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G. J. Berzins
J. E. Valencia
J. W. Gutierrez
F. McGirt
K. R. Moore

MASTER

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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PULSED FLUORESCENT X-RAY SYSTEM WITH ON-LINE DIGITIZER AND DATA PROCESSOR

by

**G. J. Berzins, J. E. Valencia, J. W. Gutierrez,
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ABSTRACT

A pulsed source of monoenergetic x rays has been constructed for applications in which a narrow energy band and a short burst are both important. The radiation source is a high-purity, selectable foil that emits fluorescent x rays upon excitation by a bremsstrahlung pulse. A digitizer and a microcomputer are integrated into the system to aid operation and data processing. A general description, the more important system characteristics, and a few examples of applications are given.

I. INTRODUCTION

The production of monoenergetic x rays from a bremsstrahlung source that illuminates a fluorescent target has been demonstrated earlier.¹ Most of the previous work has been done with dc sources and fairly low end-point energies; little attention has been focused on pulsed systems. An advantage of dc operation is that single-photon counting can be employed, resulting in accurate determinations of some important parameters such as intensity and beam purity. The advantage of low end-point energies resides in cross sections—the probability of absorption as opposed to scattering decreases with increasing incident photon energy. The two processes become of comparable importance in most targets as incident energy exceeds about 100 keV.²

In some applications a well-defined, narrow energy band is important. In other cases, dc sources are difficult to use, and pulsed sources become very desirable. An example is the calibration of detectors with high dark currents. A second example is characterization of detectors whose response is not linear, is x-ray energy dependent, and must be mapped over a large input intensity range. Other examples include studies of transient phenomena either for their own sake or as a means to more complicated measurements. Many of the pulsed

sources that are commonly available have been designed for radiographic applications. These sources typically generate bremsstrahlung radiation with end-point energy ranging from 0.1 to 3 MeV and with target K-x-ray lines superposed on the continuum.

We have incorporated such a bremsstrahlung source into a pulsed, fluorescent x-ray system intended primarily to characterize the response of detectors. Because large numbers of pulses are typically required, we have interfaced the x-ray system with a digitizer and a microcomputer. This combination provides data acquisition that is fast, accurate, and amenable to immediate reduction and processing. The building blocks of the system are available commercially. System interfaces have been tailored for our needs and are a main subject of this report.

II. EXPERIMENTAL APPARATUS

Principal components of our system are a pulsed bremsstrahlung x-ray generator, a fluorescence chamber, a detector, a transient signal digitizer, and a microcomputer. In some instances the fluorescent target may be omitted and the detector positioned directly in the primary beam. Some of the system, diagrammed in

Fig. 1, conceptually resembles its counterpart of the dc system described in Ref. 1. Apart from geometric and structural details, a major difference is that the pulsed nature of our system requires a different type of data recording. Also, because of anticipated further applications, we operated and characterized the system in air rather than in vacuum.

A. Pulsed Bremsstrahlung X-Ray Source

The instrument that generates the primary bremsstrahlung beam is a Field Emission Corporation* (now Hewlett-Packard) Model 7322 x-ray pulser (fexitron). The end point of the x-ray energy distribution can be continuously varied from 120 to 180 keV. The x-ray tubes employ a conical, tungsten anode to generate the beam, which is limited in spatial extent by a window aperture. Either Kovar (0.003-in.-thick) or beryllium (0.025-in.-thick) exit windows are used, depending on the desired softness of the x-ray spectrum.

The measured beam intensity at 10 cm is about 100 mrad/pulse and 1100 mrad/pulse when the Kovar and beryllium window tubes, respectively, are used. The

machine operates in a single-pulse mode, with a minimum of about 10 s between pulses. Nominal pulse width is approximately 50 ns FWHM.

B. Fluorescence Chamber

The chamber provides a convenient platform for mounting the fluorescent foil, a filter, and a detector. Figures 2 and 3 show the overall experimental arrangement and a close-up of the target chamber, respectively. The chamber dimensions are such that only the rear wall (removed for most experiments) intercepts the primary (bremsstrahlung) beam. The fluorescent holder frames are also just outside that beam.

