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PORTABLE X–RAY CT MINI SYSTEM BASED ON MONOLITHITIC SEMI-INSULATING GAAS DETECTORS USING PERSPECTIVE IMAGING RECONSTRUCTION TECHNIQUES

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Abstract – The work describes the present status of development of the portable X–ray CT mini system. The system is capable to operate also as a quantum digital X–ray scanner. Detection unit is constructed from double line of 2×1024 SI GaAs pixel detectors with pitch of 250 µm. The system allows operation in the single photon counting regime and the energy separation (one energy window) with estimated spatial resolution higher than 125 µm. Developed modification of the X–ray image reconstruction based on perspective imaging techniques has been experimentally verified on testing phantoms and practically implemented for processing images of real test objects.

Keywords: X–ray imaging, single photon counting detector, image reconstruction

1. INTRODUCTION

X–ray computer tomography (X–CT) is a non–destructive testing method able to evaluate the inner structure of investigated objects [1, 2]. The cross–sectional imaging is achieved by the mathematical reconstruction of projections of a tested object [3]. Such a projection is an intensity image of transmitted X–ray photons through the evaluated object.

Small CT imaging instruments for the evaluation of small animals have been developed preferably for operation in the photon emission mode (PET). Almost all commercial CT systems use photodiodes as detectors that are covered by a scintillator [4].

This paper reports on the development of a portable quantum X–CT mini–system (XCTMS) which utilizes a monolithic semi–insulating (SI) GaAs double array of pixel detectors. The equipment is described and discussed below, including its mechanical parts, X–ray source and detection system.

2. IMAGE RECONSTRUCTION THEORY

The problem of reconstructing a function from its projections was introduced by Radon in 1917. Prototype of the first X–CT head was built by Hounsfiels. In 1979 he received the Nobel Prize for this together with Cormac who independently performed theoretical calculations into applications.

The Radon function computes projections of an image matrix along specified direction [2]. Projection of two–dimensional (2D) function $f(x,y)$ is a set of line integrals. In general, Radon transform of $f(x,y)$ along angle θ is line integral of $f(x,y)$ parallel to y' axis

$$R_\theta(x') = \int_{-\infty}^{\infty} f(x'\cos\theta - y'\sin\theta, x'\sin\theta + y'\cos\theta)\,dy' \quad (1)$$

where $\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$.

Geometry of Radon transform is illustrated in Fig. 1. 2D dependence of $R\ (\theta,x)$ is also called a sinogram because points are transformed to sine waves. In our case, we have the opposite situation, where we look for $f(x,y)$ function (or slice of testing object) from a known or measured sinogram.

The projection–slice theorem in two dimensions tells that Fourier transform of the projection of a 2D function $f(x,y)$ onto a line is equal to a slice through the origin of 2D Fourier transform of that function which is parallel to the

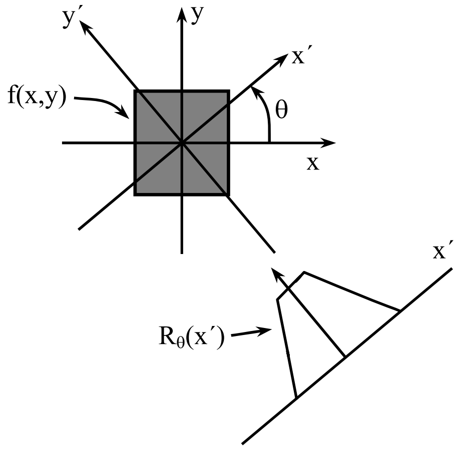

Fig. 1. Geometry of Radon transform.

