ACTIVE PIXEL SENSOR AS DOSIMETRIC DEVICE FOR INTERVENTIONAL RADIOLOGY

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Interventional Radiology

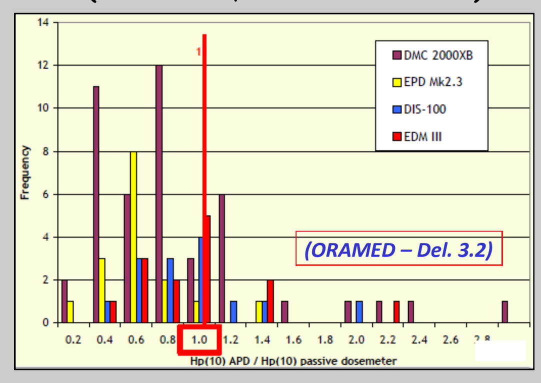
Interventional Radiology (IR) is a subspecialty of radiology comprehensive of all minimally invasive diagnostic and therapeutic procedures performed using radiological devices to obtain image guidance.

The interventional procedures are potentially harmful for interventional radiologists and medical staff due to the X-ray scattering by the patient's body. The characteristic energy range of the diffused photons spans few tens of keV.

Individual operators safety is very important and is performed via effective dose (whole body) and equivalent dose (hands, arms, legs, lens and thyroid) monitoring. The dosimeters used are usually passive dosimeters (TLD), read out at fixed time intervals, i.e. once a month, with a limited sensitivity toward the lower part of the scattered photon spectrum.

The concept of a real-time dosimeter capable of measuring dose and dose rate during a single procedure has been developed in the past years by several vendors.
However all of devices show some problems, either from the wearability point of view (cables, bulkiness, weight) than from the performance point of view, as for example summarized in the recent ORAMED 2011 Conference (Barcelona, 20-22 Jan. 2011).

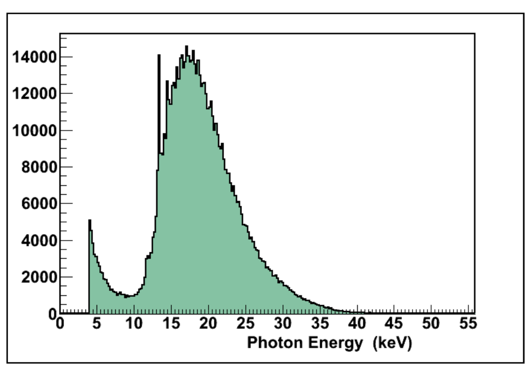
Active Dosimeters



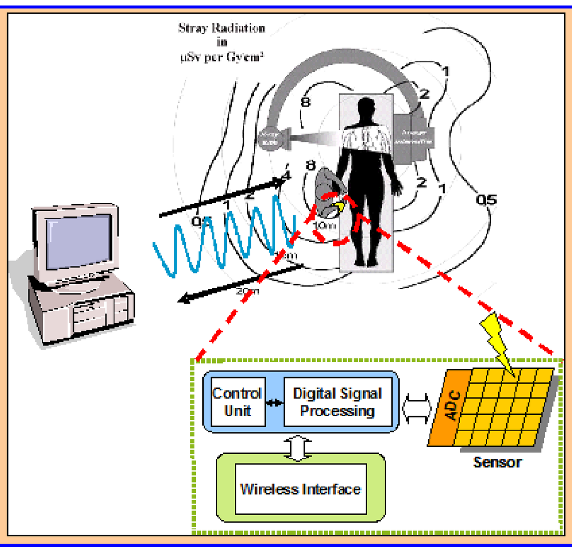
The peculiar working conditions of IR procedures (low photon energy, frequent switching between pulsed and continuous mode) make it difficult for the analized active dosimeters to closely follow the dose rate. The ratio of the response, at various working conditions, among several active dosimeters and TLD (chosen as reference) is shown in the left picture. Important deviations from unity are observed.

RAPID Project

The INFN RAPID Project (Real-time Active Pixel Dosimeter) [1] aims to develop a wearable personal dosimeter to be used during the IR procedures completely wireless.



- The main requirements are:
- sensitivity from 5 to several tens of keV photons (see right picture: diffused X-ray spectrum for a typical IR procedure);
- small form factor and low mass for the device, to have a good wearability (wristband or headband);
- dose and dose rate measurement accuracy better than 10% (in the 5% range);
- wireless device, both from the powering and the data transmission point of view.

