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Synthetic Diamond-Based Position-Sensitive Photoconductive Detector Development for the Advanced Photon Source

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Abstract

A novel x-ray beam-position detection device that we call a position-sensitive photoconductive detector (PSPCD) is designed to have synthetic diamond as its substrate material. We proved that it is feasible to use synthetic diamond to make a hard x-ray position-sensitive detector based on the photoconductivity principle and that acts as a solid-state ion chamber.

Experiments on different PSPCD samples using synthetic diamond with high-heat-flux white undulator beam, as well as with monochromatic hard x-ray beams, have been done at the Advanced Photon Source. Recent test results with the PSPCD in quadrant configuration as an x-ray beam position monitor and in a multipixel array as an x-ray beam profiler are presented in this paper.

1. Introduction

Natural diamonds as photoconductive radiation detectors (PCDs) have been studied since 1956 (Cotty, 1956). It was found that only certain diamonds, those with low impurity concentrations (specifically nitrogen), are suitable for use as radiation detectors (Kozlov et al., 1975). Natural diamonds have been used as PCDs for soft x-ray detection with a laser-produced plasma soft x-ray source and a synchrotron radiation source (Kania et al., 1990a,b). Insulating type (type IIa) synthetic diamond (from high-pressure cell) as solid-state ionization chamber radiation detectors have been studied for biological applications with alpha-particle and gamma radiation (Keddy et al., 1987). Comparing with other photoconductors, diamond is a robust and radiation-hardened material with high dark resistivity, large breakdown electric field, and sensitive to hard x-rays (Kozlov et al., 1977).

At the Advanced Photon Source (APS), synthetic diamond, especially CVD diamond, has been studied as a blade material (coated by gold or other metal) for high-heat-flux photoelectron emission-type x-ray beam position monitors (XBPM) (Shu et al., 1992). CVD diamond offers superior thermal-physical properties, such as high thermal conductivity, a low thermal expansion coefficient, and good mechanical strength and stiffness under heat, that are critical for the APS insertion-device beamline XBPM design. A x-ray-transmitting beam position monitor (TBPM) using CVD diamond has also been developed for combining filter/window and XBPM functions (Shu et al., 1994). In February 1996, a sample for a PSPCD-type TBPM, which was designed and prepared at the APS, was tested at the European Synchrotron Radiation Facility (ESRF) bemline ID-6 (Shu et al., 1997). The results showed that it is feasible to use a single CVD-diamond disk to make a hard x-ray position-sensitive detector based on the photoconductivity principle and that acts as a solid-state ion chamber (Shu and Kuzay, 1996). In this paper, recent test results with a PSPCD in quadrant configuration as an x-ray beam position monitor and in a multipixel array as an x-ray beam profiler are presented.

2. PSPCD as a X-Ray-Transmitting Beam Position Monitor

The basic concept of the x-ray TBPM is to mount the monitor blade perpendicular to the synchrotron radiation beam and to design the blade and its sensor coating in such a way that most of the x-ray beam will be transmitted through the blade. Thus, the total absorbed photon power cannot cause thermal damage to the blade.

There are two different types of the TBPM designed at the APS as shown in Figs.1a and b. Fig. 1a shows a photoemission-type TBPM, in which the CVD diamond is acting as an electrical insulating heat sink for the aluminum coating, which is the photoemission sensor material. Four current amplifiers measure the photon-electron return current from the quadrant aluminum sensor to obtain the beam position information. For a PSPCD-type TBPM, shown in Fig. 1b, the quadrant patterns of the aluminum coating were applied on both sides of the diamond disk. A DC bias voltage was used to generate the current signal, which is based on the photoconductive properties of the CVD diamond. With x-ray illumination, electrons and holes pairs are generated, which changes the conductivity of the diamond in the region where the x-ray is penetrating. By measuring the current in different quadrant areas, the x-ray beam position can be determined.

