A Detector for Low Energy (few hundred eV-20 keV) X-rays in the Presence of a High Background of High Energy X-rays

M. H. Mendenhall [a,1], F. E. Carroll [b], J. W. Waters [c] and R. H. Traeger [b]

[a] *W. M. Keck Foundation Free-Electron Laser Center, Box 1816 Station B, Vanderbilt University, Nashville, TN 37235*

[b] *Department of Radiology and Radiological Sciences, Vanderbilt University Medical Center, Nashville, TN 37232*

[c] *Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235*

Abstract

The Vanderbilt University FEL Center project for the production of monochromatic X-rays uses Compton backscattering of the infrared light from the FEL by the 40 MeV electron LINAC to produce nearly monochromatic pulses of X-rays in the 10-20 keV range. Detecting these requires the ability to distinguish the small flux of 15 keV X-rays produced by the backscattering from the large flux of X-rays from low energy to many MeV resulting from scattered electrons from the beam. We have constructed a detector using two thin silicon surface-barrier detectors as calorimeters, separated by an aluminum absorber, so that the front detector sees both high energy and low energy X-rays, and the back one sees only high energy X-rays. Using a carefully balanced differential amplifer chain, we can detect a soft X-ray flux which is only about 5% of the broadband flux observed by our detector.

PACS: 07.85.F

Key words: X-ray detection, High energy X-ray background

[1] email:marcus.h.mendenhall@vanderbilt.edu

[2] This research was performed under ONR grant ONR-N00014-94-1-1023.

1 Introduction

The Vanderbilt University Keck Free Electron Laser Center has had an ongoing development effort to produce a tunable, narrow-band source of X-rays in the 10-20 keV energy range which is of particular interest to the radiologic community for use in mammography and imaging elsewhere in the body. This is accomplished by using Compton backscattering of infrared (IR) light between 2.0 μm and 2.5 μm at nearly 180° to the incoming 40 MeV electron beam. [1] This configuration provides relatively forgiving alignment and timing of the electron bunches with respect to the photon bunches, but results in X-rays coming out along the same direction as the electron beam (which carries all the momentum in the lab frame). Detection of the beam in the vault environment is essential to allow us to tune the IR and electron beam up to the point at which we have sufficient flux to deflect and transport the X-ray beam up to the user level of our facility. This deflection will be carried out via the use of four graphite mosaic Bragg-reflector crystals which are expected to have an overall efficiency of about 10%. [2]

Our LINAC operates with about 5 μs macropulses at a repetition rate of 30 Hz, and the infrared pulses from the FEL are about 2 μs long. Within each macrobunch is a train of microbunches repeating at 2856 MHz which are about 1 ps long. Thus, our X-rays are produced as a train of 1 ps pulses over a 2 μs period at a 30 Hz rate, coincident with the production of IR photons. This makes energy spectroscopy of the X-rays using standard HPGe or Si(Li) detectors very difficult since all the X-rays arrive at the detector in a 2 μs window, which is typically the shaping time for such a detector, resulting in the energy of all the X-rays in one bunch being summed into one giant pulse. [3] Thus, using conventional detector techniques, one has no simple way to distinguish the lower-energy X-rays of interest from the broadband background. On the other hand, using a NaI(Tl) crystal and phototube as a calorimeter yields timing resolution which is a little too slow to cleanly resolve the 2 μs pulse of interest from the 5 μs pulse of background from the LINAC. Further, plastic scintillators, which would be fast enough to provide the needed timing resolution, degrade quickly in the intense radiation environment around our experiment. It is this problem which the rest of this paper addresses.

2 Detector System Description

The problem we address effectively has two parts: first, how to detect a flux of X-rays in a short pulse which precludes the use of normal spectroscopic detectors but which is somewhat too fast for NaI(Tl) detectors to easily resolve from the background; and, second, how to distinguish the low energy

X-rays of interest from the high energy background. On top of these two main considerations is a further complication, which is that the environment in which these detectors must live is a very rich source of electromagnetic interference (EMI) due to the pulse power driving our klystron which provides the power for the LINAC.

