Feasibility study of CMOS image sensors as β^- radiation detectors in radioguided surgery

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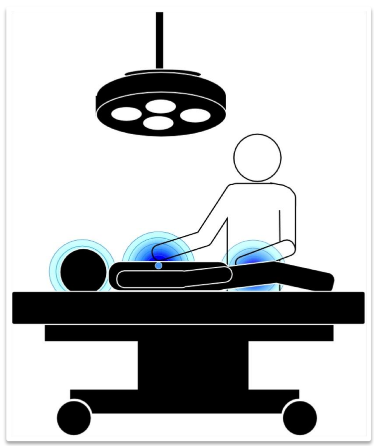
Introduction

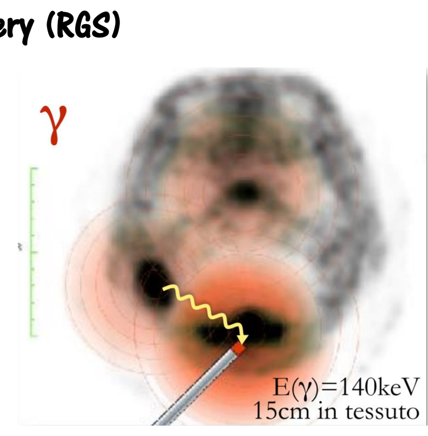
A study of the performances of CMOS image sensors as β^- detectors, with the prospect of their application in a probe for radioguided surgery is presented. This probe should provide vital and real-time information to the surgeon, regarding the location and margins of a tumor, with high resolution. CMOS image sensors seem promising for this purpose, given the low power consumption, small size, and high efficiency in detecting the single ionising particle. Horizontal scan measurements on a source of ^{90}Sr, interposing collimators of different size, aim to determine relationships between the scan fit parameters and the target dimensions, after fitting with different models. In particular, a linear dependency of scan maximum on source diameter is found. Phantoms of ^{90}Y, with different dimensions and activities, are preparated to get closer to clinical conditions. The sensitivity of the sensor to different source sizes is extrapolated, after estimating the background for various TNR (Tumor-to-Non-Tumor ratios) of captation. The significance, used as estimating criterion, suggests that the sensor MT9V011 is capable to distinguish a signal from background down to 3 mm, in 3 seconds of time acquisition, given a TNR above 18, that is realistic in clinical settings.

RadioGuided Surgery (RGS)



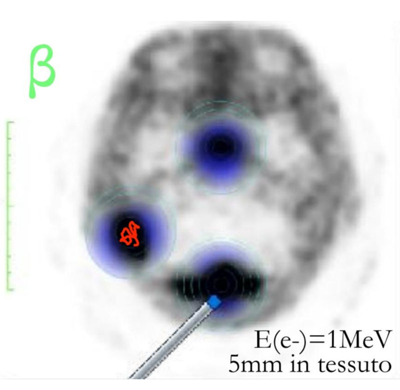
Radioguided surgery (RGS) is a intraoperative medical procedure involving a pen-shape probe for the detection of a radioactive tracer emission. RGS allows the surgeon to assess and remove tumor residuals up to a millimetric resolution.

- ✓ Radio-pharmaceutical (tracer): preferentially uptaken by tumor then by healthy tissues, administered to the patient before surgery.
- ✓ Probe (detector): manageable, enough sensitive to discriminate in real-time between signal released by tumor and background emitted by healthy tissues.



Commonly used RGS relies on γ - emitting radiopharmaceuticals. But, the use of β^-- emitters would reduce the background by healthy tissues, due to the shorter means free path of electrons in tissues, if compared to photons .

Advantages of β^- RGS: higher signal-to-noise ratio, faster response, lower exposure of patient and surgeon.



CMOS APS image sensors

APS (Active Pixel Sensor) based on the Complementary metal-oxide-semiconductor (CMOS) technology are image sensors, whose integrated circuit presents a photodetector and an active amplifier per pixel, high noise immunity and low static power consumption. Most commonly used for digital cameras, their matrix can reach up to several milions pixel and pixel size < 2 μm in a few mm².

New perspectives: as ionising radiation detectors for medical applications. Crossing the sensitive layer thickness (a few μm) a charged MIP (Minimum Ionising Particle) produces 200-300 electron-hole pairs (signal), against very low dark current (a few electrons). SNR (signal-to-noise ratio) ≈ 20 and efficiency near 100% are possible. Reduced photon interaction probability, especially for Eγ>80 keV.

The performances of the CMOS sensor MT9V011 (with and without protective filter) as β^- radiation detector, in view of its possible application in RGS, are studied. The readout of the sensor is assured by a Demo2 board and a MT9SH06 evaluation board, with an USB line to power the system, to control the sensor, and to receive data.