According to a simple carrier model, the photogenerated carriers, electrons and holes are treated as a single charge carrier, and the carrier density can be determined from the equation (Kania, 1990b)

$$\frac{dn}{dt} = \frac{P(t)}{\gamma V} - \frac{n}{\tau},$$

where P(t) is the absorbed x-ray power, τ is the carrier lifetime, n is the carrier density, γ is the average energy to form an electron hole pair, and V is the excited volume.

From the test results, we have learned that, compared to a photoemission-type TBPM, the beam position signal from a PSPCD-type TBPM has less ID gap dependence. This is caused by the higher sensitivity of the PSPCD-type TBPM to the hard x-ray radiation, so that less bending-magnet radiation contamination is contributing to the beam-position results from the PSPCD-type TBPM.

A total of eleven PSPCD-type TBPMs have been installed on the APS front-end commissioning filter/mask/windows assemblies. The thickness of the 25-mm-diameter insulating-type CVD-diamond disk is 150 μm, and the CVD-diamond disk is coated with four electronically isolated aluminum quadrant patterns. The thickness of the aluminum coating is about 0.2 μm. The PSPCD-type TBPM is located 25 m from the source and downstream of a 300-μm-thick graphite filter. During typical operating conditions at the APS (7 GeV and 100 mA with undulator gap at 11 mm), the PSPCD-type TBPM is transmitting more than 3 kW undulator white beam power with about 300 W/mm^2 power density. The power absorbed by the TBPM is 84 W with 3.6 W/mm^2 power density (Kuzay et al., 1996). When the beam is centered, each quadrant area of the PSPCD-type TBPM provides about 300 μA signal with 1.5 volt bias supply.

Unlike the photoemission-type TBPM, vacuum is not necessary for the operation of the PSPCD-type TBPM. It can be operated in an atmospheric environment as well as in vacuum. It also shows a good response to the monochromatic hard x-ray. Fig. 2 is a plot of PSPCD output response versus x-ray energy. The experiment was performed at APS undulator beamline 1-ID with a cryogenically cooled Si(111) double crystal monochromator. The PSPCD was set in an atmospheric environment during this experiment. The PSPCD output response versus bias voltage has also been measured as shown in Fig. 3.

3. PSPCD as a X-Ray-Transmitting Beam Profiler

A x-ray-transmitting beam profiler system using two linear-array PSPCDs has been designed for the APS undulator beamline commissioning. The same insulating-type CVD-diamond disk was used as the linear array substrate. On each disk, sixteen 0.2-μm-thick, 175-μm-wide aluminum strips are coated on one side, and an orthogonal single 175-μm-wide strip is coated on the other side. Hence looking through the disk, a linear array of sixteen pixels is created as the photoconductive-sensor elements, with 175 μm x 175 μm pixel size.

A schematic of the profiler system is shown in Fig. 4. During the measurement, two sets of 16 pixel linear array PSPCD are placed into the hard x-ray beam, perpendicular each other. Transmitting by the hard x-ray beam, the two arrays readout the beam vertical and horizontal profile information simultaneously. To obtain a complete beam 2-D profile, one can scan the linear array across the beam. Fig. 5 shows a set of APS undulator white beam profiles directly measured by a 16 pixel linear-array-PSPCD scanning across the beam with two different undulator magnet gap settings. A 12.7-mm-thick aluminum filter was used for these measurements to eliminate most of the soft x-rays.

A prototype of 2-D imaging PSPCD has been built at the APS. As shown in Fig. 6, sixteen aluminum strips are coated on both sides of the CVD-diamond disk creating a 16 x 16 pixel two-dimensional array with 175 μm x 175 μm pixel size. Preliminary tests proved that a 2-D hard x-ray beam profile image could be read out by a multichannel current amplifier with pulsed bias electronics. We have tested single pixel response of this 2-D imaging PSPCD using undulator white beam with a 150 μm x 150 μm aperture. It was found that the pixels in this 2-D array PSPCD do not cross talk.

4. Conclusion

We have developed a novel position-sensitive photoconductive detector using insulating-type CVD diamond as its substrate material. Several different configurations, including a quadrant pattern for a x-ray-transmitting beam position monitor and 1-D and 2-D arrays for PSPCD beam profilers, have been developed. Tests on different PSPCD devices with high-heat-flux undulator white beam, as well as with monochromatic hard x-ray beams have been done at the APS. It was proven that the insulating-type CVD diamond can be used to make a hard x-ray position-sensitive detector based on the photoconductivity principle and that acts as a solid-state ion chamber.

