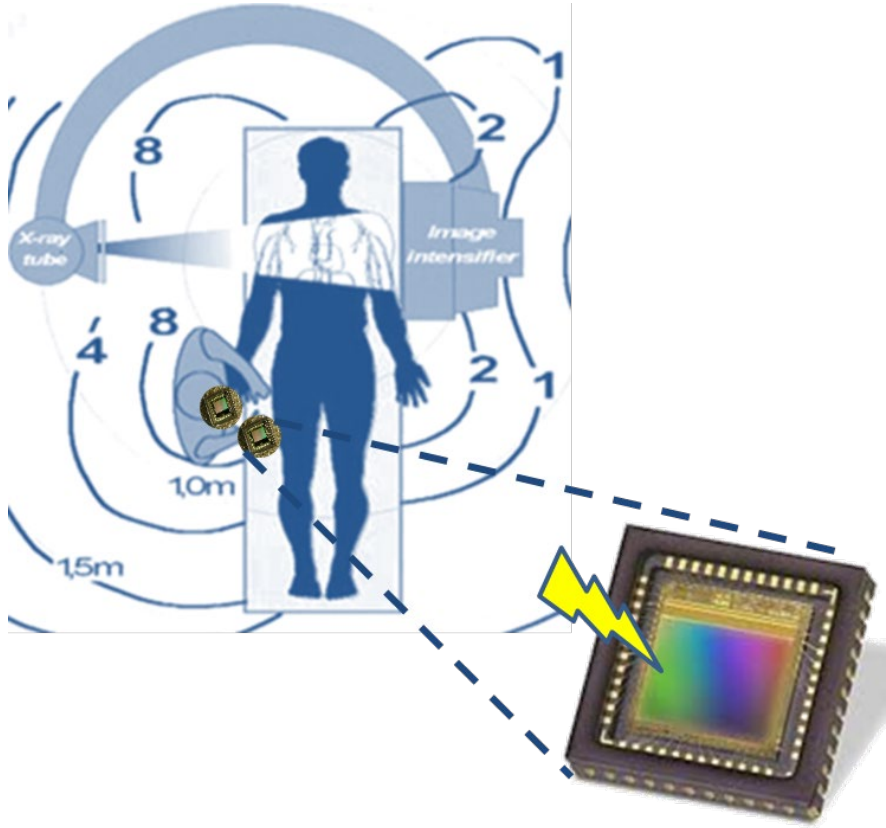
L. Servoli, P. Placidi

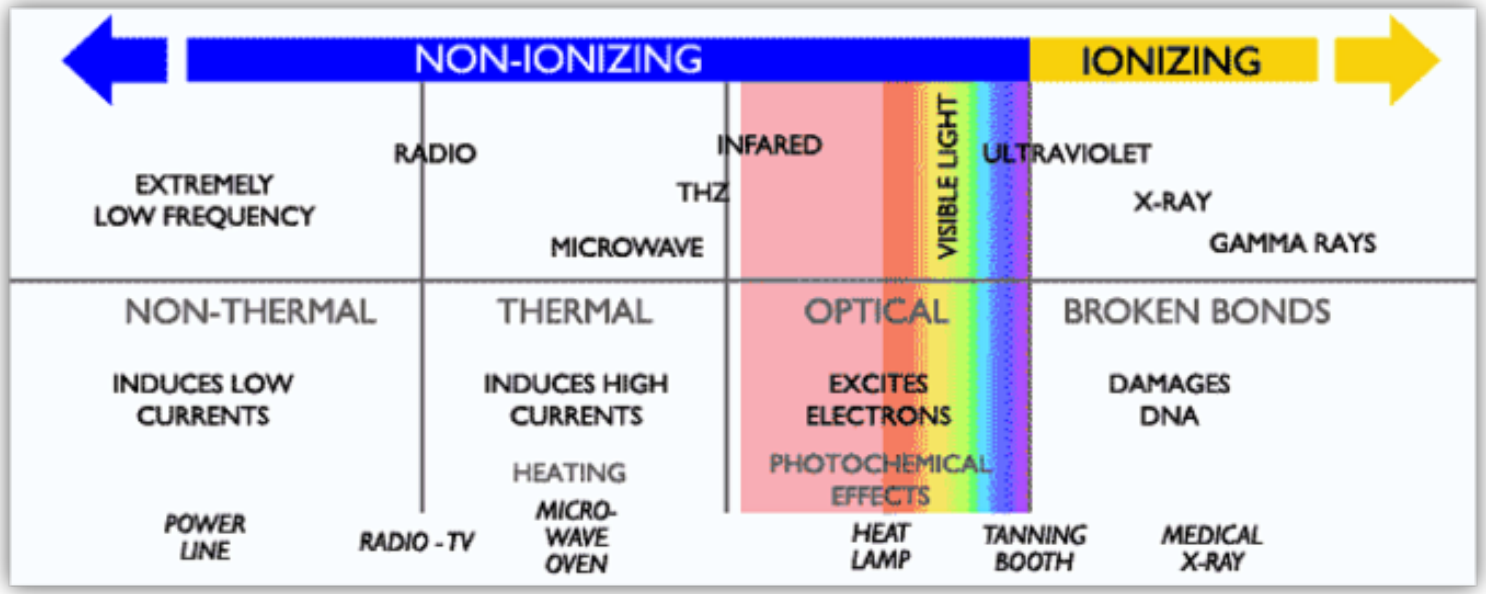
WORKSHOP Dipartimento di Ingegneria – INFN Perugia

lunedì 11 gennaio 2021, ore 10.00 – 13.00



Active pixel sensors for medical applications

Clinical Applications of Ionizing Radiation



Ionizing Radiation in Medicine

- Diagnostics
- Therapy
- Dosimetry

Clinical Applications of Ionizing Radiation

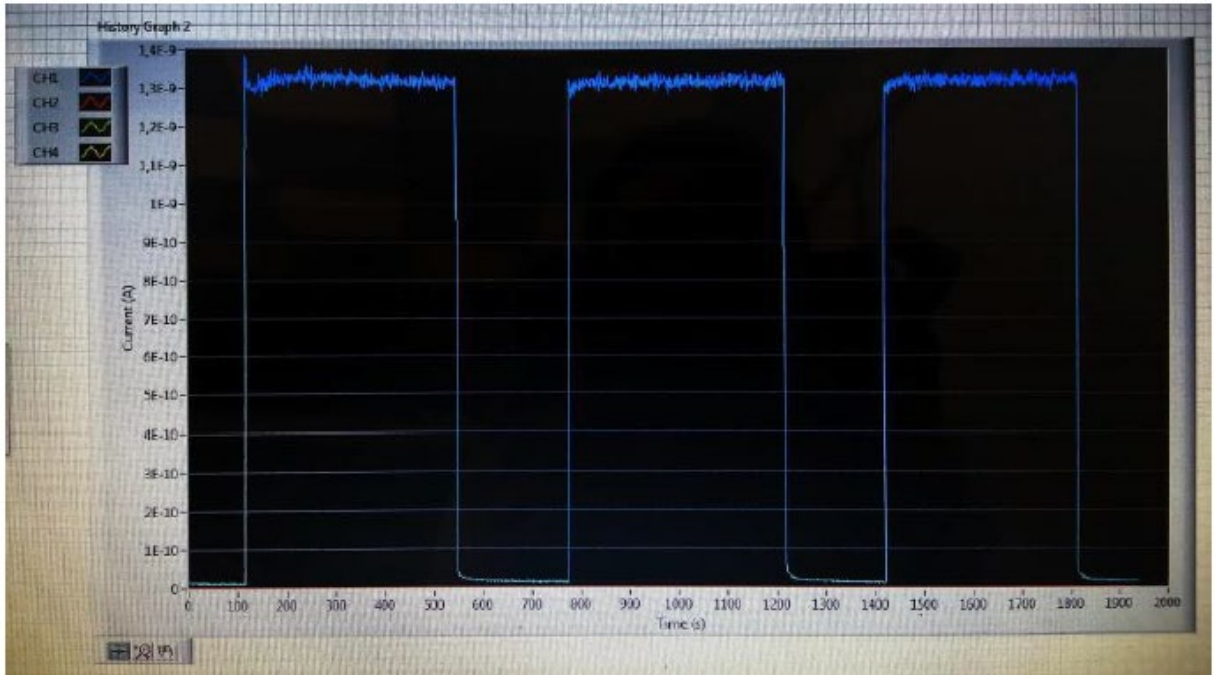
- Sensors
- DAQ
- Calibration
- Quality Assurance

Why Active Pixel Sensors?