projection line. This can be described by the following operator formula

$$F_1 P_1 = S_1 F_2 , \qquad (2)$$

where F_1 and F_2 are the 1D and 2D Fourier transform operators, P_1 is the projection, which projects a 2D function onto a line and S_1 is a slice operator, which extracts a 1D central slice from a function. This means that if we had an infinite number of 1D projections of an object taken at an infinite number of angles we could perfectly reconstruct the original object. It is possible to find an explicit formula for the inverse Radon transform. However, the inverse Radon transform shows instabilities for noisy data. For this reason a stabilized and discrete version known as the filtered back projection algorithm is used. Filtered back projection can be expressed by the equation

$$f(x,y) = \int_0^{\pi} q(x\cos\theta + y\sin\theta, \theta)\, d\theta, \qquad (3)$$

where q is a 2D function of filtered projections. Ram–Lak and Shepp-Logan filters are commonly used in X–CT algorithms. Nevertheless filtered back projection needs many projections (several hundred or more) to obtain a correct image because of many effects coming into X–ray sinogram such as fluorescence, X–ray scattering, beam hardening, phase effects, etc. Perspective approach uses an iterative scheme of tomographic reconstruction. Its advantage is that we can get a good image even from noisy data and low number of projections [3].

3. DESCRIPTION OF THE CONSTRUCTED PORTABLE XCTMS DEVICE

Construction of the XCTMS device is based on the approach where an evaluated object is located between the X–ray source and the detection unit. One of the stepper motors ensures a full rotation of the X–ray source & detection unit coupled system around the object (see Fig. 2). The other stepper allows for its linear positioning along the z direction. As a fan–beam configuration (diverging beam) is used, the micro–adjustable slit ensures that the width of the X–ray beam is little wider than the detector double array width and irradiates only the active area of the pixel detectors.

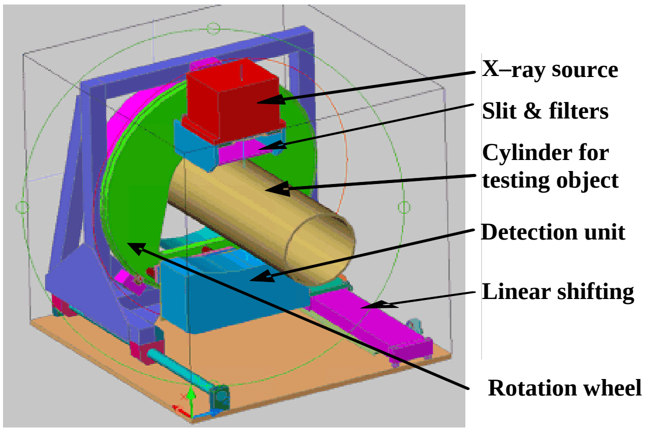

Fig. 2. 3-D visualization of the portable XCTMS device.

The X–ray source (Source–Ray Inc.: Model SB–80–500) with a tungsten anode operates in an accelerating voltage range of 35–80 kV at a maximum current of 500 μA with a maximum focal spot size smaller than 46 μm at a maximum power of 40 W [6]. X–rays generated by the source pass through two filters, selectable from 2×8 positions in two rotatable carousels, followed by a micro–adjustable slit, which restricts the width of the cone (into which X–ray photons are emitted) into a narrow, almost one–dimensional beam.

The detection unit consists of 16 input mini–modules, each with 2×64 monolithic SI GaAs pixel detectors with a pitch of 250 μm arranged along two lines on the chip and assembled into an arc. The detection double array incorporates 2×1024 pixels over a total length of 261.5 mm. A small gap, corresponding to 1.5 pixels, is maintained between each two neighbouring modules to prevent the outer pixels from damage. Fig. 4a shows the construction of the input mini–module. It consists of the chip with the pixel detectors based on SI GaAs with a thickness of 250 μm (Fig. 4b).