A total of eleven CVD-diamond PSPCD-type TBPMs have been installed on the APS front end for commissioning use. The linear array PSPCD beam profiler has been routinely used for direct measurements of the undulator white beam profile. More tests with hard x-rays and gamma-rays are planed for the CVD-diamond 2-D imaging PSPCD. Potential applications include a high-dose-rate beam profiler for fourth-generation synchrotron radiation facilities, such as free-electron lasers.

Figure 1

Fig. 1a, Schematic of the photoemission-type TBPM, where the CVD diamond is acting as an electrical insulating heat sink for the aluminum coating, which is the photoemission-sensor material.

Fig. 1b, Schematic of photoconductive-type TBPM, where the quadrant patterns of the aluminum coating were applied on both sides of the diamond disk.

Figure 2

A plot of the PSPCD output response versus x-ray energy.

Figure 3

A plot of the PSPCD output response versus bias voltage.

Figure 4

A schematic of the CVD diamond PSPCD profiler system with two sets of 16 pixel linear array PSPCDs and readout electronics.

Figure 5

A set of APS undulator white beam profiles directly measured by a 16 pixel linear-array-PSPCD scanning across the beam with two different undulator magnet gap settings G = 15 mm (left) and G = 30 mm (right).

Figure 6

Photograph of the APS prototype two-dimensional imaging PSPCD.