Sensors (Active or Passive):
Materials: Gas, semiconductors, films, scintillating crystals or fibers,…

Typical active mode:

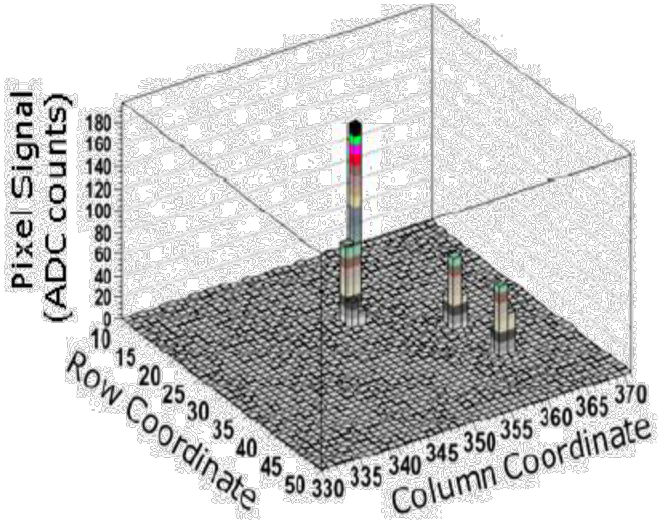
energy deposition measurement → current mode



Why Active Pixel Sensors?

Unique properties of APS from sensing point of view:
single interaction detection → counting mode or analog sum mode

→ low noise (ENC ~ few electrons)
→ small pixel size (~ few micrometer)
→ thin sensitive layer (~ few micrometer ~ pixel size)
→ low cost if CMOS Image Sensors (CIS)
→ high S/N for charged particles (> 20 for MIPs)
→ detection efficiency for charged particle ~ 100%
→ detection efficiency for interacting photons > 98 %
→ various form factor and number of pixels (0.05 → 14 Mpixels)
→ low power supply, low power consumption



1. Probe for radioguided surgery

Scenario: Oncological Radioguided Surgery procedures (INFN + UNIPG + Sapienza)

Working principle:

→ Radiopharmaceuticals administration ($\beta^- \rightarrow {}^{90}Y$)
→ Uptake from 4 to 30 times in tumor than in healthy tissues
→ Detecting probe (***CMOS Image Sensor : VGA type***)

- ***Need to verify in real-time the complete resection of a tumor before closing the surgical incision***

Requirements:

- millimetric spatial resolution
- significant help to intraoperative visual
- minimise the removed healthy tissue
- reduce the probability of tumor recurrence

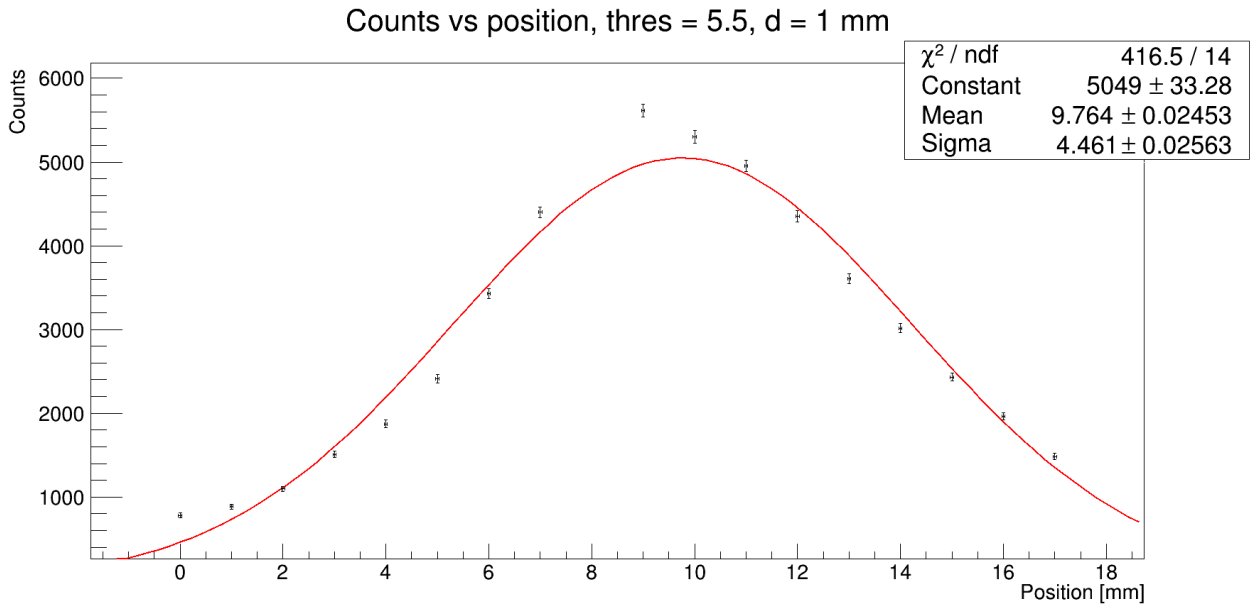
→ ***almost blind to photons, 100% detection efficiency for electrons***

Results

Tumour detection → 1 mm spot:

Limited by vertical distance of sensor from emission spot

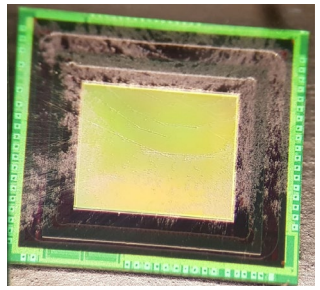
Collim. diameter [mm]	Time to reach 3σ [sec]
1	24.6 ± 0.7
3	0.458 ± 0.002
5	0.31 ± 0.03
7	0.088 ± 0.007



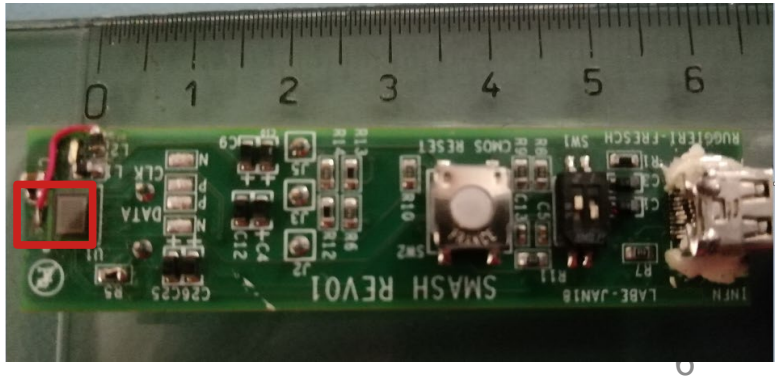
Limit of tumour diameter vs observation time:

Limited by protection layer thickness in front of sensor.