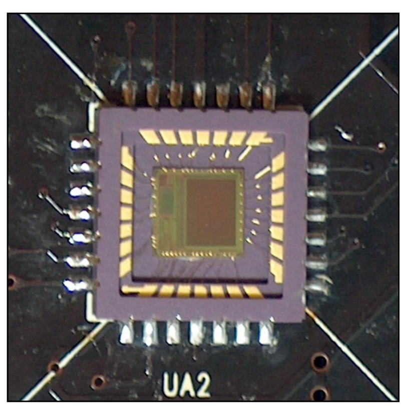


The proposed prototype architecture (left picture) relies on the following components:

- an X-ray sensor using an Active Pixel Sensor (APS) architecture;
- a digital signal processing unit;
- a control unit;
- a wireless interface;
- an external PC to control all the system and to record the transmitted data.

CMOS Active Pixel Sensors

In recent years APS, commonly exploited for imaging applications, have been proposed for detecting single ionizing particle, such as minimum ionizing particles in high-energy physics applications or X-ray as an alternative to customary architectures based on microstrips or hybrid pixel arrays.



In APS schemes, each pixel includes a few control devices (usually, MOSFETs), which take care of photodiode buffering, precharge and reset.
This system potentially improves the signal-to-noise ratio (S/N) and thus makes the adoption of dedicated fabrication technologies (e.g., high-resistivity or epitaxial substrates) unnecessary.

CMOS image sensors (see photo) have been studied as X-ray detectors showing reasonable efficiency for photon energies up to several tens of keV, despite the small sensitive volume.The high spatial segmentation of CMOS APS sensors (e.g., 640 x 480 pixels for sensor complying with Video Graphics Array standard) allows to measure high photon fluxes (up to 100.000 photons/mm^2/s) with small statistical uncertainty (~1%),

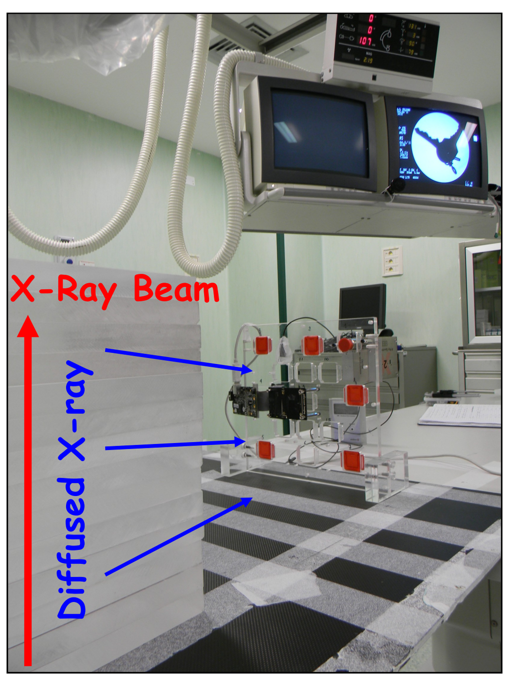
Another characteristic of CMOS image sensors is the direct sensitivity to low energy photons (down to 1 keV without entrance window material), considerably lower than the commercially available dosimeters (featuring a lower limit around 15-20 keV).

In addition, by relying on a fully standard CMOS technology, a complete radiation sensor system, including sensitive device as well as read-out, signal processing and data transmission sections, can be implemented in a single chip, allowing for a true System-On-Chip solution for the dosimeter in the RAPID Project framework.

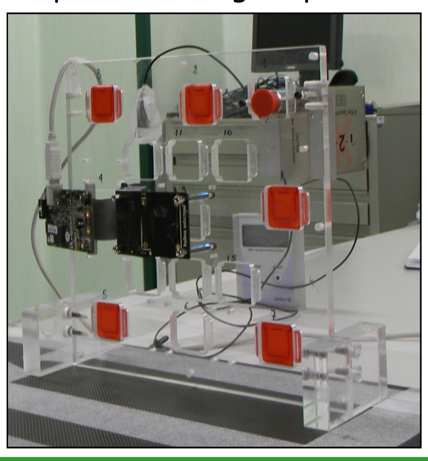
We have tested 3 different sensors, whose main characteristics are summarized in the table:

Sensor Name	Sensor Type	Pixel Size (µm)	Matrix dimension
Sensor A	Non-epitaxial	10.0	256x256
Sensor B	Epitaxial	5.6	640x480
Sensor C	Epitaxial	3.2	2048x1536

