Results about imaging with silicon strips for Angiography and Mammography

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Abstract.

We present results obtained with a single photon counting system consisting of 384 silicon microstrips of 100 micron pitch equipped with 6 RX64 ASICs. The ASIC includes a charge preamplifier, a shaper, a discriminator and a 20-bit counter for each of its 64 channels. The energy resolution of the system has been measured in the range from 8 keV to 32 keV using fluorescence X-ray lines from several targets, using either an Am-241 source or an X-ray tube. Then, the efficiency of the system has been determined using the specially developed quasi-monochromatic X-ray beams in the energy range 18-36 KeV. Good efficiency has been obtained in the edge-on configuration, which is more suitable for the intended applications. The spatial resolution of the system has been verified using a special microfocus X-ray tube equipped with capillaries. Finally, images of angiographic and mammographic test objects have been obtained with dual energy X-ray beams and have then been processed with the dual energy subtraction technique. In particular, the contrast for the angiographic test object has been evaluated for different concentrations of an iodate solution injected into 1 mm and 2 mm diameter vessels. Further developments, including a double threshold version of the ASIC, are also discussed.

INTRODUCTION

This paper reports about the design and the first X-ray imaging results obtained with a one-dimensional array of silicon strips. Such an array, consisting of microstrips with 100 μm pitch and 10 mm length, was chosen for the following reasons:

- a good spatial resolution can be obtained with a reduced number of channels;
- spatial resolution in silicon is Compton scattering limited in our energy range (18-40 keV), so reducing the pitch below 50-100 μm is not really useful.

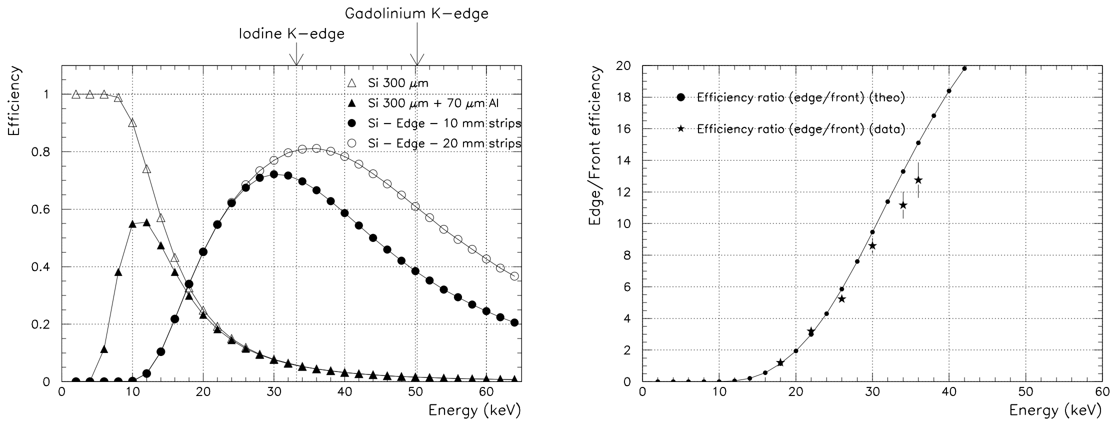

FIGURE 1. (Left) Photoelectric conversion efficiency vs. energy for silicon of 300 μm thickness with strips perpendicular (front) or parallel (edge) to the incoming beam. (Right) Ratio of edge to front configuration efficiency vs. energy: calculation (continuous line) and experimental data (stars). Cross-section data from the XCOM database of NIST at http://physics.nist.gov/PhysRefData.

In addition, some important advantages of a digital, single photon counting system for X-ray imaging have been considered: (i) a higher efficiency with respect to conventional screen-film systems can be obtained (to achieve this, at energies above 18 keV, edge-on orientation of the strips is necessary, see figure 1); (ii) digital processing, transfer and storage of images is more convenient; (iii) by implementing a double threshold scheme (see below) in the front-end electronics, double energy imaging with simultaneous exposure becomes possible.

In fact, the dual energy technique introduced by Alvarez and Macovski[1] (see also [2]) allows to isolate materials characterized by a different energy dependence of the linear attenuation coefficient. This technique can be implemented in a small-scale installation thanks to the development of quasi-monochromatic beams[3, 4, 5]. The applications foreseen for our detector are dual energy angiography at the iodine K-edge ($\approx$ 33 keV), and later at the gadolinium K-edge ($\approx$ 50 keV), and dual energy mammography.