50 μm thickness

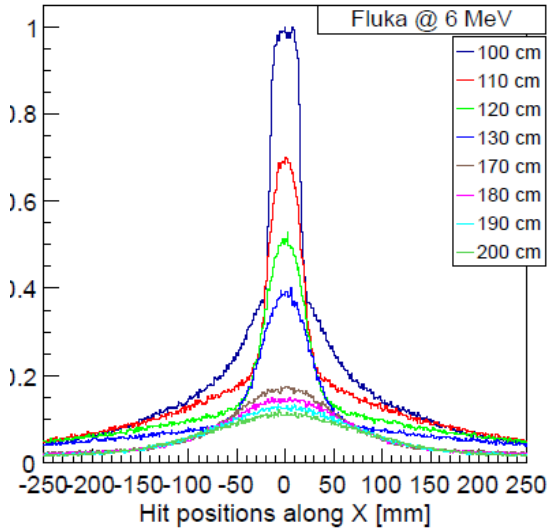


Probelike PCB finger

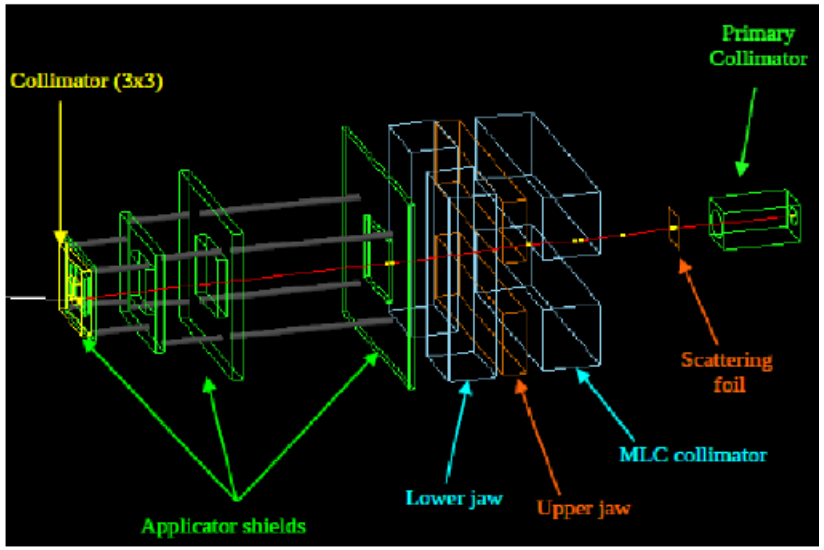


2. Radiotherapy beam characterization

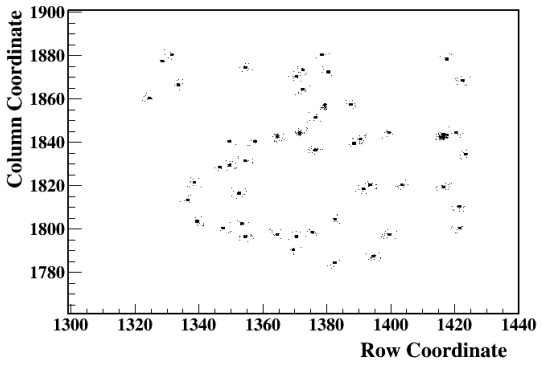
Scenario: Quality Assurance of Radiotherapy Photon and Electron Beams



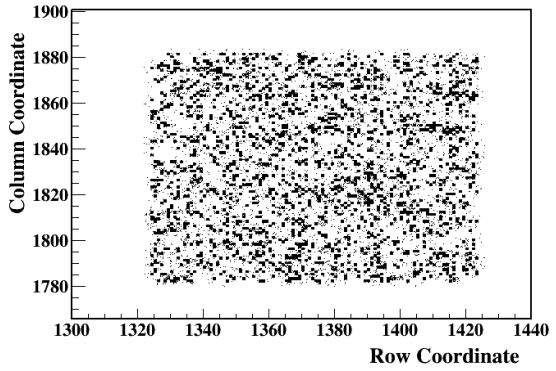
Measurement of radiation beam profile point by point



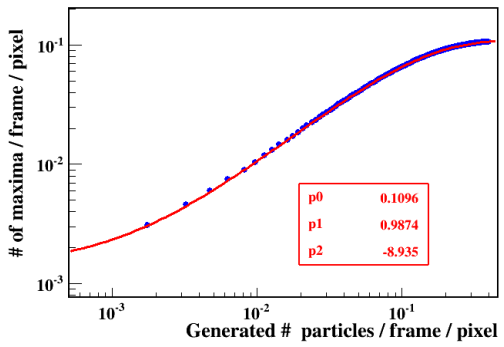
50 electrons/10000 pixel



1850 electrons/10000 pixel



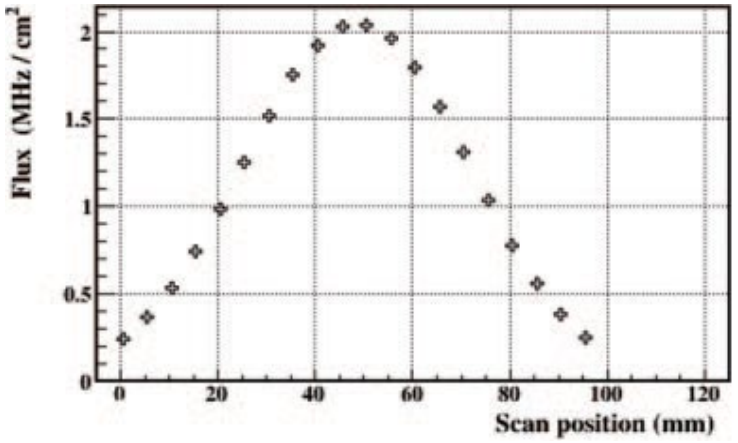
Non-linear calibration

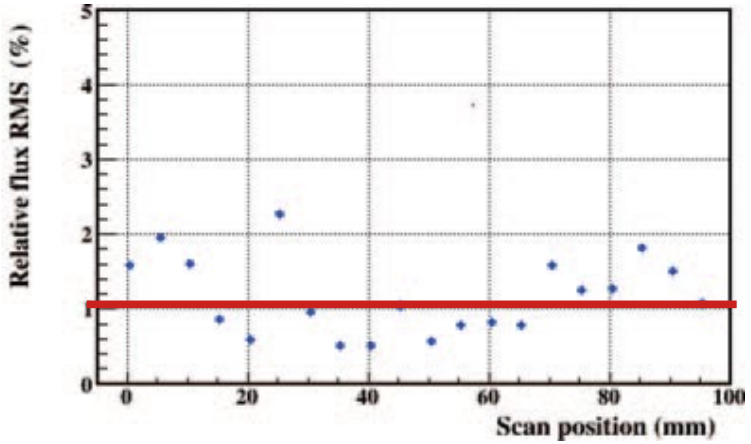


Uncertainty below 1% up to 10-20 MHz/cm²

1 deposited patent

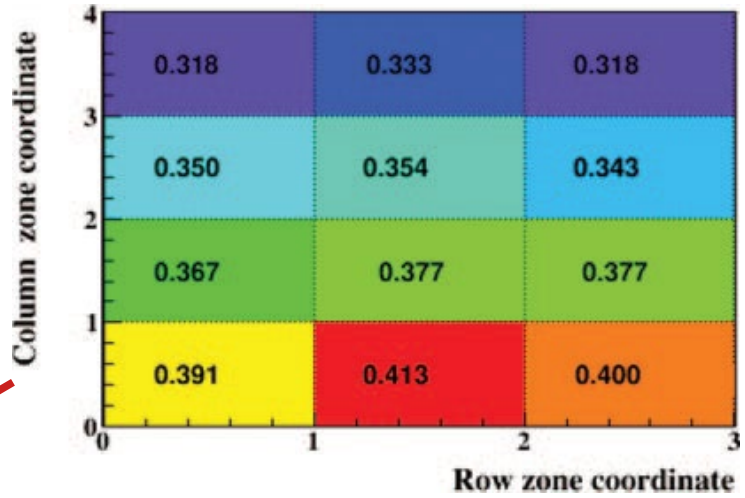
Scenario: Quality Assurance of Radiotherapy Photon and Electron Beams





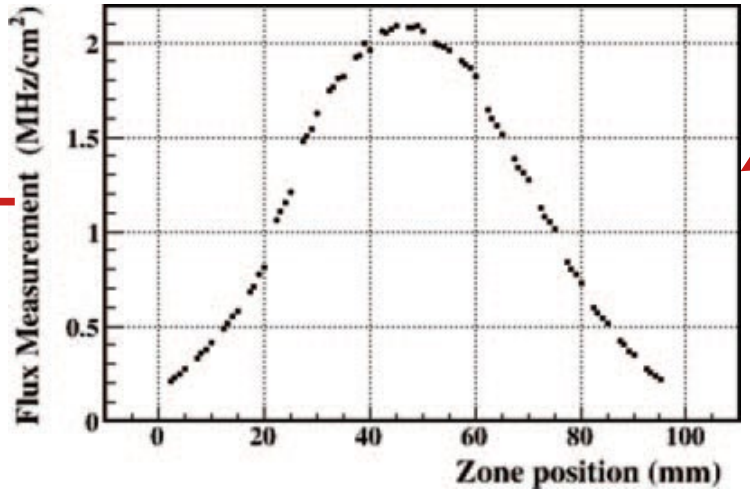
1%

Sensor area subdivided into smaller zones → multiple measurement at the same time



Possibility to measure high flux gradients.

Fundamental for small field protocols.