The first problem, finding an X-ray calorimeter which was simple to use, reasonably resistant to radiation damage, and compact, was solved by the use of a Silicon Surface Barrier Detector (SBD) as our detecting medium. Normally, these detectors are used for charged particle spectroscopy, rather than as calorimeters. However, they have good sensitivity to photons over a wide energy range, from just above the bandgap of Si (around 0.8 eV) to X-rays (with the sensitivity depending primarily on whether the detector is thick enough to absorb the photons of interest). Also, they are available [3] in a wide variety of sizes, packages, and thicknesses, thereby providing us with the adaptability needed to fit our experiment. By selecting the material thickness, we can choose a detector which absorbs most of the lower energy X-rays without having such a large sensitive volume as to absorb any more of the high energy X-rays than necessary. For our purposes, where energy spectroscopy is not a goal, there is no need to cool the detector, either.

To estimate the optimum thickness of the detector, one must take into account two factors: the efficiency with which the detector detects low energy X-rays and the transparency of the detector to high energy X-rays. To make a detailed calculation of this optimum value would require a knowledge of the spectrum of the high energy X-rays we are trying to ignore. Although it might be possible to determine this spectrum, it would not be easy because of the pulsed nature of our electron beam. Instead, we consider primarily the first factor and treat the second by default. It is apparent that if the detector is too thin, so that most of the low energy X-rays pass through, the total signal becomes smaller and fades into the electromagnetic interference present in our system. On the other hand, if the detector is very thick compared to the absorption length for the low energy X-rays, it stops all of the low energy X-rays but also stops more of the high energy X-rays than necessary. Between these two points, we chose to make the detector approximately the thickness which would absorb 50% of the low energy X-rays. From standard tables [4][5] we find that the attenuation length (to e^{-1}) for 14 keV X-rays in Si is 350 μm, so we chose the nearest value available to this for our detector thickness.

We tested a detector based on a single Si SBD and quickly discovered that the background present in our system was more than 100 times the signal we were expecting for the startup of the Compton system. Various attempts at digital subtraction were made, in which the background produced with the IR beam

[3] from, *e.g.*, EG&G, Inc., Ortec division

Fig. 1. Two Layer Detector

off was subtracted from the signal with the IR on. However, the background drifts with time, and we could only suppress a factor of a few of the background due to this. This was clearly insufficient, so we took the approach that it was necessary to subtract the background on a shot-by-shot basis. To do this, we had to be able to independently measure both the signal plus background and the background. Our second generation detector provided us this ability.

The second (and final) generation detector we built consisted of two SBDs separated by an aluminum absorber (Figure 1). This system stopped most of the low energy X-rays in the Si detector, and the rest of them in a 1.6 mm layer of aluminum. The second SBD, behind the aluminum, was thus only sensitive to the high energy X-rays which made it through the absorber. Here again, we made a reasonable assumption about the thickness of the absorber. We wanted it to be thick enough to stop essentially all the low energy X-rays, but thin enough that we minimized its interaction with the high energy ones. If the absorber were too thick, we would have two different effects in it which would distort the signal in the rear detector. First, the high energy X-rays would be somewhat attenuated by the absorber. Second, we could get Compton shower generation in it, which could result in a conversion of high energy X-rays into multiple low energy X-rays, and possibly increase the signal detected by the rear detector. The actual value is not very critical (see discussion in section 4). Any thickness significantly greater than the half-value thickness would probably suffice. Our goal was to keep the apparent background on the two detectors as similar as possible, so we could use a balanced differential amplifier chain (see below) to minimize EMI pickup in the detected signal.

3 Electronics

One of the primary challenges of this project was the presence of a broad spectrum of EMI sources close to the detector. On top of this, we thought it unwise to place active electronics near the detector, due to the relatively high radiation environment present, which could result in two problems. First, the location where the detector sits is subject to a time-averaged radiation flux of 100 R/hour (1 Gy/hour) which results in moderately rapid degradation of electronic components. More seriously, for our project, this radiation is

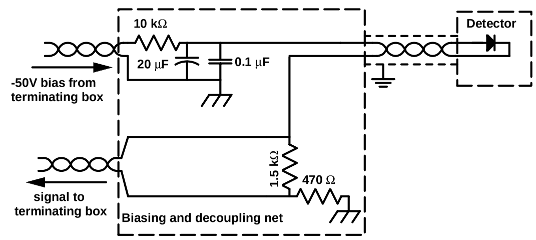

Fig. 2. Ground Decoupling and Bias Network

actually present with the time structure of the electron beam, and it is very likely that any electronics present would act as detectors in exactly the same manner as our SBDs. Thus, we felt compelled to mount the power supplies and amplifiers for the system in a lab area, well shielded from the radiation, at the end of about 10 m of cable. The signal we needed to detect was a 25 μV pulse, about 2 μs wide, in the presence of 10 mV of noise of various descriptions.