Typical foil thicknesses are about one mean free path of the fluorescent x-ray. Thus, with the foil at 45° to both the beam axis and the detector axis, about 24% of the x rays generated on the far side are transmitted. This configuration permits a satisfactory compromise between signal intensity and signal-to-scattered background ratio. Table I summarizes our set of fluorescent foils.

In addition to the scatter from the fluorescent foil, other sources of background are air scatter, backscatter and reradiation from the room wall (20-cm concrete), and leakage from the x-ray tube housing. Air scatter is

*Use of brand names or trade names does not necessarily imply endorsement by the Laboratory.

Fig. 1. Diagram of the pulsed fluorescent x-ray system.

Fig. 2. Photograph of pulsed x-ray generator. The fluorescence chamber is on the lab bench in the middle of the picture. The operating console is on the right, and the high-voltage unit is on the extreme left. The bremsstrahlung tube head and a detector are attached to the fluorescence box. Also visible are a detector power supply (connected to detector) and a spare detector at far end of bench.

Fig. 3. Close-up view of fluorescence chamber, looking toward the tube head. A target foil and a filter hang from the top of the chamber.

TABLE 1. Fluorescent Foils Used with Pulsed System

Symbol	Material Atomic No.	Thickness ^a (mg/cm ²)	X-ray energy (keV) ^b		
			(k _{α₁})	(k _{α₂})	[k _β (ave)]
Ti	22	8.52	4.50	4.51	4.9
Fe	26	15.9	6.39	6.40	7.1
Cu	29	17.6	8.03	8.05	8.9
Mo	42	50.5	17.37	17.48	19.7
Sn	50	87.4	25.04	25.27	28.6
Gd	64	128	42.31	43.00	49.0
Ta	73	224	56.28	57.54	65.7

^aDetermined by weighing sample of known area.

^bFrom Ref. 3. The k_{α₂}:k_{α₁}:k_β intensity ratios are approximately 50:100:20 (see Ref. 2 or Ref. 3 for detailed values).

comparable with that from about a mil (0.0025 cm) of most target materials and cannot be eliminated without evacuating the chamber. The room wall, which serves as a beam stop, is far enough away and has not posed a measurable problem. Leakage from the housing, though negligible in radiological terms, can contribute a significant background. A 3-mm-thick lead sleeve and a tapered (average thickness about 6 mm) lead collimator have reduced this leakage background about a hundred-fold.

C. Detectors

In many applications the sensor (x-ray converting material) or the detector (sensor plus immediate electronics) is the object of study or of calibration. For the exercises described here, we used diffused junction silicon photodiodes mounted on a housing that contained the biasing electronics but no amplification. The diodes were 150 μm and 300 μm thick, p-doped, and of nominally 10 kilohm · cm resistivity. Full-depletion voltages were about 45 V and 90 V, respectively. Normal dark currents at room temperature were a few tens of nanoamperes in the active element and up to 1 μA in the guard ring.

One type of sensor configuration employs two diodes of different areas on a common silicon substrate and with a common negative side contact. A separate guard ring surrounds each of the diodes. These sensors were made for special applications where swings in the input signals exceed the dynamic range of a single diode plus its electronics.

D. Digitizer

Signals from the detector (either directly from the photodiodes or from associated integrating and amplifying electronics) are digitized by a Transiac Model 2001 digitizer. The digitizer has a specified maximum sampling rate of 100 MHz and a specified analog bandwidth of 50 MHz. It is CAMAC compatible in order to interface with a microcomputer.

Functions such as sampling rate and memory size are selected through front panel controls or (as implemented in our case) through microcomputer commands. Trigger signals are obtained either directly from the flexitron monitor output or from a monitor detector in or near the beam. In either case, conditioning the trigger signal with nuclear instrumentation (NIM) modules has been helpful.

During initial experiments we found the digitizer to be extremely sensitive to electromagnetic interference from the x-ray pulser. Most of the noise appeared to be picked up by the input connection on the front panel. A practical solution was to place a grounded, copper shield over the front.