The efficiency of 300 μm thick silicon in the usual “front” configuration is too low in the interesting energy range (see figure 1, left panel); for this reason we have adopted the so called “edge-on” configuration which, for a strip length of 10 mm and an inactive Si layer of 0.765 mm, gives a reasonable efficiency; this has been verified with quasi-monochromatic beams, as shown in figure 1, right panel.

THE DETECTOR AND THE RX64 ASIC

Our silicon microstrip detectors (0.1 mm pitch, 10 mm length) are AC-coupled ones with FOXFET biasing[1], featuring a low current of about 60 pA per strip at 100 V bias voltage, which is a key requirement for low noise performance. A picture of the corner

[1] They were designed and manufactured by ITC-IRST, Trento, Italy

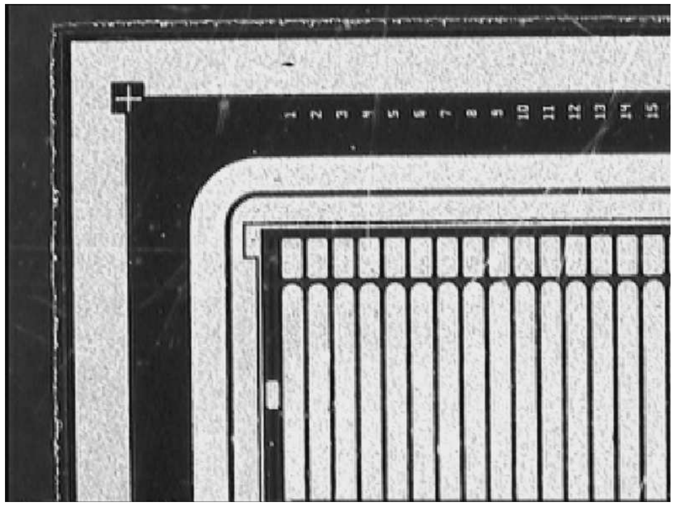

FIGURE 2. Picture of a corner of the microstrip detector.

FIGURE 3. Detail of the pitch adapter which connects the detector (top) to each of the 6 RX64 ASICs (bottom).

of one detector is shown in figure 2, where the bias line and the guard ring are visible around the strips.

The RX64 ASIC integrates 64 channels of front-end (preamplifier, shaper, discriminator) and 64 counters with 20 bit range, as well as several internal DACs. It can be controlled by a purely digital interface. Detail on the ASIC design and performance are given in [6, 7].

Results presented in the following have been obtained with two prototypes, the first one featuring 128 equipped channels (132 microstrip detector read by two ASICs), the second one featuring 384 equipped channels (400 microstrip detector read by six ASICs). For the second prototype, a pitch adapter was inserted in between detector and ASIC (see figure 3), in order to simplify the task of bonding strips to electronic channels and also to allow reworking of the assemblies.

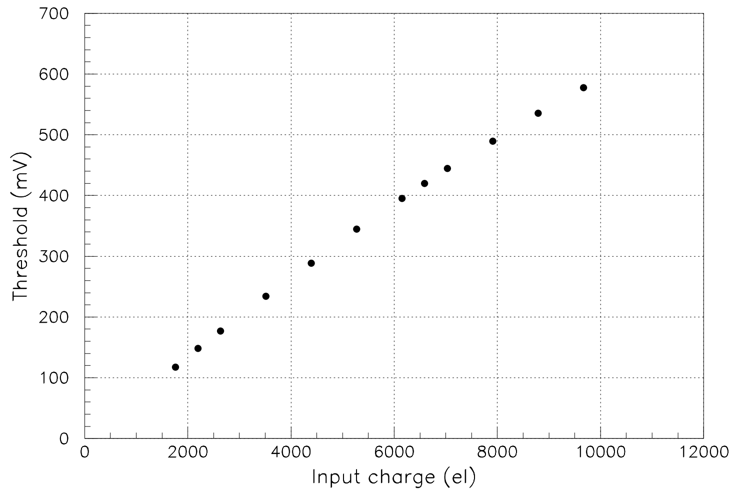

FIGURE 4. Correlation between injected test charge (electrons) and measured signal (mV).

ENERGY RESOLUTION

The performance of the two prototypes was tested with several methods, starting from internal calibration, which means injecting a known charge at the input of each electronic channel by means of a test capacitor (75 fF). Dealing with a digital system, the analog performance must be obtained via discriminator threshold scans. Figure 4 (a summary of 12 such scans) shows that the RX64 response is reasonably linear up to $\approx$ 8000 electrons (29 keV), after which some saturation is observed.