The total length of the double array on the chip is 16.25 mm. The operational bias of the SI GaAs detectors is ranged between 150 and 300 V. The pixel detectors are dc–coupled to the inputs of two ASICs–type DX64 readout chips [7], by wire bonding via pitch adapters, which adjust the pitch of the pixel detectors to the input pads of the ASICs. The readout chips have two discrimination levels and 20–bit counters for each channel; hence one energy window is available within one evaluation scan. The devices are glued and wire–bonded onto an input PCB (printed circuit board) with dimensions of about 16 mm × 120 mm. The PCBs are fixed onto Peltier coolers which stabilize the working temperature of the detectors and the input electronic circuitry at about 15° C using a thick Cu holder.

The measurement of the performance of the SI GaAs detectors using ASIC DX64 readout chips was performed. For the measurement eight detectors with four different diameters of the Schottky contact were used [8]. The measured reverse I–V characteristics of all detectors at RT are depicted in Fig. 3. The breakdown voltage increases with the decreasing of the detector area while the reverse saturation current is reduced from 30 nA (0.75 mm contact) down to 5 nA (0.20 mm contact) at operating reverse bias voltage of 220 V.

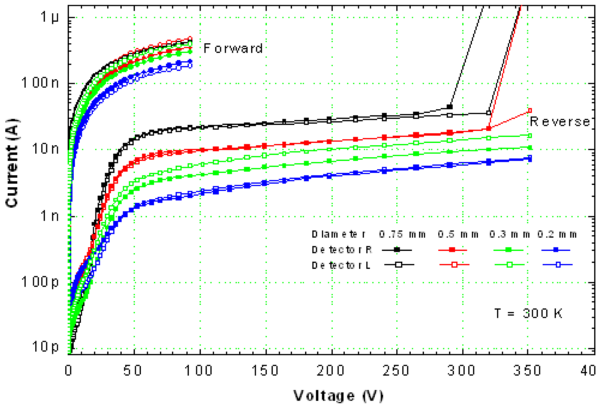

Fig. 3. Current–voltage characteristics of fabricated detectors.

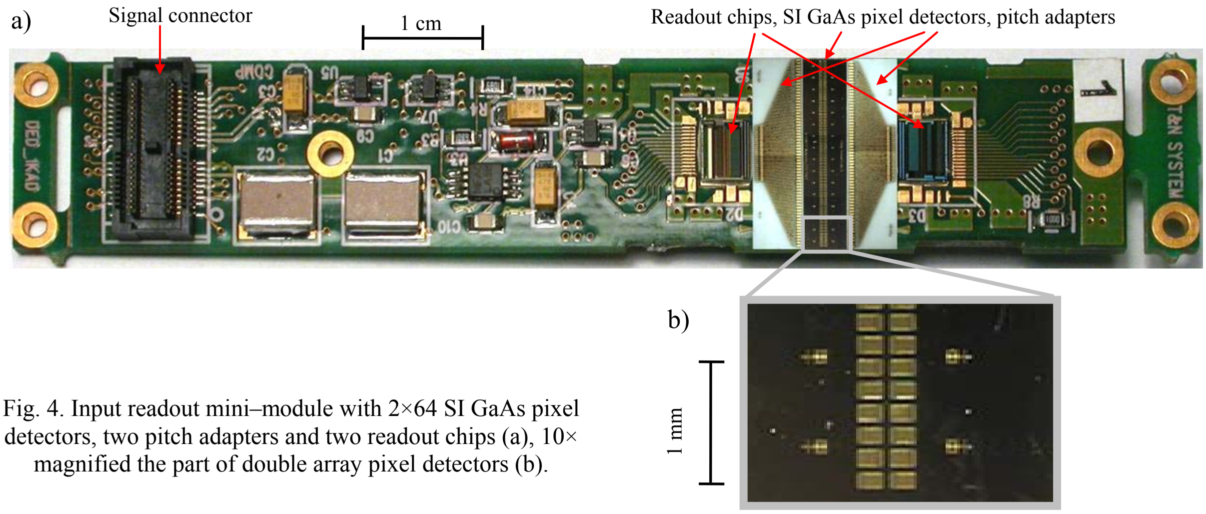

Fig. 4. Input readout mini–module with 2×64 SI GaAs pixel detectors, two pitch adapters and two readout chips (a), 10× magnified the part of double array pixel detectors (b).