Experimental Setup



A phantom made of 30x30x3 cm^3 PMMA slabs was used to diffuse the X-ray photons from a Toshiba Infinix VC-i or a Toshiba Infinix CS-i interventional angiography systems.
Because X-ray tube parameters during Interventional Radiology may vary, due either to the protocol than to the patient-specific case, and because the voltage value (ranging from 60 to 110 kV) is important to fix the energy spectrum of the diffused photons, many settings have been used to test the response of the sensors.
The sensors are fixed in a plastic holder hosting also an Amptek X-123 precision spectrometer, a Unfors EDD-30 active dosimeter and 5 TLD for passive dosimetry. The holder was placed at different distances from the phantom (0 to ~ 100 cm), the typical range of medical staff distances from the patient during IR procedures.

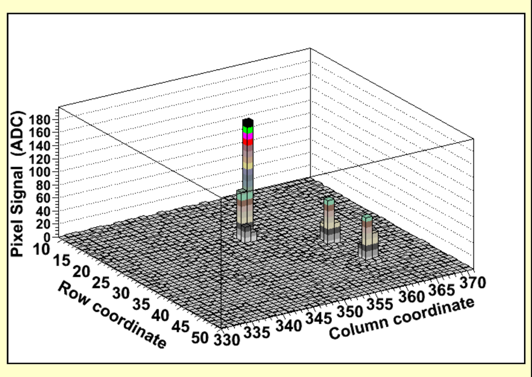


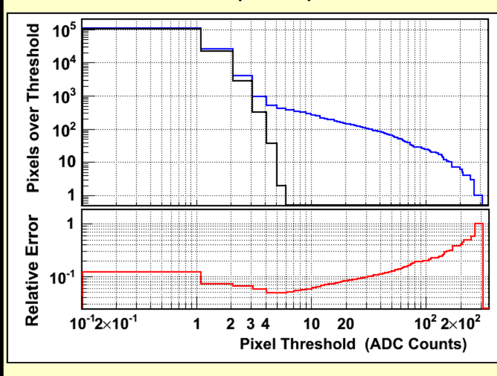
Several hundred frames with X-ray beam on were recorded at each distance, in order to obtain data samples with small statistical error. A complete set of pixel pedestal and noise has been acquired in the absence of X-ray beam at each distance.
The TLDs have been used to evaluate for each irradiation session the dose at the sensor position.
The EDD-30 has been used to give an independent dose measurement.

Analysis

Photon Finding Algorithm

Interacting photons produce signal in a small cluster of adjacent pixels (see right picture). The photon finding algorithm localizes all clusters, whose central pixel has a signal greater than a given threshold.
To evaluate the purity vs efficiency of the algorithm, it has been applied also to frames where the X-ray tube was switched off.

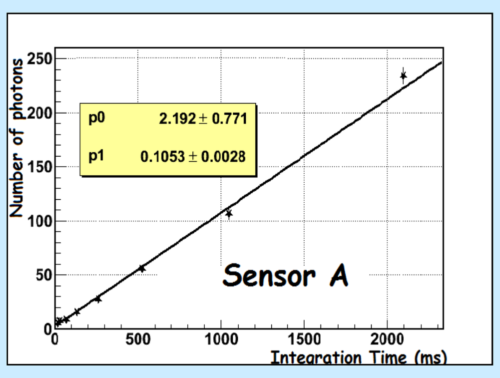


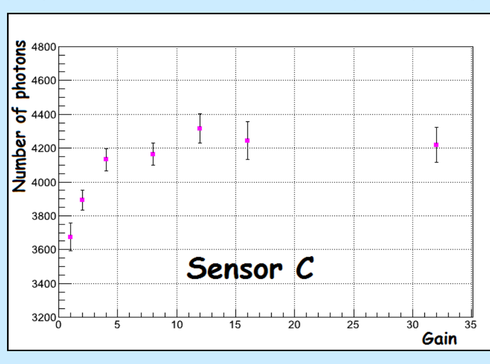


The figure in the left shows the amount of pixels over a given threshold for the **beam off case** (black line), the beam-on (blue line) and the relative uncertainty (red line). It should be noticed that after 6 ADC no pixel is greater than the threshold, and the relative uncertainty has a minimum value at 5 ADC, with a small increase in the 2-10 ADC region.
Hence the threshold to define the central pixel for a cluster has been fixed at 10, to take into account also some possible non-gaussian behaviour of some pixels.