To achieve this goal, we designed a doubly-differential amplifier system to cancel as many noise sources as possible. First, the two SBDs are mounted in a small aluminum box which can be placed directly in the path of our X-rays, with both terminals of each SBD floating off ground. The signal from the SBDs is transmitted on shielded cable to a box about 20 cm away. In this box is a biasing and decoupling network (Figure 2) which converts the unbalanced loads of the detector into an approximately balanced signal for driving a 100 Ω balanced line. We implement the transmission line with Category 5 twisted-pair cable, which spans the 10 m distance from the vault to the experimental area. In the experimental area, we have a terminating box which receives this signal, provides the necessary 100 Ω loads, and feeds the resulting signals to the differential amplifiers.

The differential amplifier system consists of three [4] variable-gain and bandwidth differential amplifier modules. The signal from each detector is sent to an amplifier, which removes much of the common-mode signal which is generated both by the parasitic capacitances in the detector box and by the biasing network's ground-isolation resistors. However, there is still some of the EMI pickup which finds its way into to differential-mode signal at the first stage of the amplification. Because of the careful matching of the two arms of the system, though, this EMI pickup is nearly identical on both amplifiers. The second stage of differential amplification accomplishes two goals: first, it subtracts off the remaining EMI and, second, it subtracts off the high energy X-ray background. The receiving network and amplifier schematic is shown in Figure 3.

[4] Tektronix, Inc. AM502

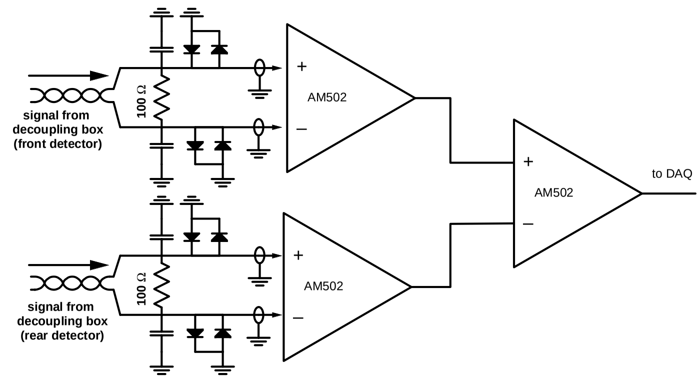

Fig. 3. Differential Amplifier Line Receiver and Network

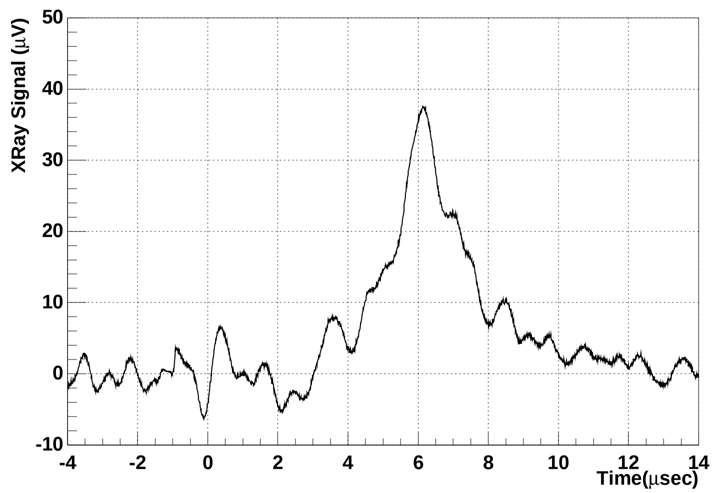

Fig. 4. Compton X-ray signal from 14 August 1998

In actual operation, we set the gain and bandwidth of the amplifier to limit excess noise pickup and to prevent saturation of the first-stage amplifiers due to the residual EMI pickup. Usually, we set the low pass -3 dB point on the amplifiers to 10 kHz, the highpass -3 dB point to either 300 kHz or 1 MHz, and the first-stage gain to 500. The second stage is then adjusted to set the overall gain of the system, to a value of typically 50, yielding an overall system gain of 25000. One note is that this amplifier chain has a fairly long propagation delay. The two stages of amplification contribute about 2 μs total delay when they are set to a bandwidth of 300 kHz.