E. Microcomputer

The microcomputer, an IBM Personal Computer, Model XT, performs five major tasks: (1) set up and configure the data acquisition functions, (2) test the data acquisition functions, (3) acquire and store on disk the digitized information with current information about the experimental parameters, (4) immediately analyze each pulse in real time, and (5) process and analyze the data after the experiment.

The first function allows the experimenter to select and program several digitizer front panel parameters such as the number of pretrigger samples, the sample record length, the sampling interval, and the offset voltage. The experimenter may also enter parameters that define important properties of the experiment such as the fexitron voltage and the geometrical configuration.

The second function allows the experimenter to verify the operation of both the data acquisition hardware and the software without actually operating the x-ray generator.

The third function is implemented using a Transiac Model PC004 CAMAC crate controller that interfaces directly to the computer. A library of support routines for the controller was written to provide general high-level language access and control of CAMAC devices such as the digitizer used in this experiment.

The fourth function allows the experimenter to display, in graphical form, both the raw digitized ex-

perimental data and the values derived by real-time analysis of the raw data. The graphics hardware used is the Hercules Graphics Adaptor, which interfaces directly to the computer and provides 720×350 resolution monochrome graphics. Again, a library of support routines was written to provide general high-level language access to the Hercules graphics hardware. The real-time data analysis consists of a combination of pulse-finding and data-fitting logic. The pulse-finding algorithm determines various characteristics of the pulse, such as the base line, start and end points, and maximum value. The data-fitting algorithm then implements a least-squares fit of the three highest points to a parabola. The final results obtained are peak height, width, and area.

The digitizer-microcomputer part of the system is shown in Fig. 4. A representative hard copy output of the pulse visible in Fig. 4 is shown in Fig. 5.

Fig. 4. Photograph of the digitizer-microcomputer part of system. A representative digitized pulse and other output are visible on the monitor screen and on the hard copy in the printer. The digitizer is the only module in the CAMAC crate (middle of rack). Some of the NIM modules at the bottom are used in certain experiments. The signal attenuators (top of monitor) reduce signal amplitude into digitizer window.

TA061984.013
Peak Height = 1889.5mv, Area = 67843.1
Width (1/4 Max.) = 48.21ns, (1/2 Max.) = 34.22ns, (3/4 Max.) = 19.38ns.

Press RETURN Key To Continue

Title = FLUORESCER TESTS
Class = 1A
Date = 06/19/1984 Time = 14:03:49
Pulse Number = 13
2001 Front Panel Data = 340000
Signal Attenuation = 15
Febetron Voltage = 29
Febetron Tube = nsoft
Sensor S/N = a068r1
Sensor Bias Voltage = -135
Configuration Delay Line = 0
Configuration Geometry = fluor
Configuration Distance = 000
Configuration Filter Material = be
Configuration Filter Thickness = 000
Operator Message = 0000000000000000
End of Message

Fig. 5. Typical hard copy output of digitized and processed signal.

III. SYSTEM CHARACTERIZATION

A. X-Ray Output Jitter

Pulse-to-pulse variations in the digitized signal can arise from variations in the x-ray pulser output and from sampling limitations in the digitizer. In our system the former appears to be the more significant effect.

We examined the effect of sampling by comparing the digitized signal with that recorded on a fast oscilloscope (Tektronix 7104). The signal from the detector was split by a matched "T" and simultaneously recorded with the two instruments. The results, compared in Table II, show the differences to be about equal to the reading error on the scope trace.

Pulse-to-pulse jitter of the bremsstrahlung beam is illustrated in Table III. The spread about average values is about twice as large as differences between the readings from digital and analog records. The data in Table III were recorded with the digital system. An "old" ($\geq 15,000$ pulses) x-ray tube was used in the flexitron when these data were recorded, so that "worst case" rather than "typical" variations are shown.

Note that the pulse width given in Table III differs from that in Table II and also from the nominal specification of 50 ns. Narrower pulses arise when the soft x-ray component in the primary beam is filtered out. We attribute the ~ 70 -ns width in Table II to an old x-ray tube. Wider pulses can also result when the detector response time is long and must be convolved with the x-ray pulse.