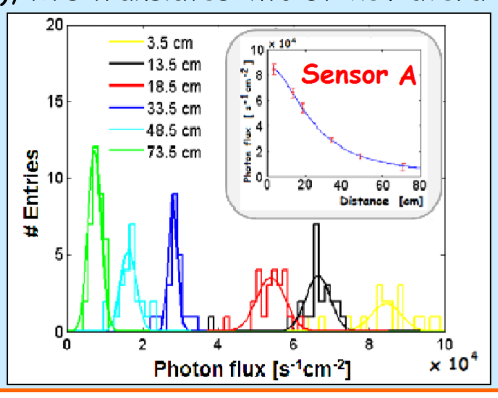
Sensor parameters

The two main sensor parameters to be studied are the pixel integration time and the gain of the electronic chain. The integration time impacts on the number of photons detected in a single frame. It is also important to define the dead time and the measurement rate. The picture shows for Sensor A the linear dependance, up to 2 s, of the number of detected photons in a frame. At 1 Hz rate, with a 3% dead time, we could reach a 3% statistical error.





The gain impacts on the photon finding efficiency and on the dynamic range of the response for each pixel.
For Sensor C for example we find that the efficiency reaches a plateaux at a gain of 4; for such a gain the dynamic range for each pixel is 23 keV. Because the released charge is shared in average among several pixels (40% in the highest), this translates into 57 keV average limit, well over the 23 keV peak of the diffusion spectrum.

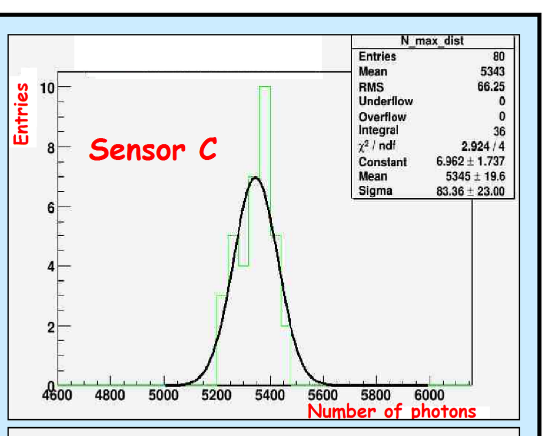


The response to the diffused photons has also been studied as a function of the sensor distance from the PMMA phantom. The photon flux for Sensor A, measured for each recorded frame, has been reported in the side figure at various distances. The distributions follow nicely the Poissonian statistic, while the Inverse Root Distance Law has been confirmed (see fit in the inset).

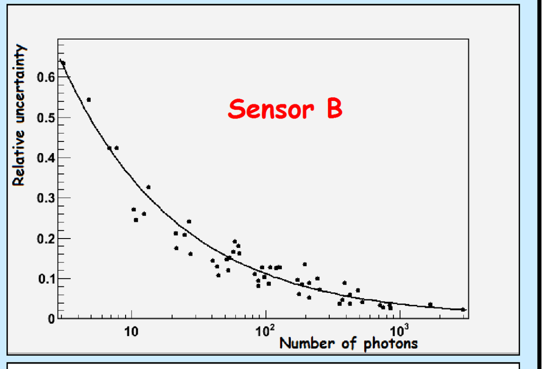
Dosimetric Observables

Two dosimetric observables have been defined:

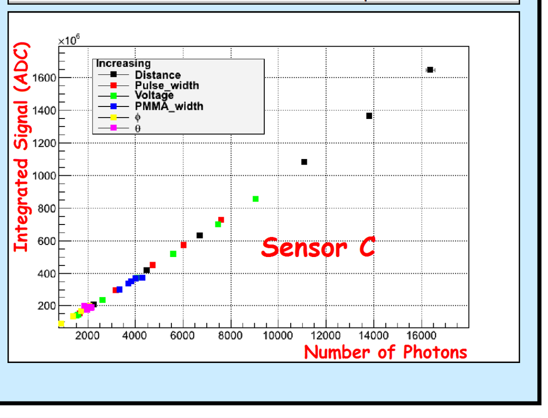
- **The number of detected photons** (photon flux);
- **The cumulative measured signal from all the photons** (measured energy flux);



The distribution of number of detected photons in one frame is shown in the upper plot, with a superimposed gaussian fit (Sensor C).