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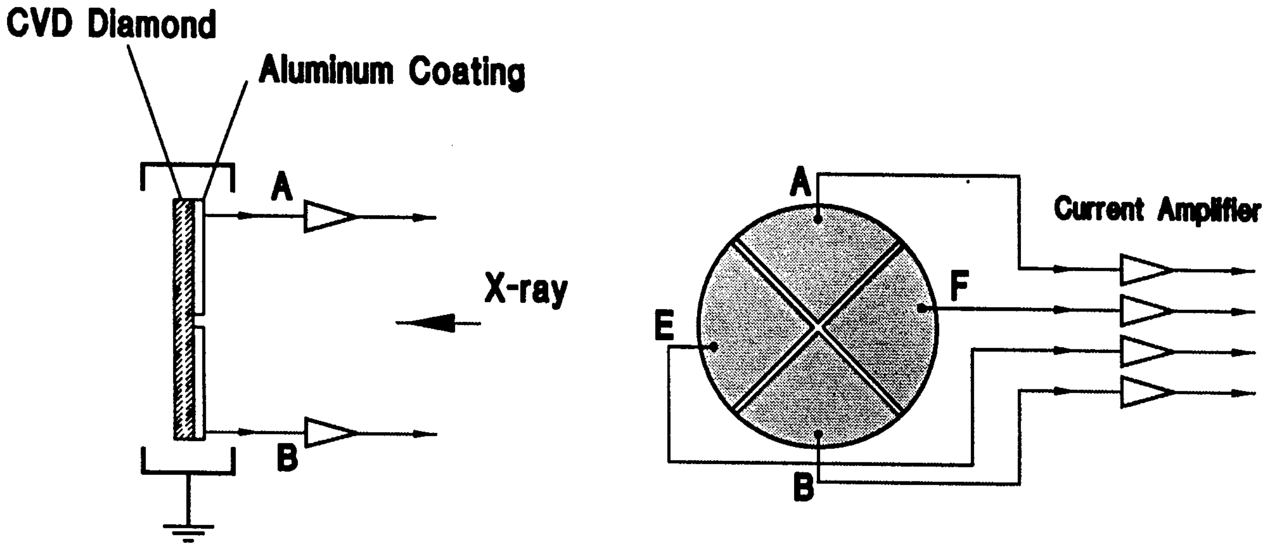
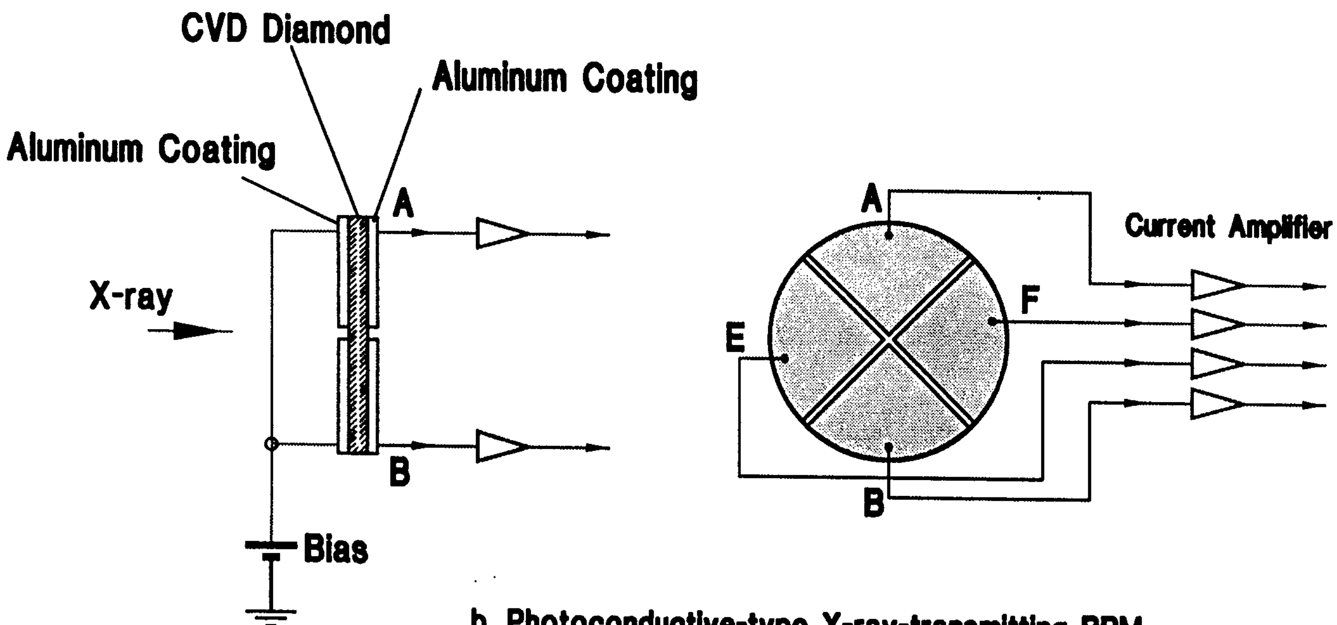
Keywords

Beam position monitor, Beam profiler, Image, x-ray, CVD diamond.