We have not observed a significant difference in jitter as a function of pulse width. We have also looked for any dependence of jitter on machine parameters, such as charging voltage, and on operating procedures, such as time delay between charging and firing. There appears to be little effect as long as operation is confined to

TABLE II. Comparison Between Digital and Analog Records of Same X-Ray Fluorescence Pulse

Pulse No.	Height (mV)	Width at % of Height (ns)		
		25%	50%	75%
1 digital	352.5	87.2	69.8	52.6
1 analog	348	85	71	53
2 digital	350.1	86.5	71.7	54.6
2 analog	348	86	71	54
3 digital	349.1	89.6	73.6	55.5
3 analog	348.0	86.0	72.0	55.0
ave. dif.	2.6	2.1	1.2	0.5
(%)	0.7	2.4	1.6	0.9

TABLE III. Representative Variations in Bremsstrahlung Pulse Characteristics^a

Pulse No.	Height (mV)	Width at 50% of Height (ns)	Area (mV · ns)
1	416.5	24.8	11248
2	431.3	27.1	12348
3	407.1	26.3	11638
4	422.8	24.4	11448
5	436.0	25.1	11996
6	402.7	26.8	11502
average	419.4	25.7	11696
std. dev. (%)	3.1	4.4	3.5

^aPulses were generated with an old tube. Variations are more representative of "worst case" rather than "typical" condition.

specified parameter ranges and recommended procedures. A noticeable twofold to threefold improvement in jitter resulted when the old tube was replaced with a new one. The pulse width also decreased.

B. Beam Intensity and Spatial Uniformity

1. Primary Beam. The dose in the primary beam was directly measured with thermoluminescent dosimeters (TLDs) for both the beryllium and the Kovar window tubes. The respective dose on axis and 10 cm from the tubes was about 1100 mrad and about 100 mrad per pulse at 150 keV end point. The reading for the beryllium window tube is probably low because of the known falloff in TLD response^{4,5} to x rays of energy below 20 keV. The equivalent dose deduced from silicon sensor response is somewhat higher (about 2400 and 400 rad per pulse from the hard and soft tubes, respectively). We have been unable to reconcile these differences.

The beam intensity follows the inverse square law for distances greater than about 10 cm from the window. It is, however, affected by air absorption. The effective source position, located by triangulation from multiple pinhole images, was found to be 5.8 mm behind the beryllium and 3.7 mm behind the Kovar window. At distances closer than 10 cm, effects of source geometry are no longer negligible. The source diameter, measured with a pinhole image, is ~ 4 mm. Furthermore, the source spot is shaped like a "donut," a consequence of the arrowhead shape of the anode.⁶ A photograph of a pinhole image is shown in Fig. 6.

Fig. 6. Photograph of pinhole image of bremsstrahlung source. The image was recorded through a 0.5-mm-diam pinhole and with a magnification of 6. An optically fluorescent screen was pressed against the film to increase sensitivity. Note the structure in the ~ 4 -mm-diam source.

Because the extreme tip of the anode cone is not illuminated by electrons, the spatial distribution is affected as well. Figure 7 shows a series of film exposures by the direct beam at various distances from the tube. Note the penumbra effects in the center of the beam at close distances. We assume these result from shadowing by the anode tip.

2. Fluorescent Beam. The fluorescent foil intercepts the entire beam and becomes an extended source, averaging out spatial variations in the primary beam. Film placed in the detector plane was uniformly exposed at all fluorescent energies.

The intensity of the fluorescent beam at the detector plane (10 cm from the intersection of the primary beam axis and the detector axis) was determined with the diffused junction silicon detectors described in Sec. II.C. The time-honored assumption about linearity of silicon photodiodes, at least at these levels, appears supported by some of our results and by other data.⁷ The measured values, interpreted with the aid of cross-section data² as $\text{eV}/\text{cm}^2 \cdot \text{pulse}$, are given in Table IV. The generally accepted value of 3.6 eV/e was used for the energy-to-charge conversion factor of silicon.

