Real-time Secondary Electron Emission Detector for High-rate X-ray Crystallography

R.Chechik¹⁾, A.Breskin¹⁾, I.Frumkin²⁾, A.Gabriel³⁾ and M.Kocsis⁴⁾

¹⁾The Weizmann Institute of Science, Rehovot 76100, Israel

²⁾Technion, Haifa 32000, Israel

³⁾European Molecular Biology Laboratory, Grenoble Outstation, 38042 Grenoble Cedex, France

⁴⁾European Synchrotron Radiation Facility, 38043 Grenoble Cedex, France

Abstract

We present first results of the application of a novel digital X-ray imaging detector, based on secondary electron emission from a solid converter, to high-rate crystallographic studies. Results from diffraction and small-angle scattering experiments from several crystallized proteins, performed at the European Synchrotron Radiation Facility, ESRF, Grenoble, are presented and discussed in comparison with a phosphor-based imaging system. Future developments of this detector system are proposed.

I. INTRODUCTION

Intense X-ray beams, particularly from Synchrotron Radiation sources, are currently used in modern biology for the study of complex macro-molecular structures. The principal techniques for such studies are crystallography and small-angle scattering. The method takes advantage of the intense and highly parallel X-ray beam, enabling the detection of minute flux from sites of very weak scattering and diffracting power, typical for such low-symmetry systems. The method involves the crystallization of the macro-molecular entities, under low temperature, and the detection of the scattered beam by a planar detector placed behind the sample. A common practice in protein crystallography is the so-called rotating crystal method, in which the unknown crystal specimen, irradiated by the monochromatic X-ray beam during its rotation, is occasionally fulfilling the Bragg condition and coherently reflecting the beam onto the two-dimensional detector. The non-negligible background generated by the crystal and integrated in the detector, requires the use of very small rotation steps (0.1 degree). Obviously this puts a strong demand on fast readout detectors, capable of withstanding very high radiation flux. Typically crystallography studies are performed with X-ray beams of 1-10 keV.

This application poses the following general demands [1] on the imaging X-ray detector:

- reliable operation under high incident flux, of the order of 10^6 photons/mm²s;
- localization resolution of about 100 μ m, with high linearity over surfaces of hundreds of square centimeters;
- a linear response over a large dynamic range, of at least 6 orders of magnitude.

It is also desirable to have detectors with sensitivity threshold as low as 1 photon/pixel. For most applications an image has to be generated within a few seconds and often a long sequence of images has to be accumulated over a short time scale. Some special applications which deal with dynamic or time-dependent structure evolution studies, require a very fast response of the detector.

X-ray imaging devices, currently used in the field of high-rate crystallography, are the phosphor imaging plate (IP) [2], the small-gap multi-wire proportional chamber [3], the phosphor screen / CCD [4] and the image intensifier / CCD [5] system. Other detectors under development which are potentially applicable in this field are, for example, gas microstrip chambers [6] and silicon micropad electrodes [7]. The phosphor imaging plate is not a real-time device. Its readout time is very slow (a few minutes) and it suffers from considerable spatial distortions, of mechanical and optical nature, which lead to large differences between recorded and predicted spots and require a complicated software treatment to correct for these distortions. Some limitations also exist in its dynamic range. The IP and devices based on CCD are integrating devices, which sometimes sets a limit on the signal/noise property and may also lead to dynamic range limitations. Gaseous detectors, operating in the single photon counting regime are large area devices, well suitable for dynamic studies; they have in principle very large dynamic range. However, the X-ray photon conversion in the gas medium renders these devices either too inefficient or too slow and leads to parallax problems, limiting their resolution.

We have proposed [8-11] a new type of secondary electron emission (SEE)-based X-ray imaging detector. Its operation is based on the conversion of radiation in a thin converter foil and the detection of the numerous surface-emitted low-energy (eV) electrons with a fast, low-pressure gaseous electron multiplier. The gaseous amplification process starts at the emission surface and provides high accuracy, parallax-free, localization of the X-ray conversion point, in a subnanosecond time-scale. The exponential nature of the gas amplification in the first parallel gap element and the low gas pressure operation are very important: they minimize the contribution to the signal due to direct gas ionization, emphasizing the signal due to the many slow electrons emitted from the foil surface per each converted photon. The operation principle is shown schematically in Fig. 1.

Figure 1. The operation principle of the SEE detector: X-ray photons, converted in a thin cathode foil, induce the emission of several secondary electrons, which are immediately multiplied in a low-density gas under the high electric field near the cathode.

The characteristic performance of the SEE-based X-ray detector are described in detail in our previous publications [8-11]. Most relevant for the application to high-rate crystallography with low-energy X-rays are the spatial resolution of $200\mu\text{m}$ FWHM and the good point spread function (PSF; $\text{FW10\%M} = 800\mu\text{m}$, $\text{FW1\%M} = 2.4\text{mm}$), the parallax-free imaging, the efficient operation at low X-ray energies and the high rate capability of $>1\text{ MHz/mm}^2$. Individual pulses can be resolved to within 1 ns, opening the possibility to carry out dynamic studies of very fast processes.