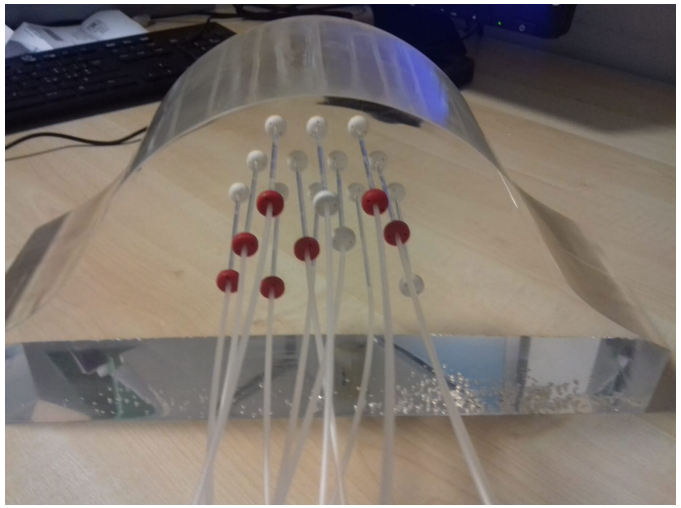


2D Finer definition of beam smaller zones → reduction of profile uncertainty

3. High Dose Rate Brachytherapy Quality Assurance

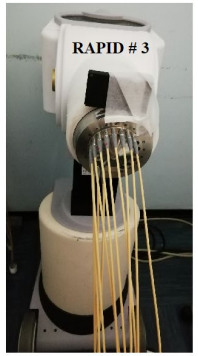
Scenario (Quality Assurance for High Dose Rate Brachytherapy procedures)

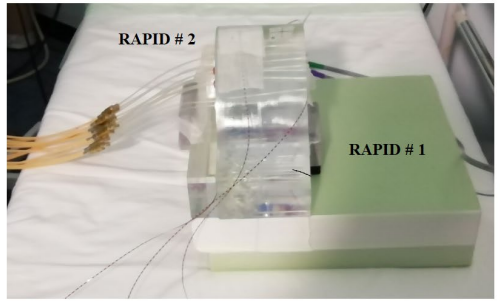
Brachytherapy consist in using radioisotopes sources to irradiate within the human body the tumour volume contouring it.

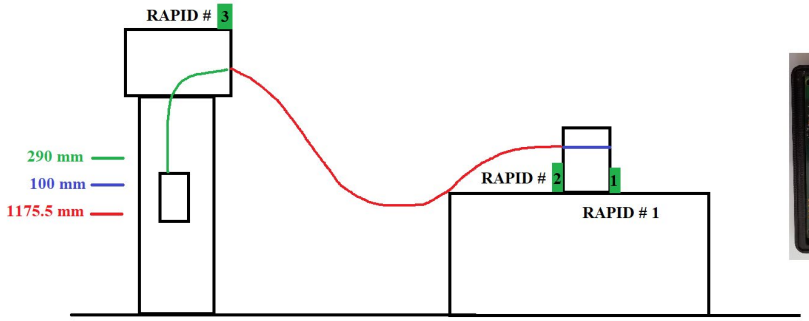


Breast phantom with 12 catheters to contour the tumour region.

^{192}Ir source will travel through them one at time, with 31 irradiation points along each catheter.



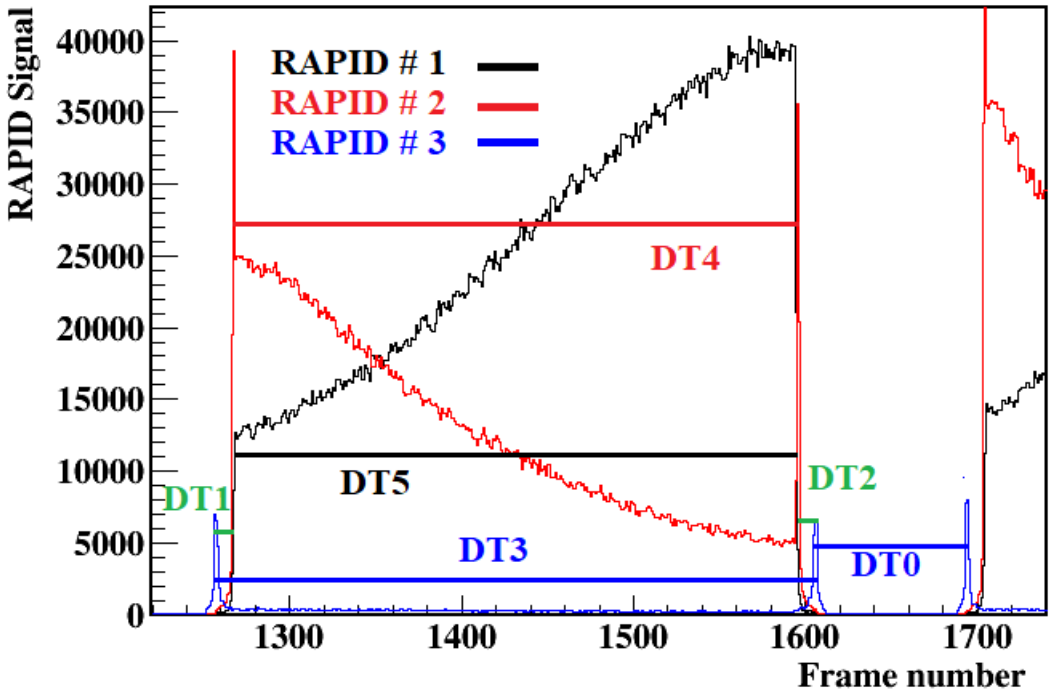




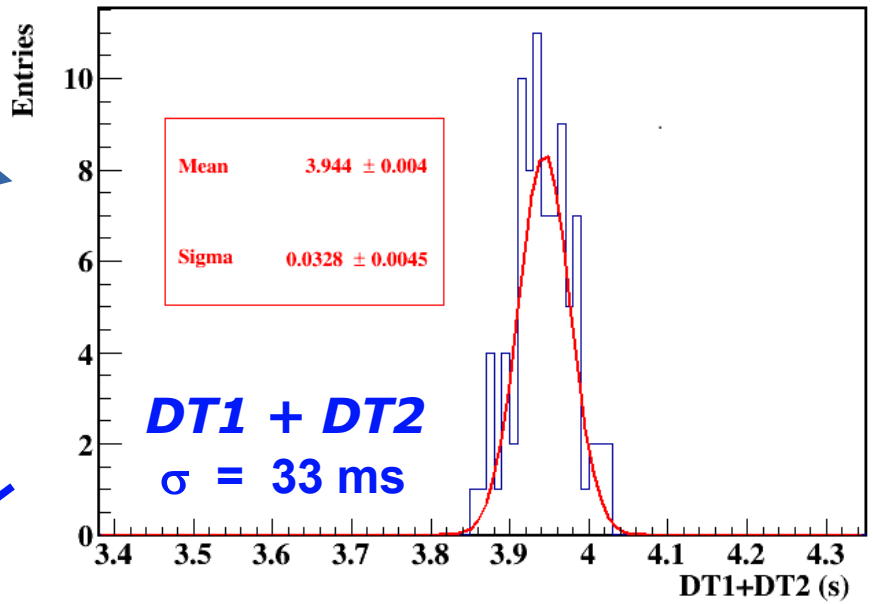
Problem: evaluate the time of irradiation for each point and the contribution during source movement outside these points.

Use VGA sensors with 200 ms integration time.

Scenario (Quality Assurance for High Dose Rate Brachytherapy procedures)



Time profile of sensors signal



Molto meglio delle misure disponibili oggi con altri sensori.