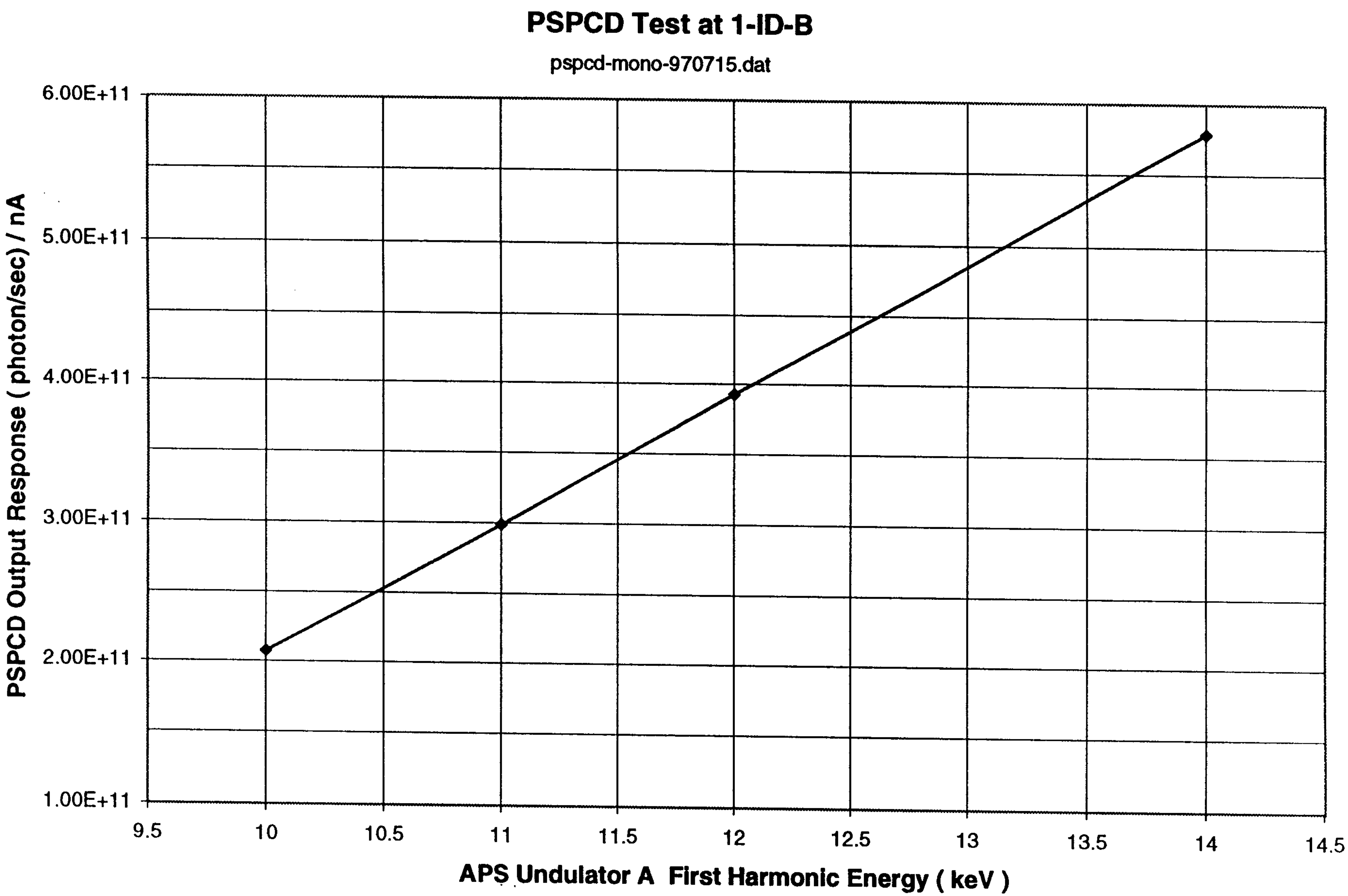


a. Photoemission-type X-ray-transmitting BPM



b. Photoconductive-type X-ray-transmitting BPM

Fig. 1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2.00E+11
1.00E+11
PSPCD Output Response (photon/sec) / nA
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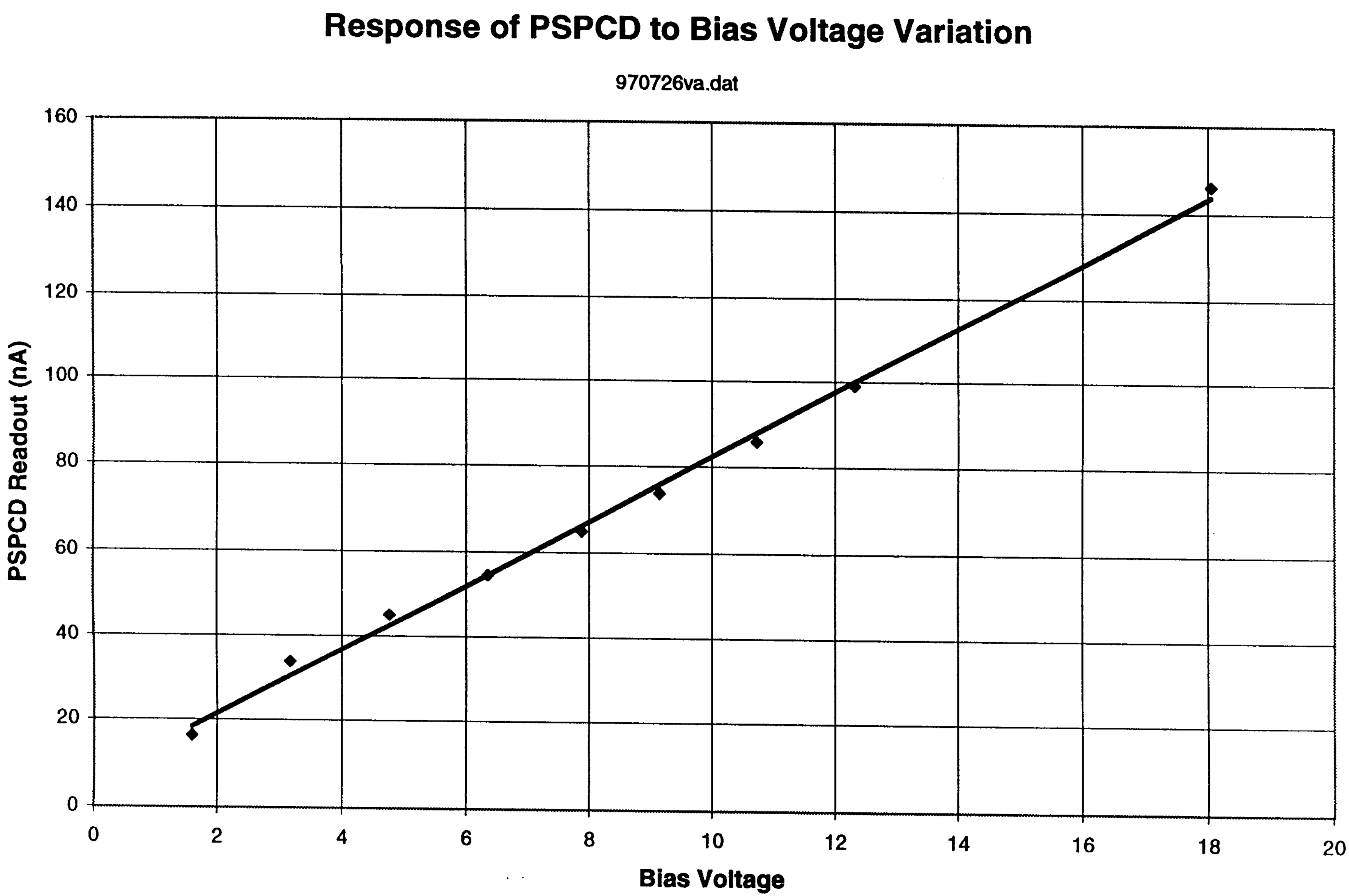
10.5
11
11.5
12
12.5
13
13.5
14
14.5
APS Undulator A First Harmonic Energy (keV)

Fig. 2


Response of PSPCD to Bias Voltage Variation
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PSPCD Readout (nA)
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140
120
100
80
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0
2
4
6
8
10
12
14
16
18
20
Bias Voltage