We describe here the results from a crystallographic test-study performed with an intense X-ray generator and with a Synchrotron Radiation Source at EMBL and ESRF, Grenoble. This new, third generation, Synchrotron provides extremely intense parallel beams over a wide energy range. In particular it opens the energy window of 2-4 keV, in which the so-called anomalous diffraction methods are established. The low-pressure operation (typically 20 Torr) of the SEE detector

is particularly suited to this low photon energy range, permitting the use of an evacuated beam line, and containing the detector gas by a very thin and highly transparent polymer foil.

II. EXPERIMENTAL SETUP

Crystallographic measurements were carried out at the European Molecular Biology Laboratory (EMBL, Grenoble) on a rotating anode X-ray generator (Siemens), where the detector replaced the routinely employed MarResearch IP system. Figure 2 presents the experimental layout and the geometry of the measurements.

Small-angle scattering measurements were performed at the ESRF, Grenoble. The detector was mounted at the *high brilliance beamline* (BL-4), delivering a collimated beam of 12 keV X-rays, with intensity of 10^{12} photons/sec. This beam intensity was compatible with the capability of the detector readout electronics, of about 2MHz. This application actually does not rely very strongly on the parallax-free property of the detector but is very demanding in terms of large dynamic range and operation under high flux.

Figure 2. Experimental layout.

An X-ray converter made of 200 nm thick Ag layer, vacuum deposited on a Mylar foil, was mounted in the detector, also acting as the cathode of the first parallel gap preamplification element (see figure 1). The detector was filled with 20 Torr of $i\text{-C}_4\text{H}_{10}$, in flow- or in sealed-mode, after a short evacuation. The second amplification element, of a multiwire proportional chamber structure, was equipped with a delay-line based readout electronics, permitting data acquisition rates of up to 2 MHz. It is based on a VXI C sized TDC [12] and a VME-based system containing the histogramming controller (VHIST) and a 256 Mbytes standard industrial memory [13]. Time resolved measurements are handled with a Time-Frame Generator used as a sequencer. A Multichannel Scaler card is used to perform various counts for data normalization. The data-acquisition hardware is controlled by a software system, fully integrated into the ESRF beamline control.

III. RESULTS AND DISCUSSION

Diffraction measurements were carried out using the X-ray generator, on several samples, including mineralogical (inorganic) and protein crystals.

Figure 3 (a) presents the raw crystallographic picture of a mineralogical (inorganic) crystal, taken with the SEE detector, obtained at a 2° rotation angle during 20 min. Figure 3(b) shows the same measurement repeated with the MarResearch IP system, which provides the image after sophisticated software corrections.

Figure 3. Raw diffraction picture of a mineralogical crystal obtained at 2° rotation with (a) the SEE detector and (b) the MarResearch IP system

The comparison gave the following results:

-crystallographic pictures provided by both systems are well correlated, although a difference in position of several peaks is seen. It should be noted that the symmetry axis of the crystallographic setup passes exactly through the middle of the IP system, while the SEE detector is somewhat shifted (the beam stop shadow appears on the upper part of its image).

-strong peaks on the picture obtained with the IP are followed by tails; such effects are not seen in the SEE detector data of figure 3 (a). The source of the tails could be optical defects of the IP system or the software image processing.

The signal-to-noise of the two systems is compared in figure 4. It is clear that the SEE detector data is dominated by statistical fluctuations while the IP data is characterized by a significant offset problem.

Figure 5 shows the crystallographic picture of the same specimen, obtained with the SEE detector at 10° rotation, during an hour. The intensity profile, at the cross-section indicated by an arrow in 5(a), is given in figure 5(b), demonstrating the two well-separated peaks, and the good PSF of the detector allowing such peak separation..

Figure 4. Intensity profile of the reflections indicated by an arrow in figure 3, obtained by the SEE detector (a) and by the IP system (b).

Figure 5. Raw diffraction pattern of a mineralogical crystal obtained with the SEE detector at 10° rotation (a) and the intensity profile at the section indicated by an arrow (b), showing peak separation.

Figure 6. Raw diffraction pattern of the protein mutant of *Seryl TRNA Synthetase* from *T. Thermophilis*, obtained with the SEE detector at 2° rotation during 1 hour.

Figure 6 shows a raw crystallographic image from the protein crystal of mutant of *Seryl TRNA Synthetase* from

T. Thermophilis, Space group: $C222_1$, unit cell: 92.6 131.5 170.4 90 90 90. The image was taken with 2° rotation during an hour. The figure shows diffraction corresponding to 2° rotation around the axis a , which is nearly parallel to the axis of oscillation and perpendicular to the X-ray beam. There is no broadening of the diffraction peaks at high resolution, e.g. there is no parallax effect. The observation of the peak profiles at high resolution (even at 170 Å interreticulate spacing) shows that the PSF of the detector is adequate for the protein crystallography.