4. Interventional Radiology application

- application requirements

INFN of Perugia

Department of Physics of Perugia

- Active Pixel Sensor characterization (high energy physics background)
- X-ray
- test

- low power sensor systems
- Real-time processing
- Wireless Sensor Network (WSN)
- portable device
- embedded software
- low cost
- rapid prototyping

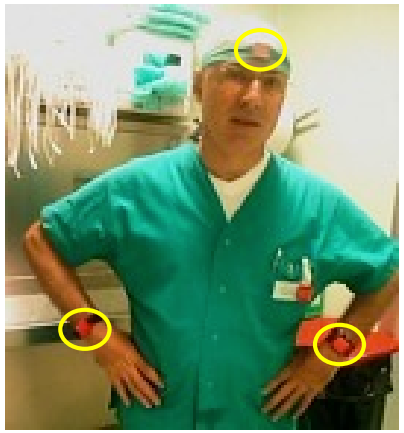
USLUmbria2 and USLUmbria1

Department of Engineering of Perugia

Implementation of a portable system based on commercial CMOS image sensors for monitoring the absorbed dose of medical operators during Interventional Radiology procedures

Interventional Radiology application

Scenario (Interventional Radiology procedures)



- high exposure of operators to scattered X-ray radiation
- legal restriction on total absorbed dose
- personal monitoring by using Passive Dosimeters (i.e. *Thermoluminescent Dosimeter* (TLD))
  - certified devices
  - energy range 10-3000 keV
  - no real time dose/dose rate measurement

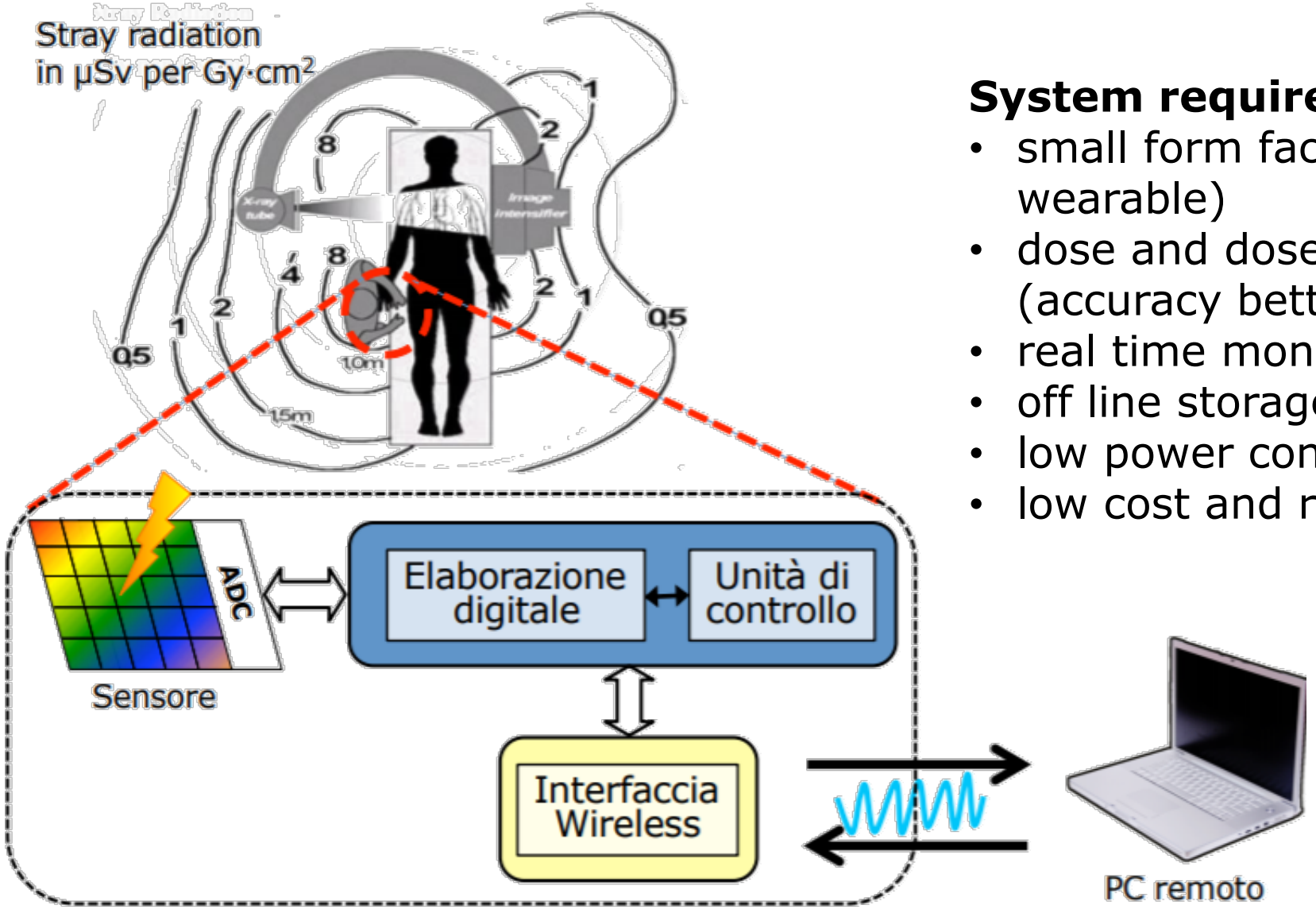
Commercial Active Personal Dosimeters

- semiconductor based sensors
- real time dose/dose rate measurement
- alarm (educational dosimetry)
- energy range$_{min}$
- performance in "pulsed operation"

Device name	Energy range	Dose rate range
Unfors EDD-30	14-120 ±10% *keV*	0.03-2000 *mSv/h*
Philips DoseAware	48-100 ±30% *keV*	0.04-300 *mSv/h*
EPD Mk2+	15-10000 ±20% *keV*	0-4000 *mSv/h*
Dosilab EDM III	20-6000 *keV*	0.0005-1000 *mSv/h*
Atomtex T3509C	*15 -10000 keV*	*100 -5000 mSv/h*
RaySafe i2	33-101 *keV*	0.004-300 *mSv/h*

[*ORAMED project: http://www.oramed-fp7.eu*]
[*E. Conti et al., IEEE Trans. on Instr. and Meas., 2013*]

Research Activity



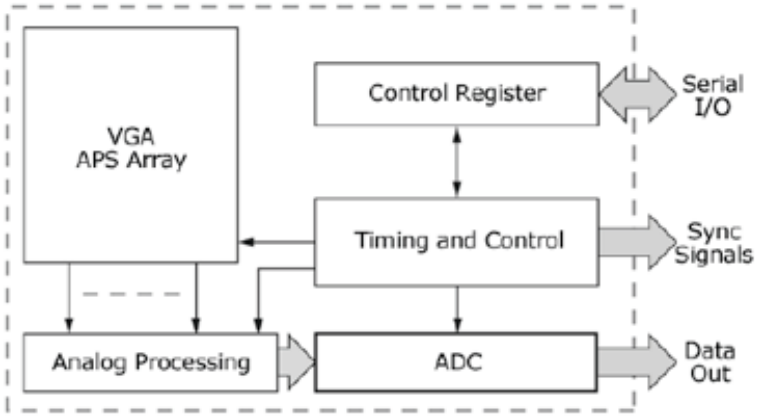
System requirements

- small form factor (portable & wearable)
- dose and dose rate measurement (accuracy better than 10%)
- real time monitoring (self-education)
- off line storage of data
- low power consumption (min 8 h)
- low cost and rapid prototyping

System Architecture (1)

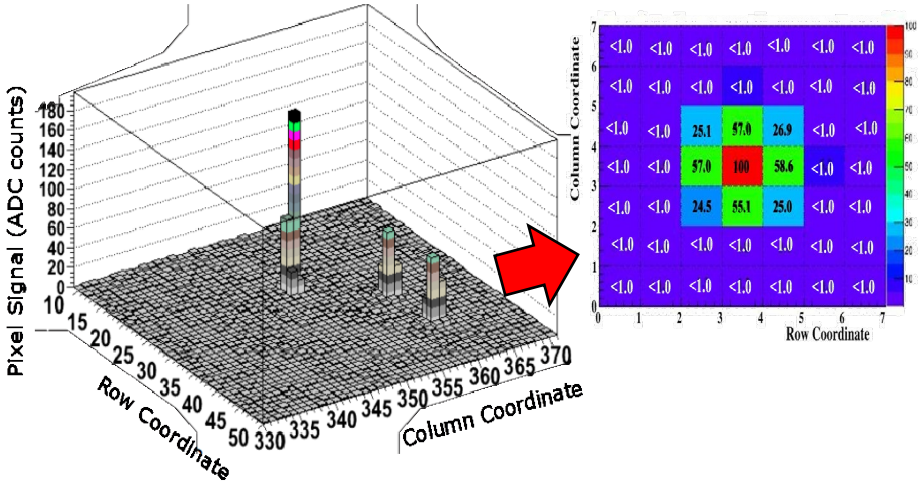
- Commercial CMOS image sensor: MT9V011 Monolithic Active Pixel Sensor (640 x 480 pixels, 5.6 x 5.6 μm^2 pixel size (307200 pixels))