The system as described above provides excellent performance. The quality of the signal resulting from about 2000 photons/micropulse is shown in Figure 4. This signal is the result of averaging 16 pulses with the IR beam on, and subtracting from that the average of 16 pulses with the IR beam off.

4 Detector Calibration

To estimate the sensitivity of SBDs to X-rays, we followed two different approaches. First, we calculated the expected sensitivity of the detector by the method described below. Then, using essentially the same method, we calculated the sensitivity of a commercial radiological calibrator. Then, by comparing the response of each detector to the same broadband X-ray source, we verified that the expected sensitivity of our system was essentially in accord with the computed value.

Our method for computing the expected response of an ionization detector to broadband X-ray source was as follows:

First, note that the absorbed fraction f of X-rays at a given energy E in a layer of material of thickness t with attenuation length $\lambda(E)$ is

$$f(E) = 1 - e^{-t/\lambda(E)} \tag{1}$$

and assuming that, at low energies, Compton showers are not generated so that if a photon is absorbed, it is entirely absorbed, the deposited energy ϵ in the detector is

$$\varepsilon = E \cdot f = E \left(1 - e^{-t/\lambda(E)}\right) \tag{2}$$

so for a source with an energy spectrum $I(E)$ the mean deposited energy per photon η is :

$$\eta = \frac{\int E \cdot I(E) \cdot \left(1 - e^{-t/\lambda(E)}\right) \, dE}{\int I(E) \, dE} \tag{3}$$

Converting the above-calculated sensitivity of each detector into a system sensitivity requires a little more work. Since the output of the system is the difference of the outputs of two detectors with an optional absorber between them, one must multiply the above sensitivity by the difference in the signal between the two detectors resulting from the absorption in the front detector and the absorber. The correction factor (assuming the front and rear detectors are identical) is

$$\begin{aligned} \varphi(E) &= 1 - ((1 - f_{det}(E)) \cdot (1 - f_{abs}(E))) \\ &= f_{det}(E) + f_{abs}(E) - f_{det}(E) \cdot f_{abs}(E) \end{aligned} \tag{4}$$

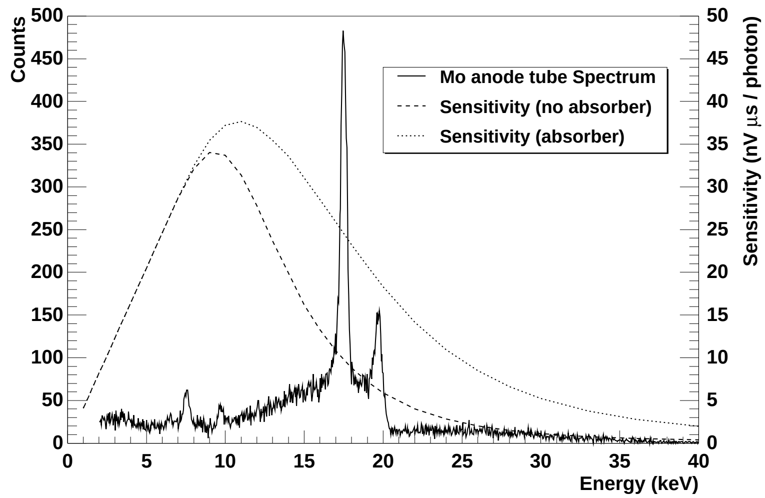

Fig. 5. Mammography Unit Energy Spectrum and Relative Sensitivity Curves for the Detector System

Note that by using an absorber, one increases the sensitivity of the differential detector at all energies. This may or may not be a desirable effect, depending upon the spectrum of the background radiation. If most of the background is at energies above those which are significantly absorbed by the absorber, and the front detector is not absorbing most of the signal of interest, an absorber which is thick enough to absorb the rest of the signal of interest may be beneficial. However, it does increase the sensitivity to photons with energies near those at which the detectors start to become transmitting; thus, if the primary source of background is at an energy only somewhat higher than that of the signal of interest, the best discrimination is obtained with no absorber. The sensitivity curves in Figure 5 illustrate this effect.