Further tests were performed by irradiating the prototypes with fluorescence X rays generated either by an americium source or by a Cu-anode X ray tube: a collection of spectra is shown in figure 5. They were used to establish the absolute energy calibration of the detector. The summary of gain and noise measurements is given in table 1, which refers to two different peaking time settings, corresponding to different gains as well. The best performance of the 384-channel prototype (last line of the table) is about 150 RMS electrons, corresponding to about 1.3 keV FWHM at 22 keV energy.

Very recently we have obtained first results on the analogue performance of the double threshold version of the RX64 ASIC (two discriminators per channel have been implemented), which indicates a moderate increase of the ENC (196 electrons) with respect to the standard ASIC; we believe that the increased noise is due to two sources: on one hand the increased temperature of ASIC and detector, due to a higher power dissipation, on the other hand the shorter shaping time. Peltier cooling is being considered in order to reduce the effects of the first source.

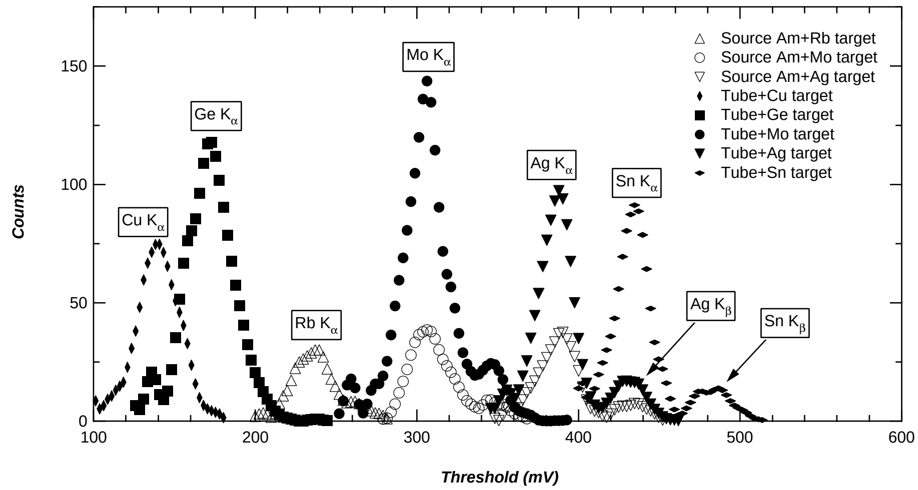

FIGURE 5. Energy spectra obtained with source or tube fluorescence setups, showing peaks ranging from 8 keV to 28 keV.

TABLE 1. Measured Gain and Noise (ENC = Equivalent Noise Charge) for several detector + ASIC configurations.

Module (P.A. = Picth Adapter)	**T(peak)***	**Gain μV/electron**	**ENC RMS electrons**
Detector + 2 x RX64	Short	61.6	131
6 x RX64	Short	63.7	176
6 x RX64	Long	82.8	131
6 x RX64 + P.A.	Short	63.7	184
6 x RX64 + P.A.	Long	82.8	148
Det. + P.A. + 6 x RX64†	Short	63.7	182
Det. + P.A. + 6 x RX64**	Short	63.7	151

* Short = 0.5 μs, Long = 1.0 μs
† standard preamplifi er setting
** optimized preamplifi er setting

SPATIAL RESOLUTION

Preliminary measurements were taken with a capillary output microbeam [8] at the Antwerp's University Micro and Trace Analysis Center (MiTAC). The microbeam has an RMS of about 28 μm (see fi gure 6), as deduced from a fluorescence measurement on a Ni-Cr wire. Beam profi les taken with our silicon detector indicate a good correlation between the known beam position and the beam centroid obtained by the detector (see fi gure 7). The maximum deviation from the straight line is ± 0.12 strips, corresponding to 12μm.

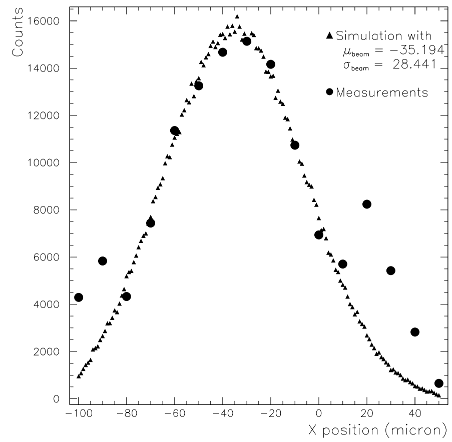

FIGURE 6. Position scan of the X-ray microbeam obtained by counting fluorescence photons from a Ni-Cr wire (big circles). Also shown is a simulation used to extract the beam size (small triangles).