Block diagram of commercial MAPS

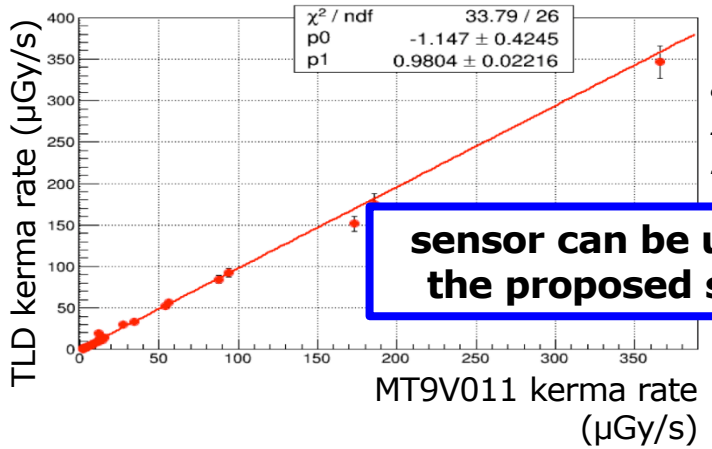


All pixels output in one frame is recorded and analyzed

cluster



- **Sensor characterization**
  - characterization in laboratory (dark condition, known X-ray sources)
  - characterization in operating room
  - characterization at certified calibration center (*Comecer*, Italy)

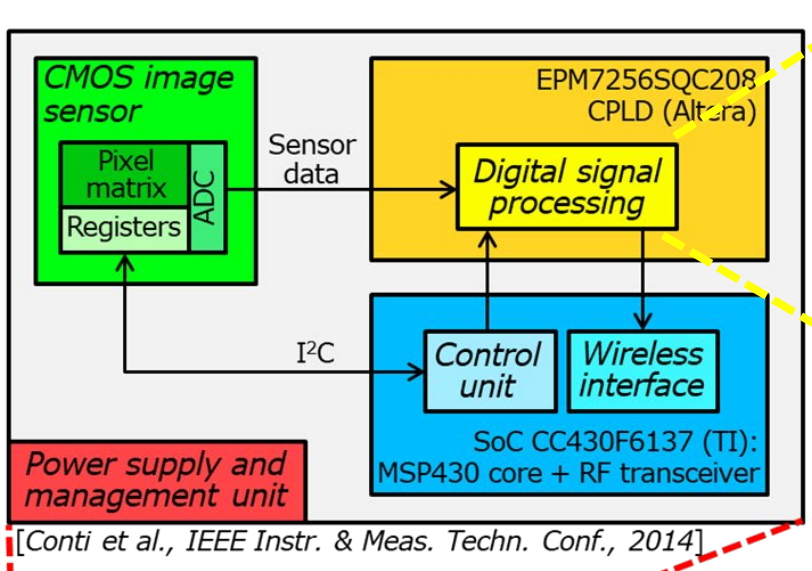


[*Conti et al., J. Instrum., 2012*]

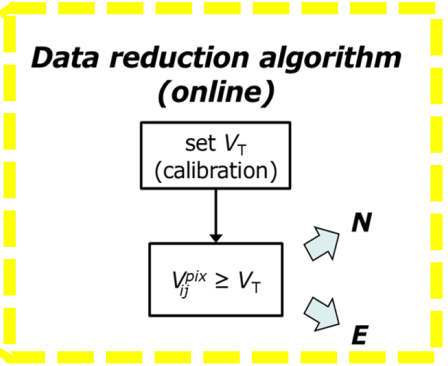
sensor can be used for the proposed system

System Architecture (2)

- Commercial CMOS image sensor with a data reduction algorithm
- Reuse of development boards -> integration of all the components in a single board (Personal Sensor Node, PSN)



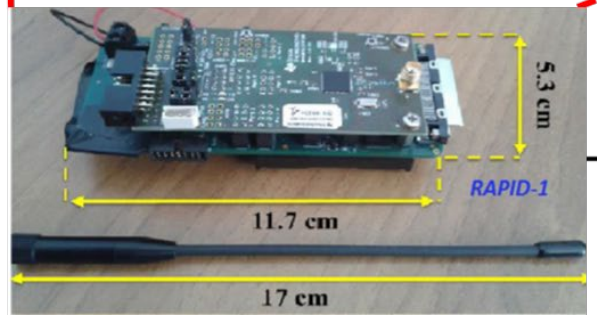
[Conti et al., IEEE Instr. & Meas. Techn. Conf., 2014]



N: # of pixel/frame

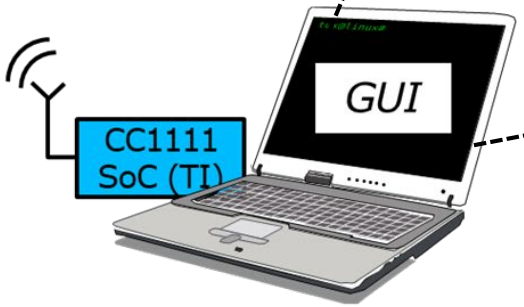
E:

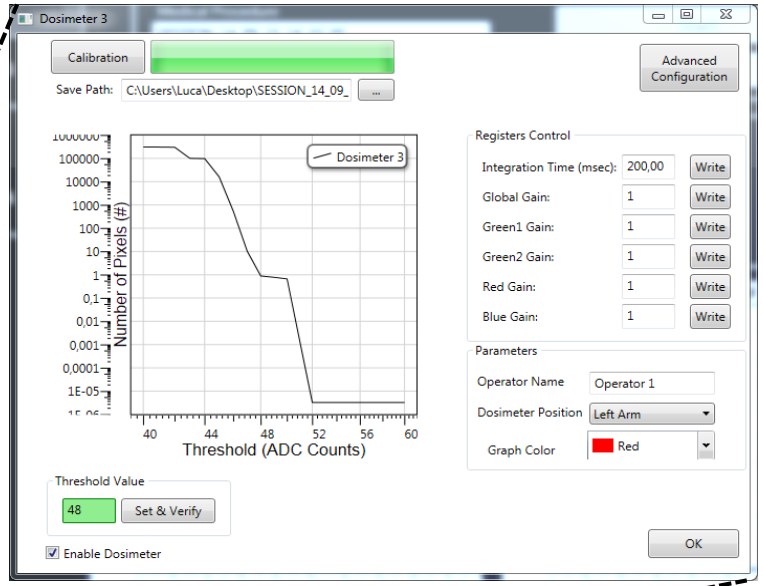
$\sum$ (S_i due to photons/frame)