Fig. 3

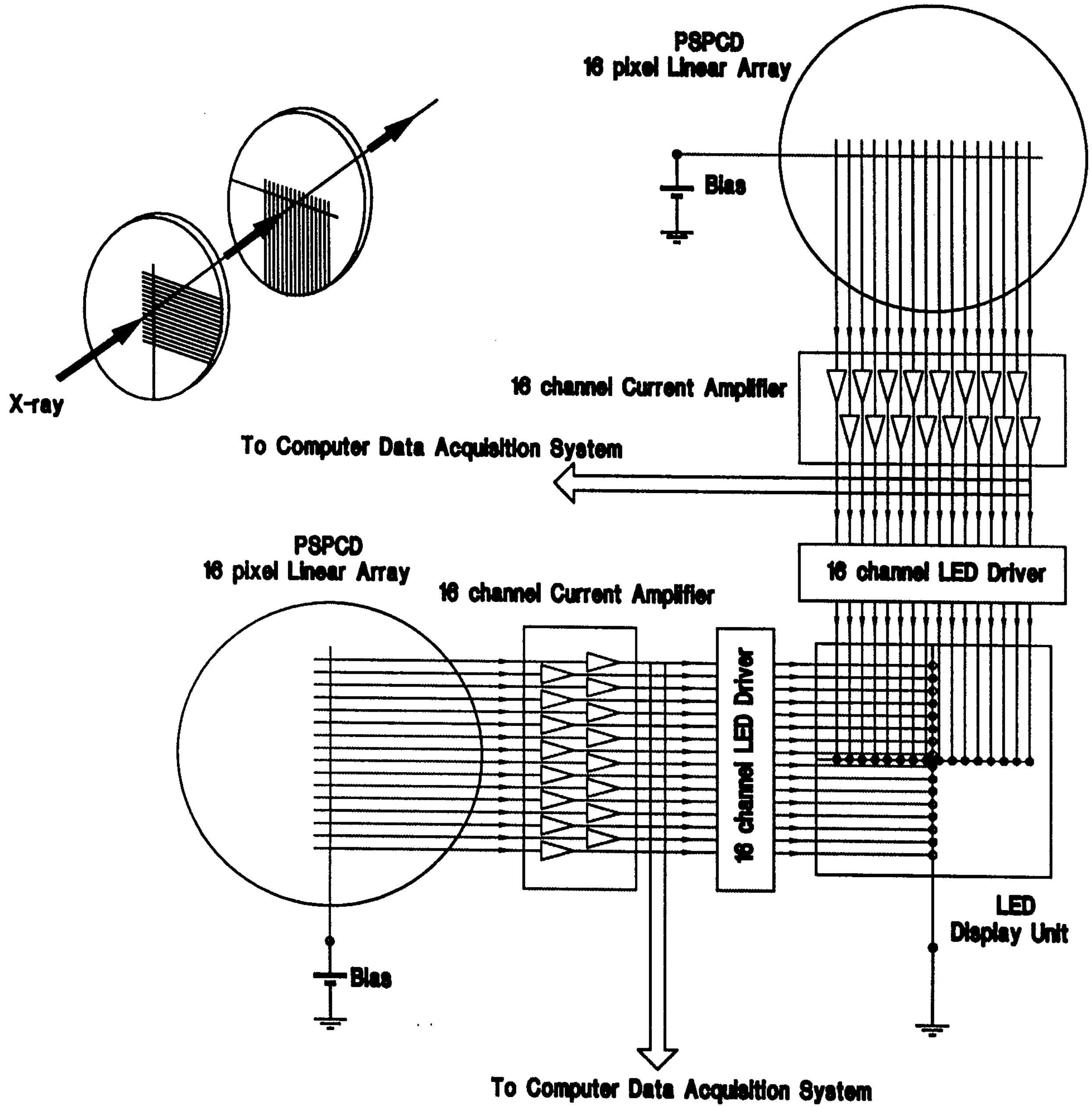
PSPCD
16 pixel Linear Array
Bias
X-ray
16 channel Current Amplifier
To Computer Data Acquisition System
16 channel LED Driver
PSPCD
16 pixel Linear Array
16 channel Current Amplifier
16 channel LED Driver
LED
Display Unit
Bias
To Computer Data Acquisition System