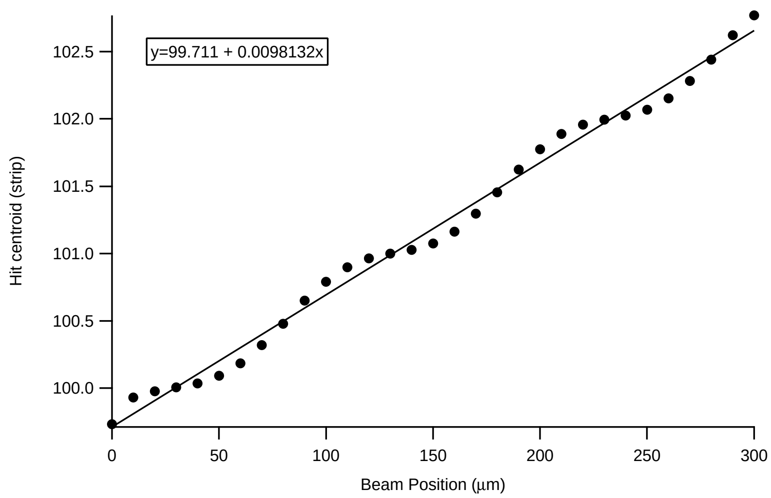

FIGURE 7. Correlation between centroid measured by microstrip detector (in strip units) and real beam position (in μm).

MAMMOGRAPHIC IMAGING TEST

The 384-channel prototype has been used for a test on the dual energy quasi-monochromatic beams at the University of Ferrara. For this test, a mammographic phantom consisting of a PMMA block with 6 mm diameter cylindrical inclusions of polyethylene and water (for more details see [9]) has been placed between the beam and the linear silicon detector. Images have been collected separately at low (18 keV) and high (36 keV) energies, since the double threshold ASIC was not yet available. A projection algorithm [2, 9] has been implemented in order to find the projection angle which makes the contrast between two chosen materials to vanish, as shown in figure

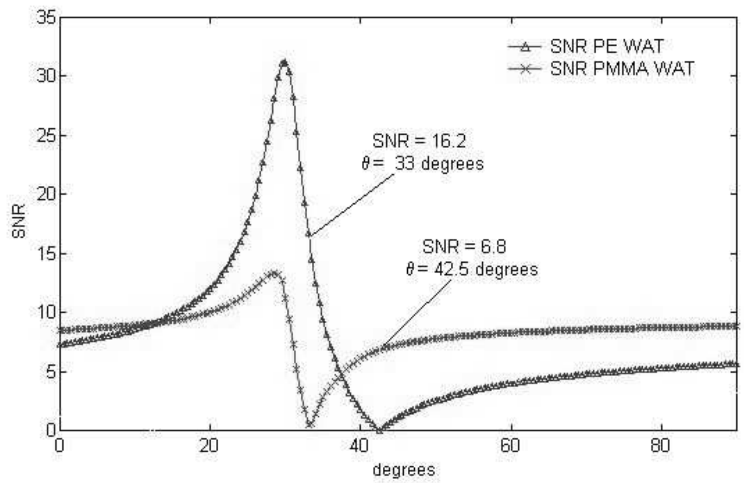

FIGURE 8. Signal-to-noise ratio vs. projection angle for the pairs of materials PE-water (triangles) and PMMA-water (crosses), obtained with the mammographic phantom.

8. Thanks to the good signal-to-noise ratio at 33 degrees (where the contrast between PMMA and water vanishes), the polyethylene pattern is well visible in the combined image, shown in figure 9 (right panel).