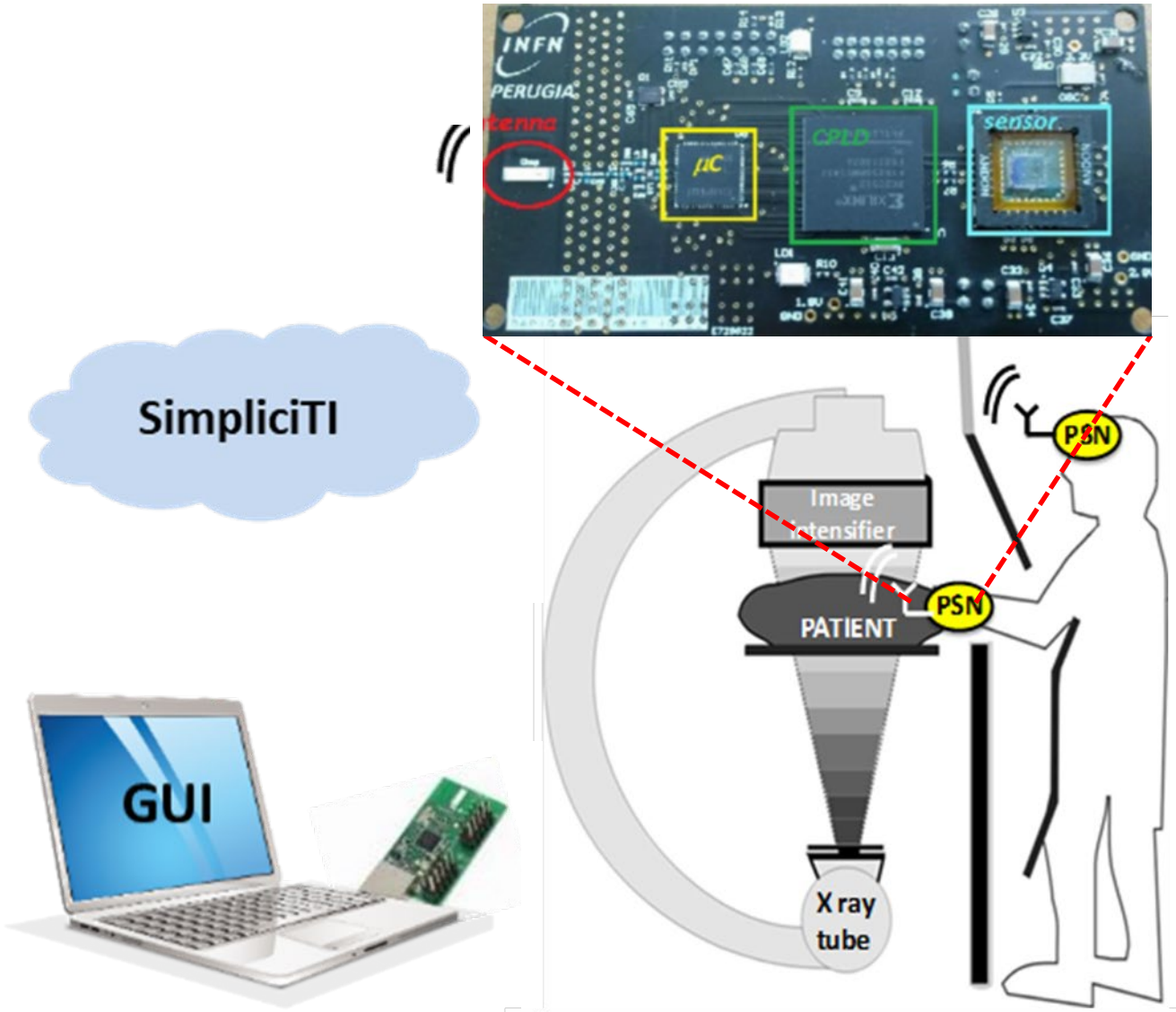
SimpliciTI wireless protocol

f=868/915 MHz





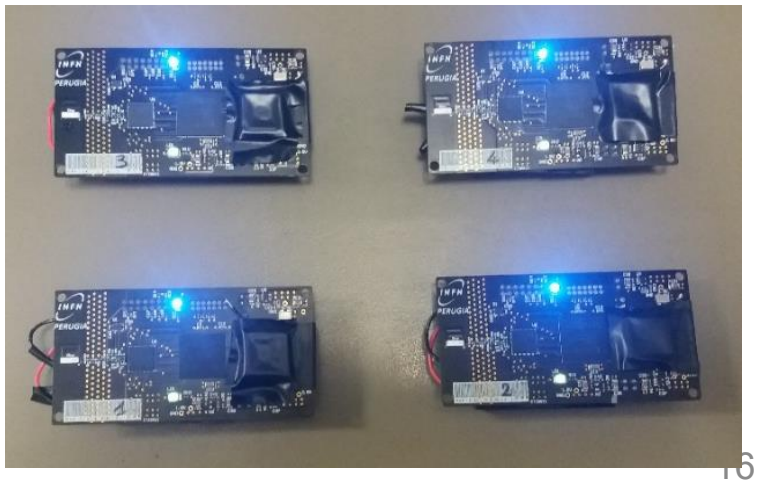
System Architecture (3)



PSN Prototypes (#1, #1.5, #2, #3)

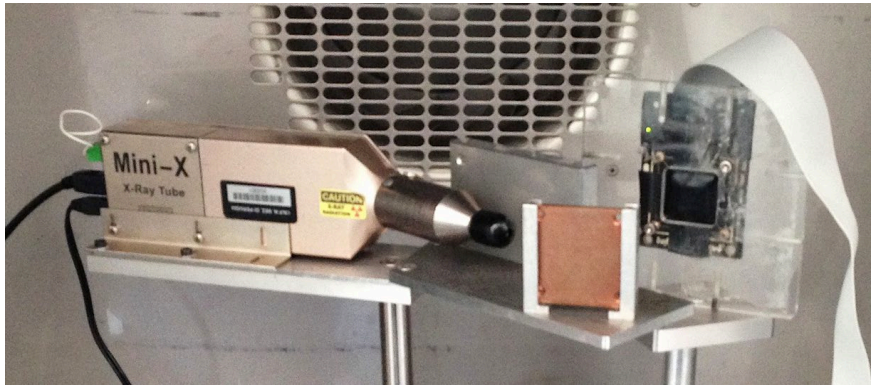
- optimization of the power consumption (55 mA@3.6 V)
- wireless interface and its interaction with the human body (distance greater than 1.5 cm)
- integration of all the components in a single board

-> network of 4-PSNs

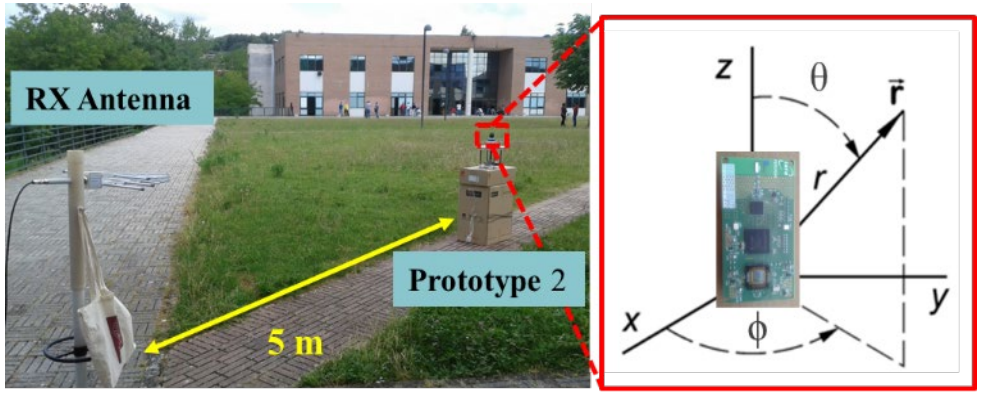


Experimental results (1)

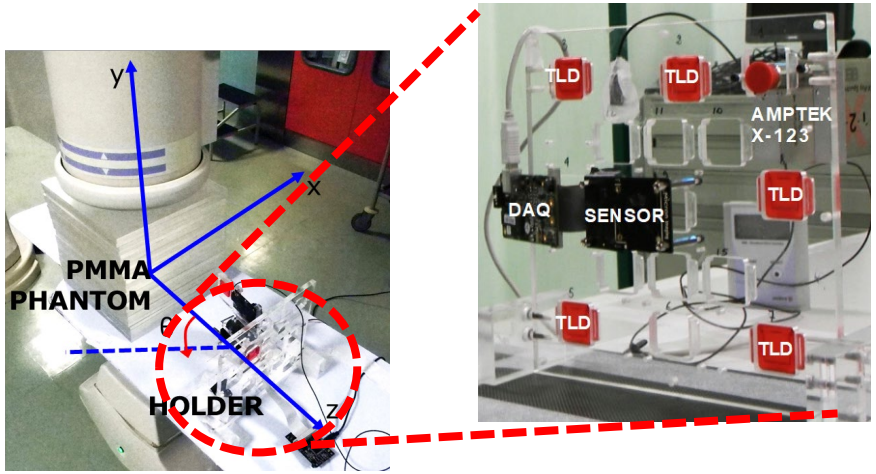
- INFN laboratory (dark condition, known X-ray sources) and facilities