The X-ray source we used for the calibration was a commercial mammography machine [5] which has a molybdenum anode tube [6], running at a beam voltage of 50 kVP and a current of 80 mA. We measured the energy spectrum of the X-ray tube (Figure 5) with a standard HPGe detector and with data from available tables of X-rays absorption [4], (Figure 6) we can numerically compute the integral in Equation 3 for both our silicon detectors and the radiological calibrator.

In the case of the calibrator, which has a window in front of the sensitive volume, it is necessary to correct the spectrum for the absorption in the window. Also, for the calibrator, which uses a gas-filled chamber, we assume the sensitive volume is "thin" at the energies transmitted by its window, so $f(E) \approx t/\lambda(E)$ which allows us to convert the readout of the calibrator (in

[5] Philips Inc., mammo Diagnost
[6] model ROT201

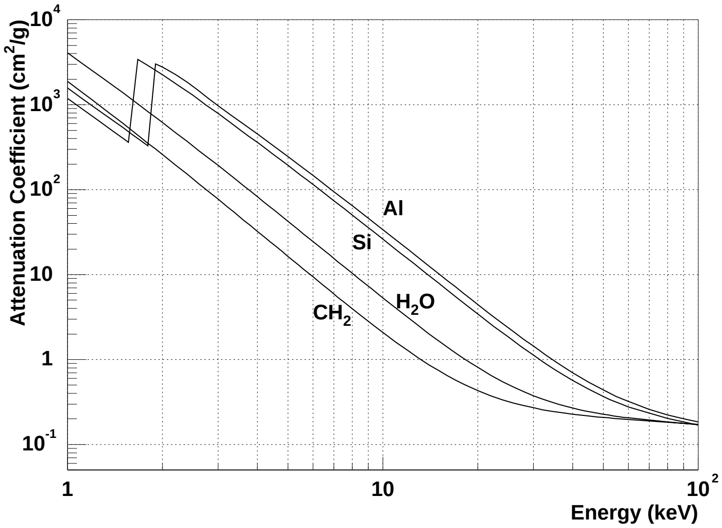

Fig. 6. X-ray Absorption in materials relevant to this paper

Rad, where 100 Rad = 1 Gy = 1 J/kg) directly to a photon count. The calibrator [7] has, per its specifications, a front window of thickness 110 mg/cm^2 (of a plastic assumed to be CH_2) and a sensitive area of 18.9 cm^2. From the spectrum (Figure 5) and the absorption data we get a mean sensitivity of the ion chamber of 22 keV cm^{2}g^{-1} (1.9×10^{-11} Rad) per photon incident on the window. Using the calibrator to intercept the entire beam from the source yielded 0.56 Rad/s or 3.1×10^{10} photons/s.

For the silicon detector, we use the technique described above to obtain mean energy deposition and the pair-production energy for Si [6] to compute the sensitivity. This yields a charge/photon which can then be inserted into our 100 Ω impedance line to produce an impulse $V\Delta t$ V·s/photon. This is quite straightforward. If Z is the line impedance, E_p is the pair production energy and ε is the energy deposited, from eqn. 2, then the charge q produced by a photon of E is $q = q_e\varepsilon/E_p$ so the voltage impulse $V\Delta t$ in the transmission line will be $V\Delta t = q \cdot Z = Zq_e\varepsilon/E_p$. For our impedance (100 Ω), and pair energy (3.9 eV), we get $V\Delta t = 4.1\,\mathrm{nV}\cdot\mu\mathrm{s/keV}$ of deposited energy.