MT9V011 Aptina sensor

Sensor:	MT9V011
Pixel size:	5.6 μm
Pixel matrix:	640 x 480
Active area	3.58 mm x 2.69 mm
ADC resolution:	10 bit
Supply voltage:	2.8 V
Operating temperature:	-20 to 60 °C
Protective filter:	Both with and without

Radioactive sources

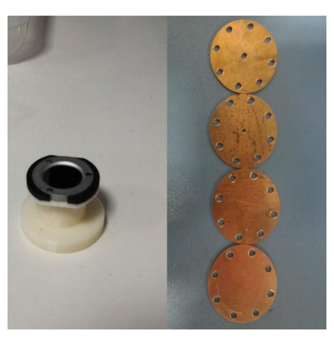
Source:	^{90}Sr	^{90}Y
Half-life:	28.79 yr	64 h
Decay product:	^{90}Y	^{90}Zr
Decay mode:	β^-	β^-
Energy endpoint:	0.546 MeV	2.28 MeV
Activity:	31.8 kBq	6 kBq/ml

sources of ^{90}Y in agar agar

Phantoms of ^{90}Y in sodium chloride solution, thickened with agar agar permit to work in more simil-clinical conditions.

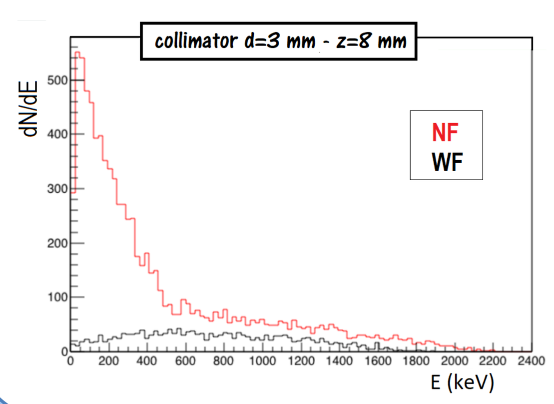
^{90}Y is used as radionuclide in DOTATOC radiopharmaceutical, in many clinical procedures. Possibility to adjust the specific activity to medical needs (6 kBq/ml), diluting in water. Phantom disks of diameter 21, 13.3 mm and heights 4.5, 5.5 mm.

^{90}Sr source and collimators



^{90}Sr flat and circular source with d = 21 mm and activity A = (31.8 ± 0.9) kBq at the time of data taking. ^{90}Sr decays in ^{90}Y with which is in secular equilibrium. Several 1-mm-thick disks of copper, central hole of diameter 1,3,5,7 mm used to collimate the source.

Simulation: effect of the filter

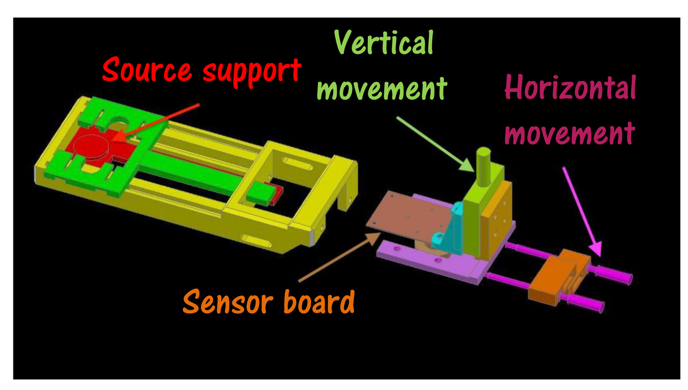


GE ANT4 simulation: energy spectrum of ^{90}Sr/^{90}Y decay electrons reaching the CMOS active surface of MT9V011 sensor with filter (WF) and without filter (NF). A collimator of diameter 3 mm, and a source-sensor distance z = 8 mm are considered. The absorption of electrons due to the resin filter is evident, especially at energy below 600 keV (by ^{90}Sr decay).The MT9V011-NF sensor, if compared to the WF one, has a greater relative efficiency of ≈ 3. In principle, it could be used also with β-emitters having endpoints lower than ^{90}Y .

Experimental setup

Custom-made mechanical setup allowing two degrees of freedom for the relative movement between sensor and source. After aligning, the sensor can be moved horizontally and vertically. During data taken, the whole setup is kept shielded from the visible light, inside a dark box.

Horizontal scan (x): in a range of 20-30 mm, divided into 1-mm steps, for describing the whole shape of the signal.
Vertical scan (z): from 2 to 6 mm, to reproduce the surgery distances.