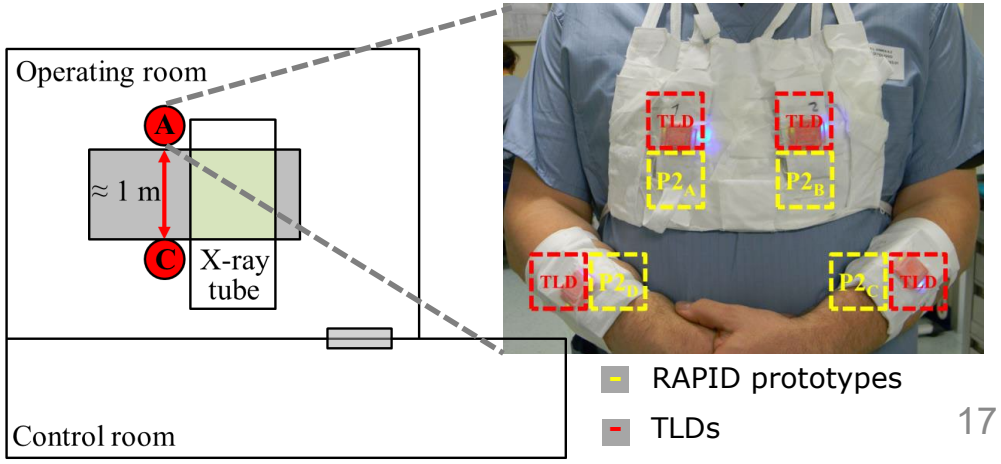


- open space (Packet Errore Rate, antenna radiation diagram)



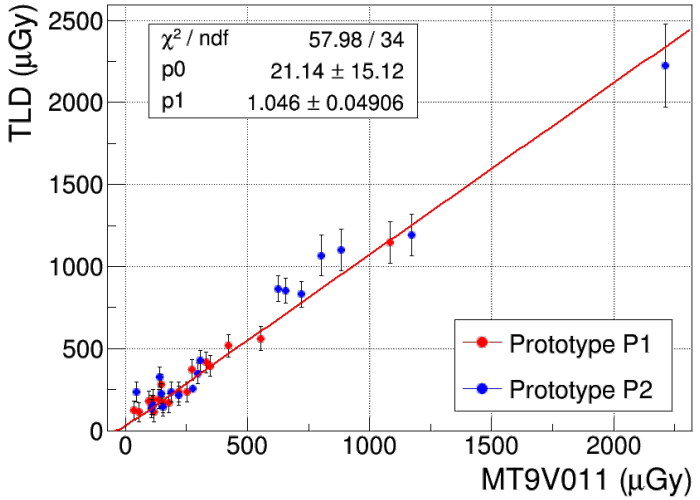
- operating room (also during IR procedures)





Experimental results (2)

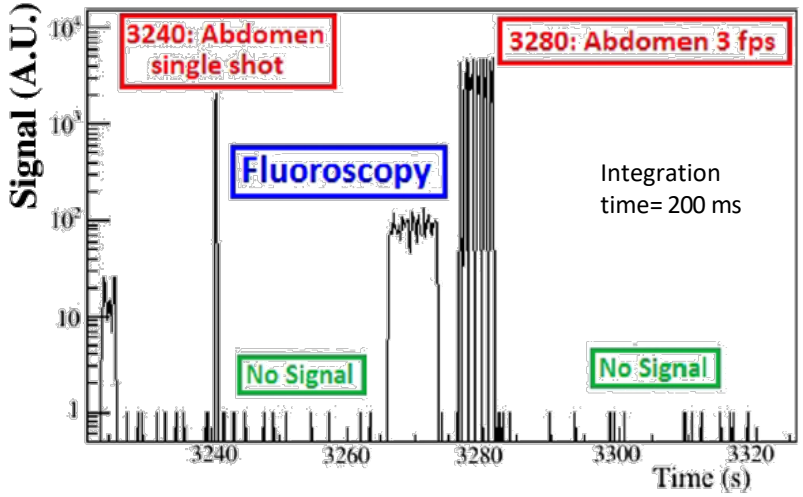
- Absorbed dose measurements



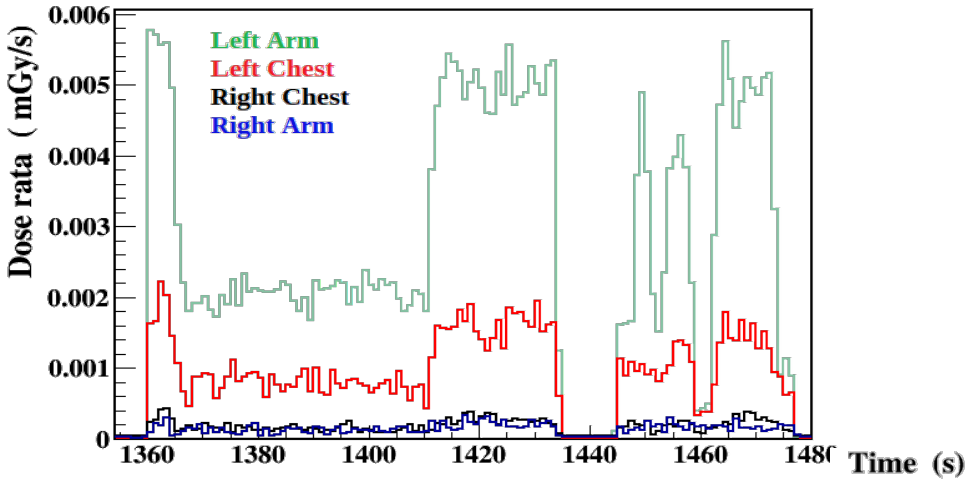
Linear correlation:

- slope ≈ 1 (accuracy);
- precision is better than TLD precision

- Time profile of irradiation



- Mapping of absorbed dose



Experimental results (3)

- The commercial CMOS image sensor is a candidate for a portable dosimetric system
- A final portable version of the system prototype has been produced, implementing data reduction algorithm, as element of a Wireless Dosimeter Network
- The final prototype has been validated in operating room during several IRad procedures with performances comparable to the passive dosimeters

Device name	Energy range	Dose rate range	Dimensions	PSN
Unfors EDD-30	14 – 120 (± 10%) keV	30 - 24000 mSv/h	6 × 11 × 22 mm^3	no
Philips DoseAware	48 - 118 (± 20%) keV	0.04 - 300 mSv/h	45 × 45 × 10 mm^3	yes
Thermoscientific EPD Mk2+	15 - 10000 (± 30%) keV	0 - 4000 mSv/h	85 × 63 × 19 mm^3	no
Dosilab EDM III	20 - 6000 keV	0.0005 - 1000 mSv/h	n.a.	no
RaySafe i2	33 - 101keV	0.040 - 300 mSv/h	45 × 45 × 10 mm^3	yes
Atomtex AT3509C	15 - 10000 keV	0.0001 - 5000 mSv/h	105 × 58 × 23 mm^3	no
RAPID System	2 - 150 keV	0.0003 - 11000 mSv/h	86 X 46 X 16 mm^3	yes

Outcome of the RAPID research activity

- *Research grants: 230 k€ (70 k€ for material; 160 k€ for people)*
  - ***Real Time Active PIxel Dosimeter** RAPID (INFN Project), **Research Grant funded by Regione Umbria** (Progetto POR Umbria FSE 2007-2013), **Research Project** (Fondazione Cassa di Risparmio di Perugia)*
  - # grants for PostDoc: 2
  - # grants for post-laurea students: 5
- Papers
  - # Conference talks and posters: 13 (Physics, Engineering, Medical, Nurse);
  - # Papers and Proceedings: 13
- Activities for students:
  - # of Bachelor and Master Thesis: 2+2
  - # of PhD Thesis: 2 (1 UNIPG + 1 UNIMORE)
  - *Alternanza Scuola Lavoro: 8* students (1 month each)
- Technology Transfer
  - 1 "knowledge transfer" agreement with a medical device firm is ongoing

Outcome of the other research activities in this field

- *Amount of research grants* (*100 k€: 60 k€ for material; 40 k€ for people*)
  - *# grants for post-laurea students: 1*
  - *# grants for PostDoc: 1*
- Papers
  - *# Conference talks and posters: 10*
  - *# Papers and Proceedings: 7*
- Activities for students:
  - *# of Master Thesis: 4*
- *Technology Transfer: 1 INFN patent*

Thank you for your attention

Hospital and ASL (8 staff):
Perugia, Foligno, Terni,
Città di Castello, Viterbo

INFN (2 staff) :
Sezione di Perugia

UNIPG (6 staff):
Dip. Fisica e Geologia
Dip. Ingegneria
Dip. Medicina

Other Institutions (6 staff):
Sapienza Univ.
Modena-Reggio Univ.
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