signal from the detector is measured (again, it is necessary to wait a short time for the equipment to stabilize). The detector is now moved out of the x-ray beam so that the beam intensity can be measured by the monitor detector and recorded on a multichannel analyzer or other appropriate electronics. This procedure is then repeated for each additional energy point.

In most cases the detector output is very small, ranging in magnitude from 0.1 nA to 0.1 fA. These signals are measured with a carefully calibrated electrometer (in our case, a Keithley model 617 programmable electrometer) that is controlled by a small computer.

Most detectors require some sort of bias voltage in order to operate properly. For normal detector applications this may be several kilovolts in magnitude. However, a bias voltage of only about 50 V is usually adequate during calibration, since our x-ray intensity levels are so low compared to the x-ray flux that the detector is intended to measure.

We typically use dry cell batteries enclosed in metal boxes and insulated with styrofoam to provide a "quiet" stable bias supply. BNC or other types of electronic connectors link this bias supply to the detector and recording electronics. We have even developed a variable battery bias supply which can provide positive or negative bias voltages from a few V to about 800 V. This supply uses a series of dry cell batteries yet still provides a low noise, low leakage current, stable bias voltage.

Low noise cables are used wherever possible to minimize electronic noise in the system. In most cases adequate noise reduction requires the use of adapter connectors to mate with the "field" type connectors on the detectors and the BNC connectors on the low noise cables. The cables need not necessarily be 50 ohm since measurements are made in a steady state mode.

For calibrating solid state detectors such as PIN or surface barrier detectors where the signal may be a factor of 10^3 to 10^4 times smaller than the electronic noise or "dark current," a beam chopper and a phase-lock amplifier must be used rather than an electrometer. For most optical applications, the only difference between an x-ray beam chopper and a light chopper is that the chopping wheel must be opaque to x-rays. For our 8- to 100-keV facility the beam chopper is fairly massive. The chopping wheel is made of 0.635-cm-thick tantalum. It is turned by a 3600 rpm synchronous motor to provide a 1000-Hz chopping frequency.

For the other two x-ray facilities described in this paper, the x-ray beam choppers are much smaller and lighter (the chopping wheel for these low energy range facilities is built of 0.159 cm thick tool steel). Both the large tantalum and small tool steel beam choppers are used in a vacuum environment and powered by special water-cooled motors which turn at 6000 rpm. The x-ray beam chopper for the 8- to 100-keV facility and one of the smaller x-ray beam choppers are shown in Figure 7.

Calibration project activities

During the last 20 years we have calibrated nearly every kind of x-ray detector in existence. We have measured the characteristics of many x-ray mirrors, scatterers, diffraction crystals, and filter materials, and we have undertaken many basic studies involving the interaction of x-rays and matter. Some of the more common detectors that we calibrate on a fairly routine basis are: plastic scintillators coupled to photodiodes, photoelectric diode detectors, and surface-barrier and diffused-junction (PIN) solid-state detectors.

The calibration curve (detector sensitivity vs energy) for a 500- μ depletion depth surface-barrier detector is shown in Figure 8. The solid curve is based on the calculated sensitivity while the points represent experimental data. For energy values above 0.6 keV, the agreement between calculated and experimental sensitivity values is quite good. The lower energy portion of the curve is governed primarily by the aluminum entrance window thickness of the detector (50 μ /cm²), while the higher energy portion is influenced by the detector thickness itself (500 μ).

Figure 9 shows the response of a 2.54-cm-thick plastic scintillator (Pilot B) coupled to a photodiode (FW114A). This figure also shows the response of an aluminum cathode photoelectric diode detector. Since this detector was windowless, and since only the two lower energy calibration facilities provide the vacuum environment that such a detector requires for operation, it was calibrated only up to 8 keV.

Figure 7. X-ray beam choppers for the high- and low-energy facilities.

Figure 8. Calibration curve for a silicon semiconductor detector with a 500 μ depletion depth

Figure 9. Calibration curves for the plastic scintillator and aluminum cathode detectors

We believe that our calibration accuracy is normally within about 10% for most detectors. There are some cases where it is worse and some where it is better. To a large degree, accuracy is governed by the magnitude of the signal and the stability of the dark current. In an ongoing attempt to improve calibration accuracy, we have participated in several cross-calibration projects, both national and international, with other laboratories.

We have recently put together a collection of four detectors which can be used for comparing calibrations throughout the 100-eV to 100 keV energy range. The collection (shown in Figure 10) contains a plastic fluor photodiode detector and three different photoelectric diode detectors (two of which are windowless). It can be made available to other laboratories by contacting the authors at LLNL.

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References

1. Games, J. L., "The Lawrence Livermore Laboratory X-ray Calibration Facility," *IEEE Trans. Nucl. Sci.*, NS-26, pp. 1420-1425, 1979.
2. Ebert, P. J., J. L. Games, and G. R. Leipelt, "Production of Monoenergetic X-ray Sources of Known Absolute Intensity," *Nucl. Instrum. Methods*, Vol. 99, pp. 29-34, 1972.
3. Games, J. L., "A Generator for Producing Monoenergetic, High Intensity, Soft X-rays," *Nucl. Instrum. Methods*, Vol. 107, pp. 7-12, 1972.
4. Games, J. L., and R. A. Hansen, "An Improved Annular-shaped Electron Gun for an X-ray Generator," *Nucl. Instrum. Methods*, Vol. 126, pp. 99-101, 1975.
5. Kuckuck, R. W., J. L. Games, and R. D. Ernst, "A High-intensity, Subkilovolt X-ray Calibration Facility Using a Cockroft-Walton Proton Accelerator," *Proceedings of the Fourth Conference on the Scientific and Industrial Applications of Small Accelerators*, 76 CH 1175-0 NPS (North Texas State University, Denton, Texas), pp. 229-233, 1976.
6. Games, J. L., and R. A. Hansen, "X-ray Induced Electron Emission from Thin Gold Foils," *J. Appl. Phys.*, Vol. 47, No. 9, pp. 3923-3928, 1976.

Figure 10 Four detectors that can be used for calibration comparisons in the 100 eV to 100 keV energy range