4. EXPERIMENTS WITH IMAGE RECONSTRUCTION

To provide good X–ray images some imperfections must be eliminated. The imperfections follow from physical properties of used devices and the applied scanning technique. The basic scanning and image reconstruction process used in our experiments can be divided to four steps:

1. Finding the optimal settings of X–ray source and scanner operating parameters.
2. Performing the scans of a tested sample with a set number of projections (given by selected rotation step angle and chosen x – axis slide position).
3. Collecting data of performed scans including the pre-processing operations.
4. Image reconstruction from obtained object projections.

Prior to the experiment, the first scan without the tested object must be performed. This scan contains information about actual background (in virtue of sensitivity of the X–ray detector) and these data are applied for building of the correction matrix. The correction matrix is subsequently applied to all succeeding scans with the tested object.

To observe a possible inaccuracy of the sample position, the testing phantom can be used. In our case, the placement of inserted metal pins in the testing phantom (one in the middle, second by the border of the plastic tube with the maximum diameter) was chosen. These features can be covered by indirect method, for example by the sinogram of the tested object calculated as (1). When the sample position and rotation is correct, the sinogram obtains a direct line located at the medium (derived by inserted middle pin) and pure sinus curve (derived by the border pin). From the sinogram in Fig. 5 it is evident, that this condition is not fulfilled. Therefore, some correction curve for linearization and rotation of the data matrix must be applied.

The used type of SI GaAs detector generates the frequency noise, which also depends on the temperature. The high frequency component of this noise brings a "background" texture of the reconstructed object. For that reason, the low–pas (LP) filtration on the slices of a projection data matrix can be performed. On the other hand, the filtration produces the blur edge effect. Therefore, the parameters of the designed low–pas filter must be set as a compromise between the two mentioned antagonistic requirements (see Fig. 6).

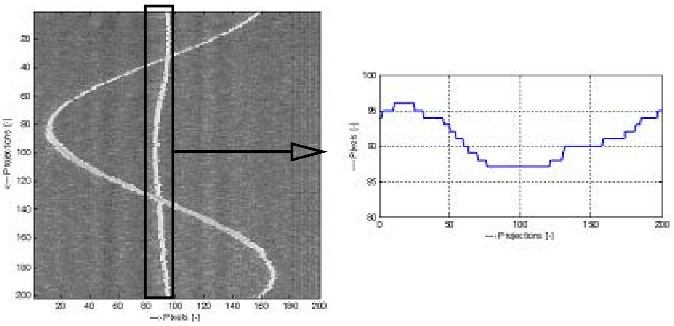

Fig. 5. Sinogram of testing phantom of 200 projections per 1.8 deg angle with dimension of 200 pixels (left), derived correction curve (right).

Algorithms for image reconstruction were written in C++ language as a console application. Parameters that could be passed to the algorithm are related to the geometry used (e.g. inter-detector distance, source-to-detector distance, source–to-object-center, angle of fan, number of projections and samples). To obtain the projection data, 200 projections and depth of 200 samples were used. Source-to-detector distance was 600 mm; source-to-object-center was 100 mm.

The tested objects were placed in the maximum distance from the X–ray source and near upon the scanner. Therefore, emitted beams can be considered as parallel and the image reconstruction method based on parallel beam can be used (that is characterized by a lower computing complexity than the fan beam method). Finally, for comparison, the fan beam reconstruction method was also applied – see Fig. 7.