Experiments carried out at the Synchrotron beam included the study of small angle scattering from *Lupolen* and from *collagen* prepared from a rat-tail.

Figure 7 is raw data small angle scattering from *Lupolen* obtained during 3 minutes, at a counting rate of 500 kHz.

Figure 8 is raw data small angle scattering from a sample of *Collagen* prepared from a rat-tail, obtained during 20 seconds at a counting rate of 850 kHz. The sample contains two *collagen* fibers crossed at a small angle. An intensity profile of a cross-section is given in figure 9, providing qualitative information for the analysis of this structured protein.

Figure 7. Small angle scattering from *lupolen*, measured with the SEE detector and with intense Synchrotron beam during 3 min, at 500 kHz.

IV. SUMMARY

The first test of the SEE-detector operation at EMBL and ESRF shows its potential applicability for static and time-resolved experiments in protein crystallography and other diffraction studies, involving intense radiation flux from the most powerful X-ray machines and Synchrotron Radiation Sources. The prospects of this detector as a substitute of non real time devices like Image Plates are under study. Equipped with a fast readout system, the SEE-detector proved its high rate capability, preserving its high performance features under fluxes exceeding 10^8 photons/sec distributed over area

of a few square millimeters. Images obtained with the Synchrotron Radiation Source during several tens of seconds are sufficiently informative, and clearly demonstrate the capability of the SEE detector concept in real-time crystallographic applications.

A new SEE detector is presently under construction at the ESRF for protein crystallography at low photon energies of 2-3 keV. However it is clear that the full potential of the high-rate capability of the detector cannot be exploited with the present, delay-line-based, data acquisition system.

Figure 8. Small angle scattering from *collagen* (rat tail) measured with the SEE detector and an intense Synchrotron beam, during 20 sec, at 850 kHz.

Figure 9. Image intensity profile in the horizontal cross section of the *collagen* small angle scattering pattern

We wish to thank Mr. M. Klin for his technical support. The research work was supported by the Foundation Mordoh Mijan de Salonique. A.Breskin is the W.P.Renther Professor of research in the peaceful use of atomic energy.

V. REFERENCES.

- [1] see for example the summary paper by A.H. Walenta in the Proceedings of the European Workshop on X-Ray Detectors for Synchrotron Radiation Sources, Aussois, France, 1991.(Ed: A.H.Walenta), University of Siegen, and other papers in this proceedings.
- [2] Molecular Dynamics, Sunnyvale, California USA or MarResearch, Hamburg, Germany
- [3] A.Lewis, N.S.Fore, C.Hall, W.Helsby, A.Jones, B.Parker, I.Sumner and J.S.Worgan, Nucl. Instrum. and Meth. A348 (1994),237.
- [4] I.Naday et al.,Nucl. Instrum. and Meth. A348 (1994)635.
- [5] J.P.Moy, Nucl. Instrum. and Meth. A348 (1994) 641
- [6] A.Oed, "properties of Microstrip Gas Chambers (MSGC) and Recent Developements", invited talk at the Vienna Wire Chamber Conference, February 1995.to be published in Nucl. Instrum. and Meth.
- [7] A.Czernak, P.Jalocha, A.Kjensmo, G.Malamud, E.Nygard, C.Ronnqvist, F.Santos, J.Straver and P.Weilhammer, Nucl. Instrum. and Meth. A360 (1995),290.
- [8] I.Frumkin, A.Breskin, R.Chechik, V.Elkind and A.Notea, Nucl. Instrum. and Meth.A329 (1993) 337.
- [9] I.Frumkin, A.Notea, A.Breskin, R.Chechik, L.Levinson, B.Weingarten and V Popov, NDT&E International,1994 Vol 27, pp 317.
- [10] A.Breskin, R.Chechik, A.Akerman, A.Gibrekhterman, V.Elkind, I.Frumkin and A.Notea, Nucl. Instrum and Meth. A348 (1994) 207.
- [11] A.Breskin, R.Chechik, A.Gibrekhterman, I.Frumkin, L.Levinson, A.Notea and B.Weingarten, Nucl. Instrum. and Meth. A353 (1994) 302.
- [12] A.Berry, Rev. Sci. Instr. Vol.64(1993)1222. and A.Berry, A.Gabriel, M.Kocsis and C.Riekel, Nucl. Instrum. and Meth. A348 (1994)334.
- [13] F.Sever, F.Epaud, F.Poncet, M.Grave and V.Ray-Bakaikoa, "Modular data acquisition system and its use in gas-filled detector readout at ESRF", presented at the SRI95 Conference on Advanced Photon Sources, Argonne National Laboratory,October 95. to be published in Rev. Sci. Instr.