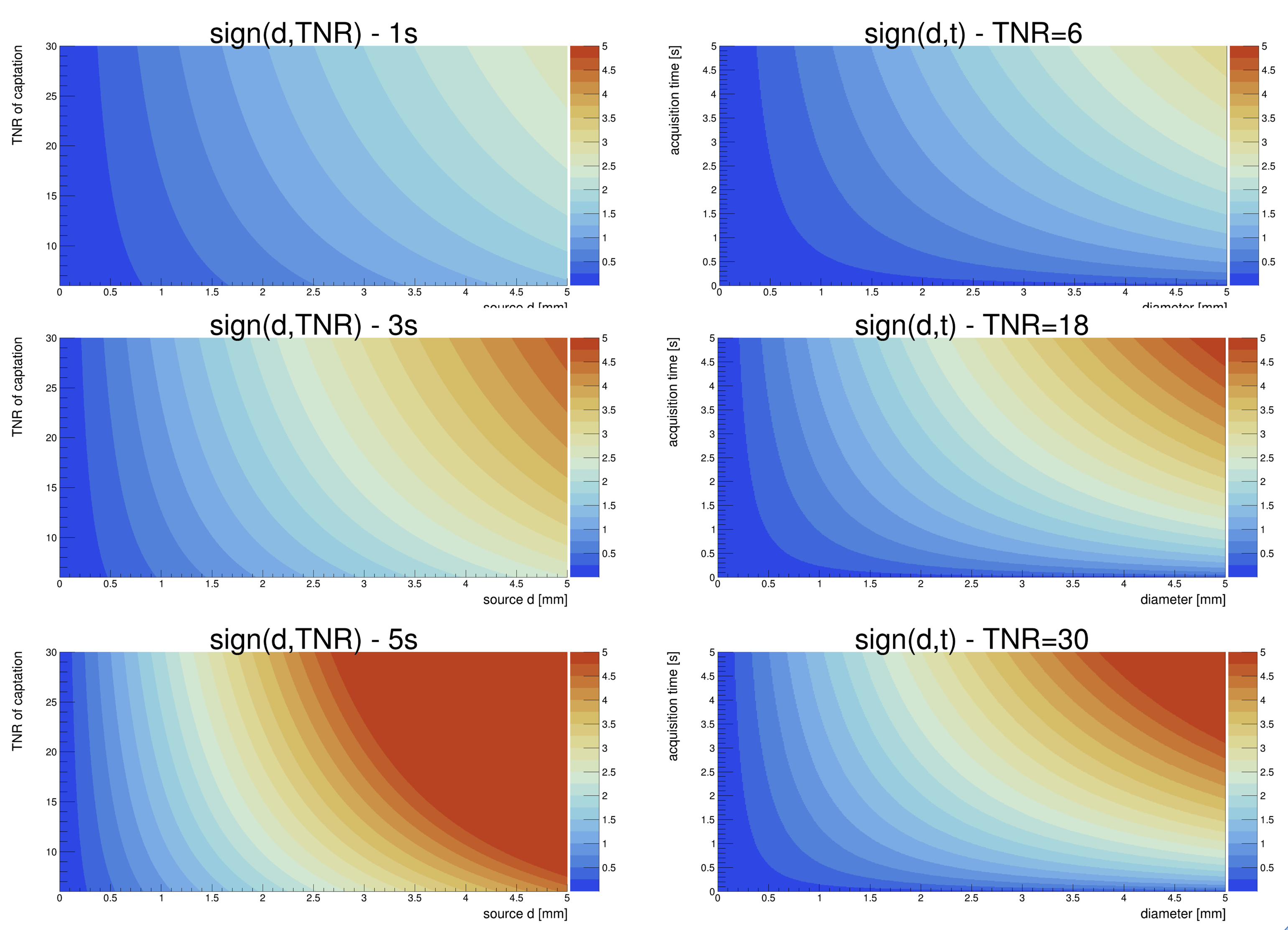
Extrapolated significance of ^{90}Y results to small diameters

The linear dependency between counts at maximum and source diameter allows to extrapolate the significance (Sign) value at maximum to small diameters (d ≤ 5 mm), after an acquisition time of a few seconds (t ≤ 5 s), assuming a SNR of captation (SNR ≤ 30) to evaluate the background. An overview on how the significance is affected by the considered parameters is provided by two-variable function plots of sign(d, TNR) with constant t (left column) and sign(d,t) with constant TNR (right column).