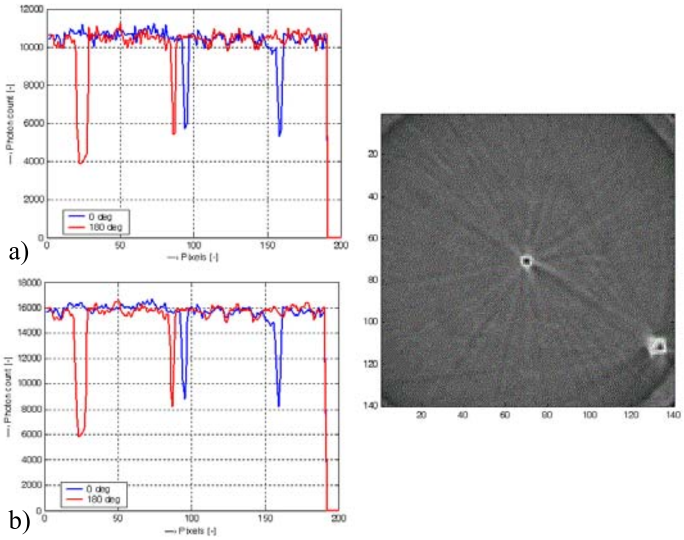

Fig. 6. Demonstration of LP filtration - $H_{LP}(z) = 1/(1 + 0.89\, z^{-1})$: original projections of 0 and 180 deg angle on the cut position of 289 (a), projections after application of the LP filter (b), resulting reconstructed image with LP filtering (right).

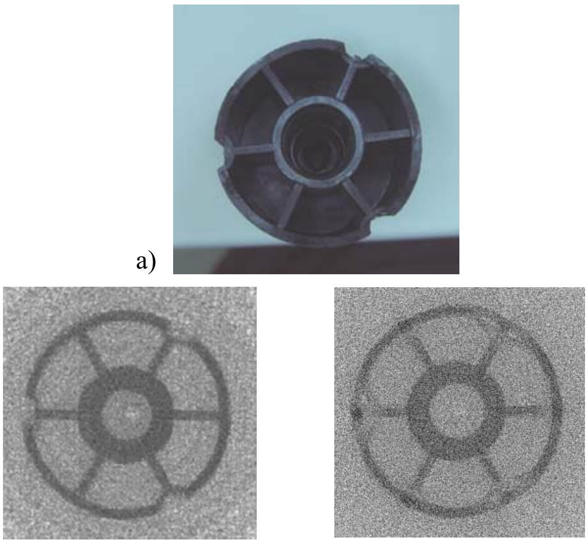

Fig. 7. Image reconstruction of the testing object: photography of the plastic tube with six capsules, diameter 40 mm (a), finally reconstructed image by the parallel beam method – 100 projections per 3.6 deg (b), reconstructed image by the fan beam method (c).

5. CONCLUSIONS

We have been developing a portable quantum X–CT mini–system based on monolithic GaAs radiation imaging detectors. The system is able to operate as an X–ray scanner or X–CT equipment with fixed objects up to a diameter of 180 mm and 250 mm in length. The detection part consists of a double array of 2×1024 SI GaAs detectors with a pitch of 250 μm. Two discrimination levels of the readout chip enable the energy selection of incident photons. The detection unit is currently close to being completed.

A high–power personal computer ensures the data collection and processing (filtered back projection or iterative reconstruction). The expected spatial resolution of the device is 125 μm. The readout time for acquiring a projection at the full length is about 6 hours for a standard 0.325 mm pace.

Developed modification of the X–ray image reconstruction based on perspective imaging techniques was experimentally verified on testing phantoms and also practically implemented for processing images of real test objects. The basic reconstruction algorithm was supplemented with modifications to eliminate some imperfections following from physical properties of used X–ray detector and applied scanning technique.

As a fan–beam configuration (diverging beam) is used, the maximum diameter of an object that can be evaluated is 180 mm. The micro–adjustable slit ensures that the width of the X–ray beam is little wider than the detector double array width and irradiates only the active area of the pixel detectors. The radiation dose for object evaluation is low. The device can also be used to examine living objects (small animals or parts of the human body, including hand or leg).

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