C. Beam Purity

The ratio of the fluorescent x-ray intensity to the background is probably the most important single parameter and for a pulsed source is also the most difficult to measure accurately because, with a pulsed system such as this, it is not possible to count and sort individual photons as with dc systems.¹ We therefore relied on the data in Ref. 1, where applicable, to be the asymptote for any of our determinations. We estimated the scattered background fraction in the recorded signal as follows. A nonfluorescing, dummy target made of polyethylene was substituted for the metal foil. The areal density of the plastic was selected to approximately match that of the particular fluorescer. First-order corrections to the signal from the dummy target were based on the density differences.

The fluorescent yield of carbon and hydrogen is known to be very small.^{2,3} The resulting x rays are of such low energy (<0.3 keV) that they are absorbed by intervening air and the 0.05-mm-thick beryllium filter normally in front of the sensor. The cross section for Compton scattering changes slowly from 1 to 200 keV and with atomic number of the target. We did not

Fig. 7. Film exposure in primary beam at four distances from tube window. Note the structure in the beam arising from source geometry.

correct for these changes, partly because the primary spectrum is a continuum and partly because the correction is a small part of the background, which itself is a small part of the total signal. Some compensation for the scattering cross-section differences occurs because those x rays scattered by air on the far side of the target and by the far side of the target itself are more visible to the

sensor through the polyethylene than through the metal foils.

We next verified that a filter placed in front of the detector reduced the signal according to tabulated cross sections.² Whenever possible, filter sets were chosen to include filters whose K-edges were just below and just above the energy of the fluorescent x ray. These results are summarized in Table V.

TABLE IV. Fluorescent Beam Intensities

Target ^a	K X Ray ^b (keV)	Estimated Intensity ^c (eV/cm ² · pulse)
Ti	4.5	1.6×10^{10}
Fe	6.4	4.1×10^{10}
Cu	8.0	5.1×10^{10}
Mo	17	1.6×10^{11}
Sn	25	2.7×10^{11}
Gd	43	1.5×10^{12d}
Ta	57	2×10^{12d}

^aSee Table I for details.

^bApproximate mean value, see Table I.

^cDeduced with the aid of cross-section data in Ref. 2.

^dIncludes contribution from L x ray.

TABLE V. Fluorescent Beam Purity

Target	Fluorescent Signal Amplitude – Total Signal Amplitude	Purity (rad) (from Ref. 1)
Ti	0.77	^a
Fe	0.93	^a
Cu	0.94	0.987
Mo	0.94	0.981
Sn	0.88	0.976 ^b
Gd	0.76 ^c	0.955
Ta	0.58 ^c	0.90 ^b

^aNo data given for Z < 29.

^bInferred from data for nearby elements.

^cIncludes contribution from L x ray.

Some details in Table V need to be addressed further. Agreement between the two sets of data appears reasonably good for $Z < 50$. The differences most probably arise from differences in experimental conditions, most notably spectral integration vs pulse height analysis. In the case of the higher Z targets, the primary-beam energy is a factor as well. All our data were taken with a primary-beam end point of 150 keV. In Ref. 1, data for copper and molybdenum were taken with 100-keV end points and for the others with 300-keV end points. Furthermore, target thicknesses (and presumably material purities) were not the same. Our targets tended to be thinner, which would improve the fluorescence/scatter ratio, but decrease the signal relative to nontarget background.

Because we have achieved nearly the purity given in Ref. 1 for copper and molybdenum, we believe our data for iron and titanium to be valid also, perhaps with a similar 3-5% difference. Extrapolation from other data in Ref. 1 supports that conclusion.

Regarding effects of primary-beam end-point energy, we observed a trend that agreed with the dependence reported in Ref. 1. In general the fluorescent signal was cleaner with lower generator voltages for lower Z targets and with higher voltages for higher Z targets. Qualitatively, this difference reflects the tradeoff between higher photoelectric cross sections for the lower energy primary photons and the necessity for the primary photons to have an energy greater than the K-shell binding energy of the target. For example, with the titanium target, our fluorescent signal fraction *increased* by about 3%, whereas with the tantalum target, it *decreased* by about 10% as the primary beam end-point energy was raised from 120 keV to 180 keV.