Fig. 4

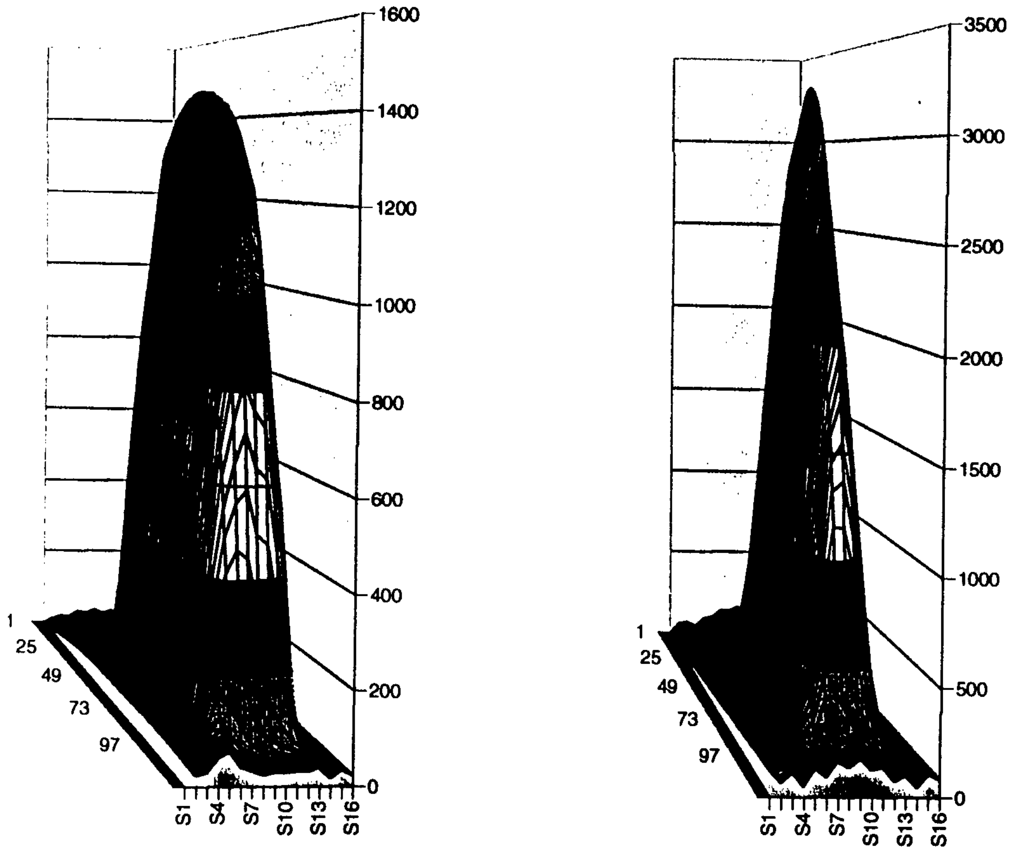
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Fig. 5

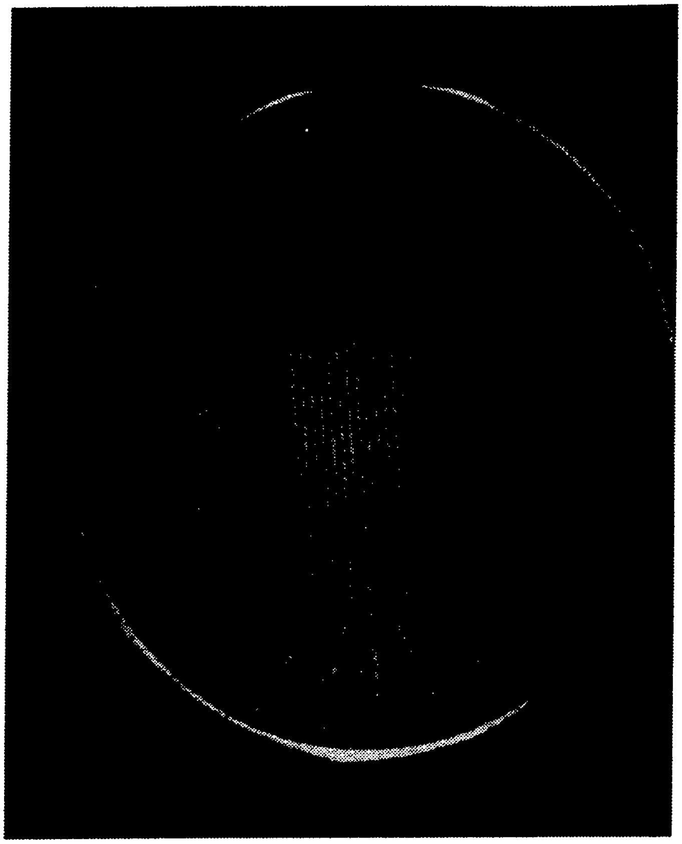

Fig. 6

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