$$Sign = \frac{S}{\sqrt{S+B}}$$

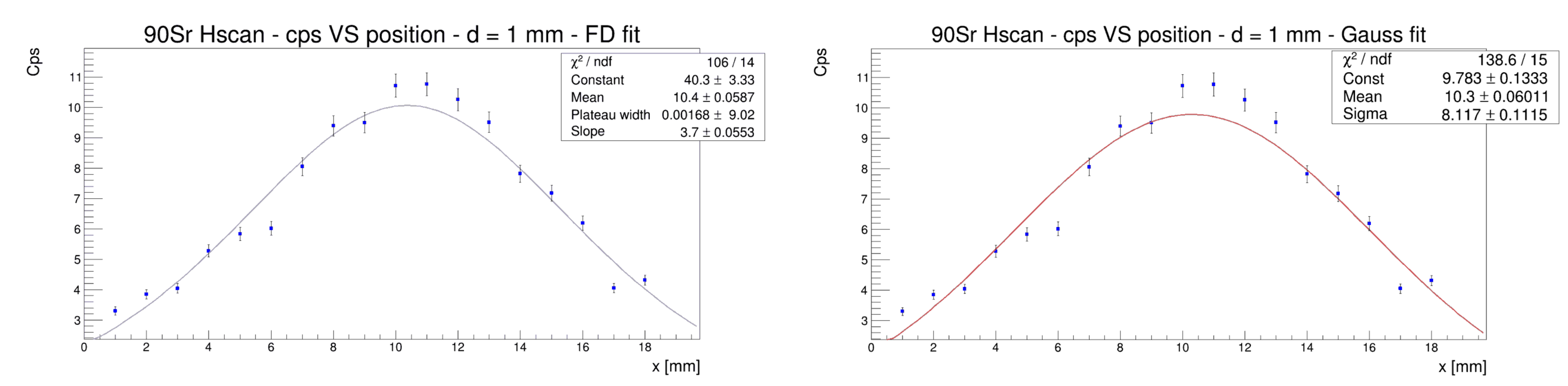
Sign = significance
S = signal
B = background

d = source diameter
SNR = signal-to-noise ratio of captation
t = acquisition time

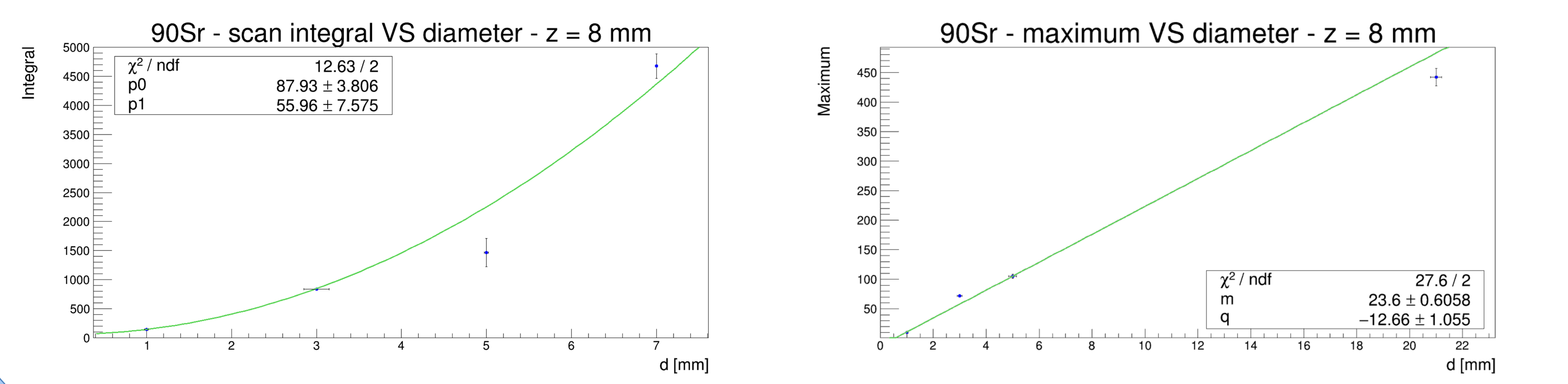


^{90}Sr horizontal scan varying source diameter

Horizontal scans on ^{90}Sr comparing two fit models, Gauss and double Fermi-Dirac function, and study of fit parameters relationship with source dimensions. Scan shown for d=1 mm:



The employment of collimators of different sizes enabled to find out a quadratic and a linear dependency of, respectively, scan integral and scan maximum on source diameter:



Conclusions

The MT9V011 sensor turned out to be promising to be used as active probe for β^- radioguided surgery. In particular, the MT9V011-NF, if compared to the WF one, has the advantage of a greater relative efficiency of about a factor 3. It showed its capability to distinguish a signal from background up to dimensions of 3 mm in a couple of seconds of time acquisition, given a TNR above 18 (plausible clinical settings).

Nevertheless, there is still extensive room for improvement of its performances: extending the active detection surface, optimising the geometrical configuration for more than one sensor, implementing an algorithm in a FPGA for directing the probe towards the signal maximum.

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