Applying the sensitivity calculation to our detector, using 300 μm thickness for the SBD, 1.6 mm thickness for the absorber, and the spectrum of the broadband source gives a mean deposited η energy per photon of 5.8 keV. The signal expected from the detector then should be

$$\begin{aligned} V_{\mathrm{out}} &= (5.8\,\mathrm{keV/photon})(3.1 \times 10^{10}\,\mathrm{photons/s})(4.1 \times 10^{-15}\,\mathrm{Vs/keV}) \\ &= 740\,\mu\mathrm{V} \end{aligned}$$

[7] Nuclear Associates / Victoreen model 06-525

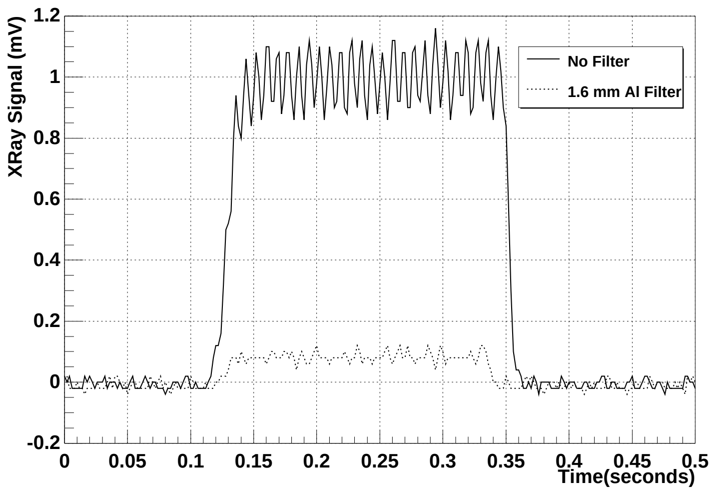

Fig. 7. Detector Calibration from the Mammography Unit

which compares quite favorably, given the complexities of the calibration, with the 1.0 mV signal we measured (see figure 7). Repeating the calculation with the spectrum as modified by a 1.6 mm absorber in front of our detector yields a mean absorbed energy of 0.51 keV/photon (incident on the absorber) and a signal of 65 μV, which is also reasonably close to the observed signal. Note that the calculations for a broadband source where the absorbers strongly modify the spectrum contain large uncertainties due to the exponential absorption in the absorbers.

5 Results

While operating the Compton backscattering system on 14 August, 1998 with this detector, we observed the first signal. Figure 4 shows the final subtracted signal (all differential amplifiers and beam on-beam off) from that run. The system was tuned to generate X-rays of an energy of 14 keV. The area corresponds to 1.4×10^3 X-rays/pulse which at our repetition rate of 30 Hz indicates a flux of 4×10^4 photons/s.

6 Conclusion

The detection of pulsed X-rays in the presence of a large background of much higher energy radiation is feasible. The system described in this work has successfully seen the narrow-band 14 keV X-ray signal from Compton backscattering the FEL.

It was necessary to pay close attention to the electronic details of this system to achieve peak performance. We have not yet investigated whether better noise performance could be obtained by using hybrid amplifiers close to the detectors to boost the signal before it is transmitted to the remote receiver. Because of the radiation environment near the detectors, we have strong reservations about placing active components close to the detector, but there may be improvements that would be seen if this were done.

7 Acknowledgements

Data analysis was done using the free ROOT system from CERN (*http://root.cern.ch*) and we would like to thank the developers and maintainers of that package.

References

[1] F. E. Carroll, J. W. Waters, R. H. Traeger, M. H. Mendenhall, W. W. Clark, and C. A. Brau. Production of tunable, monochromatic, X-rays by the Vanderbilt free-electron laser. In *LASE'99*. SPIE, 1999.

[2] P.A. Tompkins. Application of graphite mosaic monochromator crystals for X-ray transport. *J. of X-Ray Sci. and Technol.*, 4:301–311, 1994.

[3] J. G. Timothy and R. P. Madden. Photon detectors for the ultra violet and X-ray region. In E-E. Koch, editor, *Handbook on Synchrotron Radiation*, volume 1A, chapter Photoconductive detectors, pages 344–355. North Holland, Amsterdam, 1983.

[4] J. H. Hubbell. Photon mass attenuation and energy absorption coefficients from 1 kev to 20 mev. *Int. J. Appl. Radia. & Isotopes*, 33:1269–1290, 1982.

[5] Photon cross sections database. http://physics.nist.gov/PhysRefData/Xcom, April 1999.

[6] Wei-Kan Chu, James W. Mayer, and Marc-A. Nicolet. *Backscattering spectrometry*. Academic Press, New York, 1978.