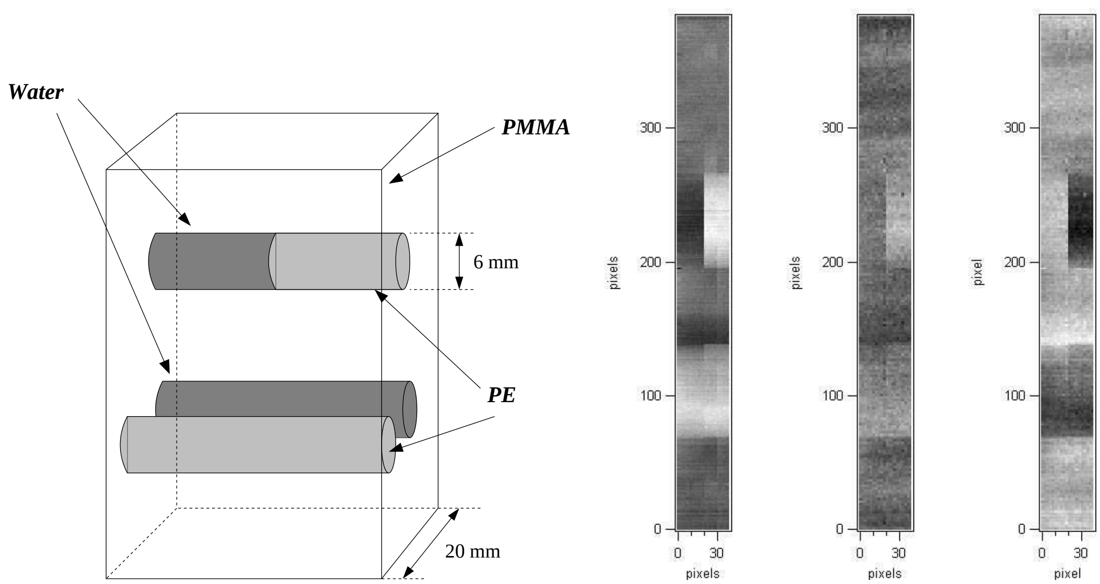

FIGURE 9. Slice of the mammographic phantom (extreme left), image at low energy (left) and at high energy (right); combined image at 33 degrees projection angle (extreme right).

ANGIOGRAPHIC IMAGING TEST

A dedicated fixed energy angiographic beam line based on the quasi-monochromatic beams [5] has been installed at the Bologna University. We have performed a test with our 384-channel prototype and an angiographic phantom (see figure 10) containing four small tubes (1 or 2 mm diameter) filled with an iodate solution at various concentrations.

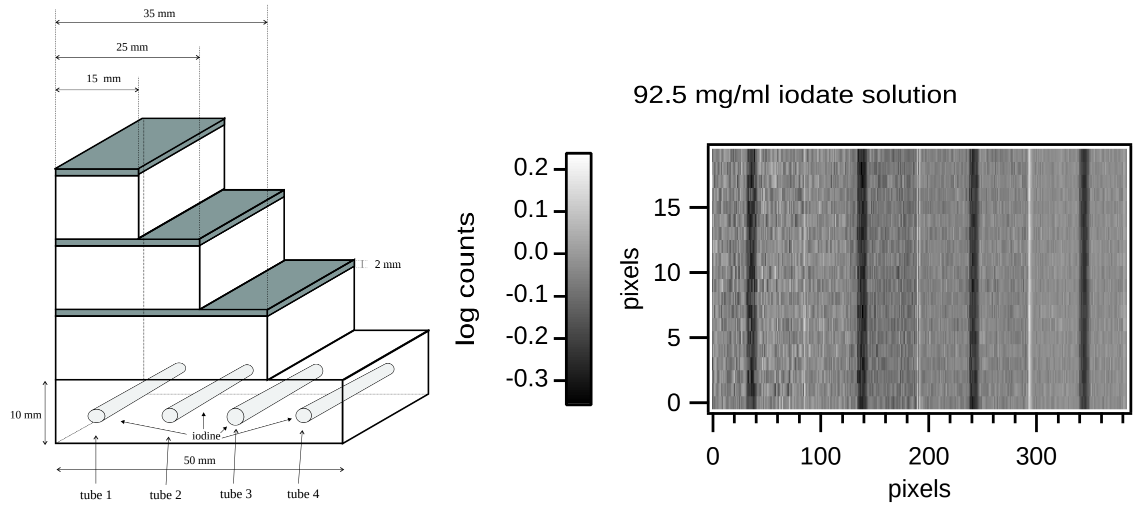

FIGURE 10. (Left) The angiographic phantom. Four steps of PMMA and three layers of aluminium provide the background structure, while 4 tubes in the lower part can be filled with the iodate solution. (Right) Logarithmically subtracted image of the angiographic phantom for 1 mm tubes at 92.5 mg/ml concentration.