We also observed a Z and energy dependence in the data treatment. Namely, the fluorescent fraction determined by using signal amplitudes differed by as much as 10% from that determined from integrated signals. For low- Z targets there was little difference, the integral showing a 1-3% higher fraction. For the higher Z , on the other hand, values deduced from integrated signals tended to be 8-10% lower than those from signal amplitudes. We believe that this phenomenon arises from details related to the pulse structure and pulse generation. Since the machine discharge does not result in a perfect square wave of voltage vs time, there is necessarily a time dependence in the primary-beam spectrum, with an associated spectral dependence of beam purity.

IV. EXAMPLES OF APPLICATIONS

A. Linearity Measurements

A straightforward example is the application of our system (without using the fluorescent feature) to transfer curve measurements. Figure 8 shows the response of a silicon photodiode as a function of incident intensity, controlled by $1/r^2$ dependence. Note the saturation of the signal amplitude—a function of the biasing and the electrical load. The integral of the signal, on the other hand, remains linear over the range of this measurement. (The departure from unity slope is accounted for by air transmission.) This somewhat trivial example illustrates the usefulness and ease of the digital system, compared with at least one alternative—that of reading film records of a scope trace.

B. Crosstalk Between Sensor Elements on a Common Substrate

Figure 9 shows the signal transfer curve of the smaller of the two diodes (1.3 mm diam and 16.2 mm diam) of

Fig. 8. Example of system application to transfer curve measurements.

Fig. 9. Example of system application to identification of crosstalk among silicon elements on a common substrate.

the special sensor described in Sec. II.C. The biasing circuitry includes 50-ohm loads on the low side of the two active areas and an ~ 3 -kilohm isolation between the guard rings and ground.

Note in Fig. 9 that both the signal amplitude and the integral increase in a superlinear manner above a relative dose of about 70. At this point the guard rings and the larger area diode are all drawing sufficient currents to change the voltage drop across the respective junctions. The resulting distortion of the electric field within the crystal produces a net funneling of extra electrons into the smaller diode, with an attendant "anomalous" increase in its signal.

Note further that the increase in the integral is greater than that in the signal amplitude, the latter increase being barely perceptible. The digital system has again proved very useful in identifying this difference and in parametric tracking of performance.

C. Signal Dependence on Angle of Incidence and on Energy

As a third example we show the effect of incident angle on signal at various energies. For simple geometries such an effect can be readily calculated. However, in this case the detector uses a spherical filter in front of a silicon photodiode. The results are plotted in Fig. 10. Such information is important in unfolding data from continuum-emitting sources.

D. Pulse Width Measurements

A pulse width measurement is one of the standard tasks of the system software. One example of its application is illustrated in Table VI, which compares pulse

Fig. 10. Measurement of the detector response as a function of angle of incidence and of incident x-ray energy.

TABLE VI. Fluorescent Foil Pulse Widths

Target	K X-Ray Energy (keV)	Pulse Width at 50% of Peak Height (ns)
Ti	4.5	50.9
Fe	6.4	51.3
Cu	8.0	49.5
Mo	17	39.6
Sn	25	36.8
Gd	48	33.3
Ta	57	31.3

widths observed with the various fluorescing foils. A second example involves the examination of the light output decay from various scintillators, including plastic, CsI(Tl), ZnS, CaWO₄, and Gd₂OS. The decay of these ranges from nanoseconds to nearly a millisecond. Data from all of these were captured following commands to the microcomputer to adjust sampling interval and window width as needed.

V. CONCLUDING COMMENTS

Our pulsed fluorescent x-ray system is proving to be very useful in several applications that require measurement of relative responses. Absolute measurements of such fluorescent x-ray intensities are very difficult to make—a generally recognized and acknowledged fact. A goal for upcoming work is to measure these more accurately, ideally by improving existing techniques and by adding corroborative ones.

The digitizer-microcomputer aspect of the system has proved to be at least as useful as anticipated. A goal in this area is to expand the data-processing capabilities by (1) adding custom routines for specific applications and (2) adapting routines such as least-squares algorithms, fast Fourier transforms, etc., to our library.

A parallel effort has been undertaken to assemble a code to calculate results for a variety of experimental configurations. Once developed, this tool should be useful for optimizing experiments and for identifying errors. Results to date are encouraging, but first-order discrepancies suggest that considerable additional effort will be needed.

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