The variation from frame to frame follows nicely the Poissonian statistic, as demonstrated on the center picture where we have fitted with an Inverse Square Root function all the experimental data taken in different conditions (Sensor B).
To reach an uncertainty below 5% in the photon measurement in each frame, of the order of 500-600 photons need to be detected.

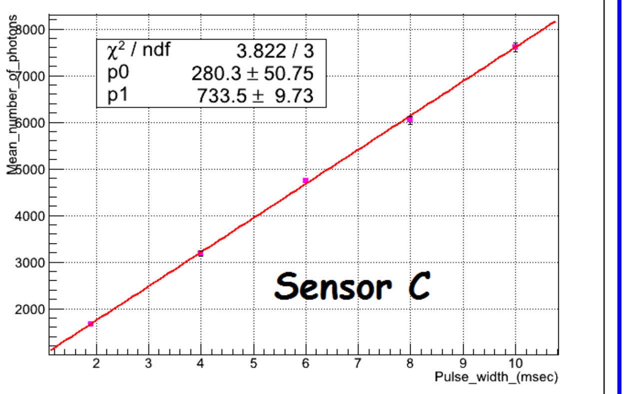


The same holds for the measured energy flux, whose main uncertainty source is the poissonian statistic due to the photon counting.
In the lower plot the linear correlation between the two dosimetric observables, measured by Sensor C in all the experimental conditions, is shown.

X-ray tube parameters

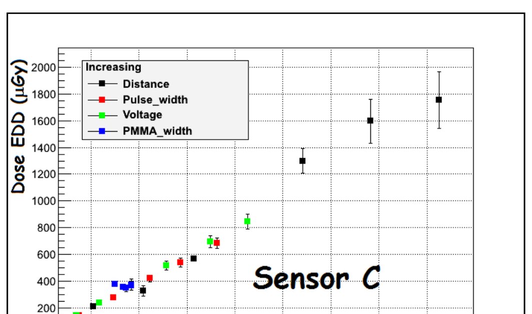
Several working parameters have been explored to test the response of the sensors, namely:

- pulsed or continuos mode;
- tube current;
- tube voltage;
- pulse frequency;
- pulse width;



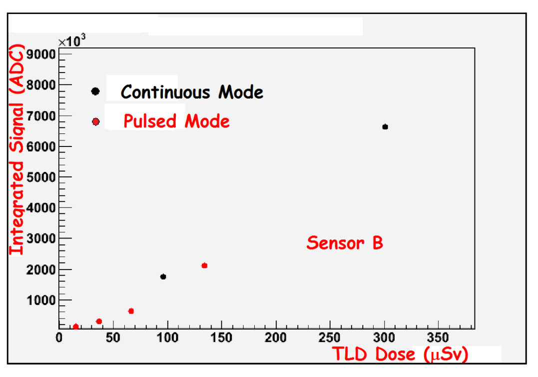
In all cases the dependence of the response from the parameter was linear. As an example in the graphs on the right is shown the variation of the number of detected pixels in a frame as a function

Comparing Sensors with Commercial Dosimeters



Finally the three sensors' response has been compared with measurements performer using both TLD and EDD-30 dosimeters.
A reasonable linearity could be observed in all cases and for both dosimetric variables: detected number of photons and integrated photon signal.

In the left picture the correlation between EDD-30 dose measurements and Sensor C integrated signal has been verified varying many type of parameters over the usual range typical of the IR procedures.



In the right picture the response of Sensor B, for both continuous and pulsed mode of operation, shows that the difference reported at ORAMED 2011 Conference for other commercial active dosimeters, is much reduced, hence pointing to the possibility for Active Pixel Sensors to solve this problem.

Conclusions

CMOS Active Pixel Sensors have been studied as potential detectors for diffused X-ray during Interventional Radiology procedures.

Three different sensors have been extensively tested varying all the relevant parameters of the interventional radiology system and of the sensors. Two candidate dosimetric observables were defined, the number of detected photons and the integrated photon signal.

Both variables show a linear correlation with the dose measured by two commercial dosimetric systems, passive (TLD) and active (Unfors EDD-30).

The sensor response is scarcely dependent by IR operational mode (pulsed or continuous)

The CMOS Active Pixel Sensors have the potential for being considered as sensor element of a personal wearable dosimetric system for the RAPID Project.

Reference:
[1] M. Paolucci et al.: **A real time active pixel dosimeter for interventional radiology.** Rad. Meas. 46 (2011) 1271-1276.