One of the images obtained off-line by logarithmic subtraction between a high energy (35.5 keV) and a low energy (31.5 keV) image is presented in figure 10, for a concentration of 92.5 mg/ml, which represents 1/4 of the standard concentration presently used in clinical practice. The background structures present in the phantom are effectively removed by this procedure. A summary of the signal-to-noise ratios obtained with 1 mm diameter tubes is shown in figure 11 as a function of the iodate concentration, toghether with a theoretical calculation based on the structure of the phantom. The noise contrast was evaluated over one pixel only. Usable values of the SNR are achieved down to 92.5 mg/ml concentration, and in some cases even for 46.25 mg/ml.

SUMMARY AND OUTLOOK

We have developed a relatively simple linear X-ray detector for scanning mode radiography, based on a 100 μm pitch silicon microstrip detector and on the RX64 ASIC. Prototypes with 128 and 384 strips of 10 mm length have been built and tested with internal calibration, fluorescence X-rays and quasi-monochromatic beams in the energy range from 8 to 36 keV. The obtained energy resolution (about 150 rms electrons, i.e. 1.3 keV FWHM at the Ag K_α peak at 22.1 keV) is well adapted to the energy spread of the presently available quasi-monochromatic beams. The efficiency for photoelectric conversion in edge mode with 10 mm active silicon (preceded by about 0.8 mm inac-

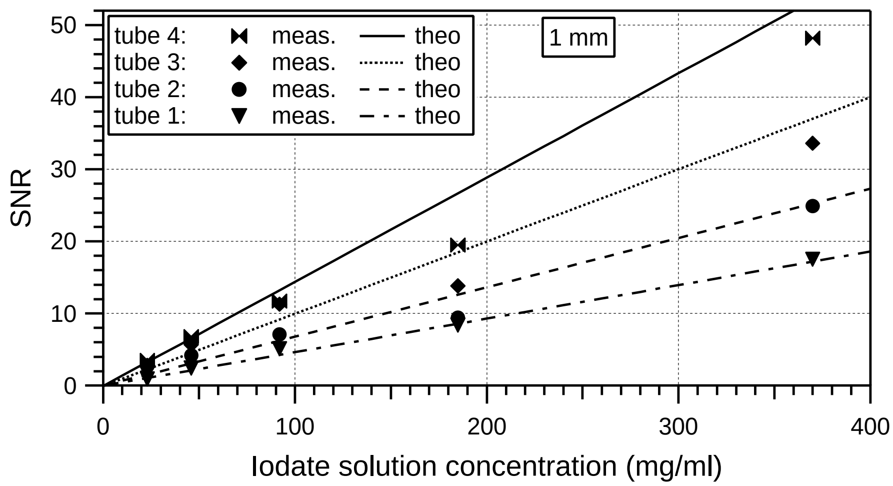

FIGURE 11. Measured (points) and calculated (lines) SNR values for the angiographic phantom vs. iodate concentration, for 1 mm diameter tubes.

tive silicon) is sufficient to perform double energy mammography (for example at 18 and 36 keV) and double energy angiography at the iodine K-edge. Recent preliminary imaging results with a mammographic phantom consisting of PMMA, PE and water indicate that contrast cancellation between PMMA and water can be obtained by the projection method, keeping a signal-to-noise ratio of 16 for polyethylene. Imaging tests with an angiographic phantom containing 1 mm tubes indicate that it is possible to obtain good contrast at iodate concentrations well below the current clinical practice one of 370 mg/ml. The first results on the performance of the double threshold version of the RX64 ASIC show that the Equivalent Noise Charge is only 30% higher than the one obtained with the standard ASIC, in spite of the increased complexity and level of digital noise inside the ASIC. Future developments will include the following points:

- implementing larger detectors to match the image size required in the clinical applications;
- measuring the DQE and MTF of the system using the capillary output X-ray beam at MiTAC, Antwerp University;
- implementing synchronization of X-ray counting with the diastolic phase of the hearth cycle for coronary angiography;
- considering the possibilities for angiography at the gadolinium K-edge at 50 KeV;
- building a full-size mammography detector with the double threshold version of the RX64.

Extensive MonteCarlo simulations of the different setups are under way (see e.g. [10]) in order to better understand present results and to plan future versions of the system.

ACKNOWLEDGMENTS

We are grateful to B. Pini for help with assembly of detectors and ASICs, to E. Filoni for the layout of the pitch adapter and to F. Rotondo for help with cabling. R. Wheadon gave us precious assistance in setting up the automated bonding procedure. This work was supported by the Ministero dell'Università e Ricerca Scientifica e Tecnologica (MURST) of Italy under contract N. COFIN-2000-MM02095297-003, and partially supported by the Polish State Committee for Scientific Research.

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