Development of a portable gamma-imaging device with coded aperture

Olivier Gal, Mehdi Gmar, Frédéric Lainé, Erwan Manach
LIST (CEA – Technological Research), CEA-Saclay, France

Fabrice Lamadie, Christophe Le Goaller, Charly Mahé
DDCO (CEA – Nuclear Energy), CEA-Marcoule, France

Oleg P. Ivanov
Kurchatov Institute, Moscow, Russia

Outline

- **Gamma imaging in nuclear facilities**
- **Gamma-imaging systems developed at CEA**
- **Development and tests of a camera with coded mask**
- **Gamma imaging with a semi-conductor pixel detector**
- **Conclusions**

Gamma imaging in nuclear facilities

Gamma imaging is a powerful tool for **radioactivity mapping in irradiating cells**:

- measurements from distance
- very little manual operation
- "direct" interpretation of measurements

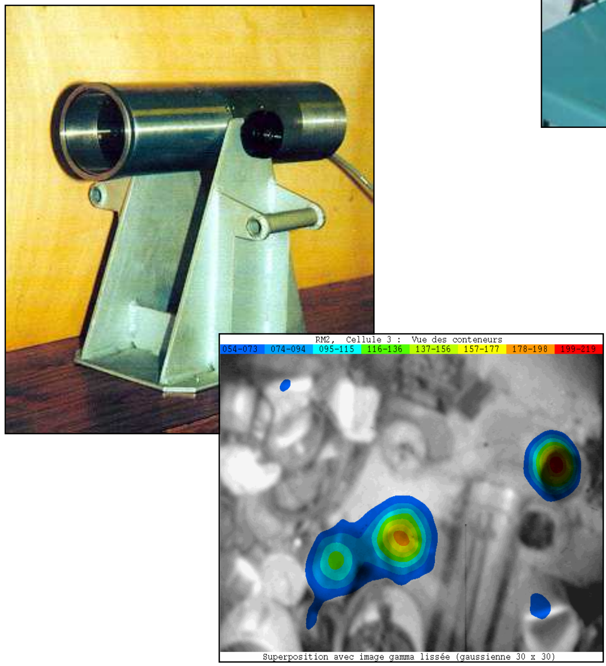
Applications:

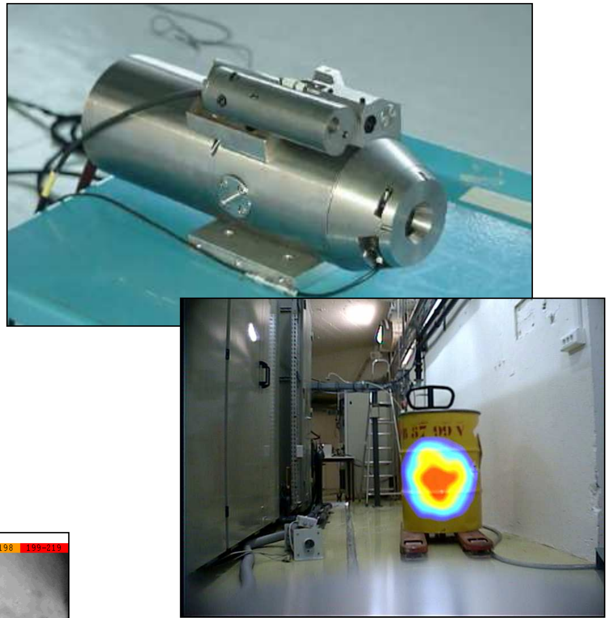
- **decontamination**
- intervention in hot cell
- **dismantling**

Gamma-imaging systems developed at CEA

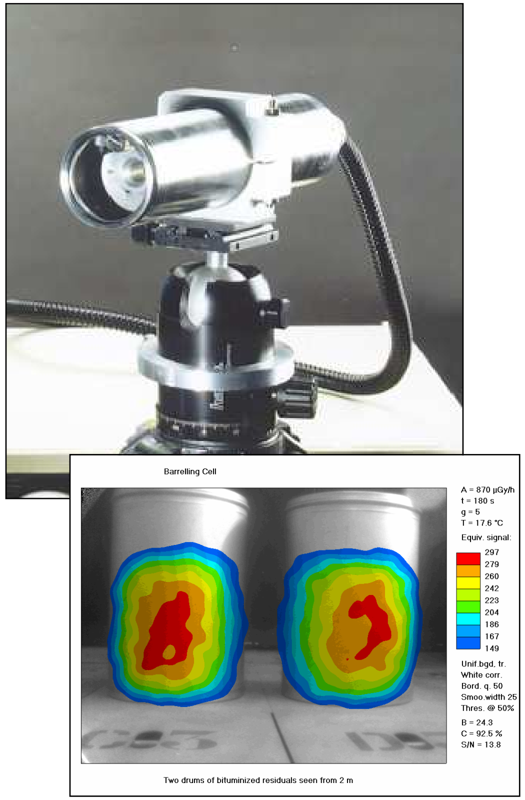
Since the 90’s, the **CEA** is involved in the development of **compact gamma cameras**.

Aladin 1 (1995)
42 kg





Aladin 2/3 (1997)
37 kg



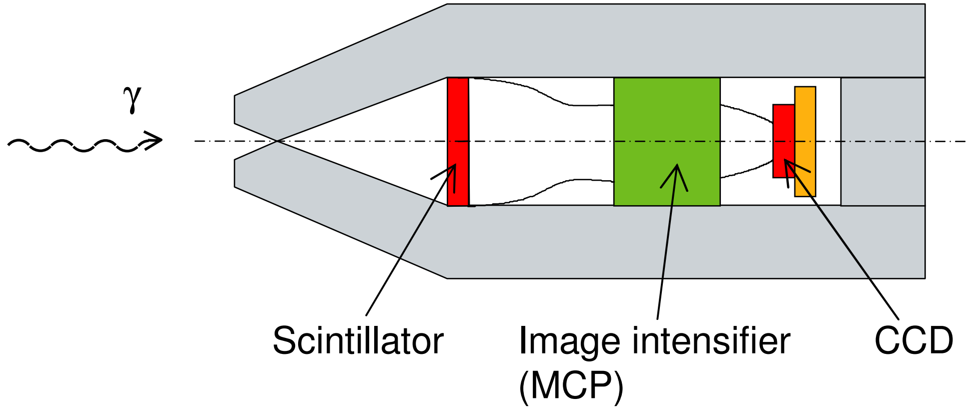
Cartogam™ (2000)
16 kg

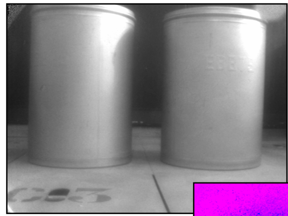
➡ ***TT to Canberra-Euriys***

Gamma-imaging systems developed at CEA

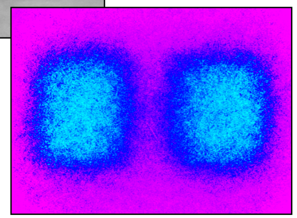
Working principle:

- Denal shielding + double-cone collimator (pinhole)
- **Scintillator CsI:Tl** 4 mm **+ intensified CCD camera** (Ø 4 cm)
- **Visible and gamma images by the same detection line**



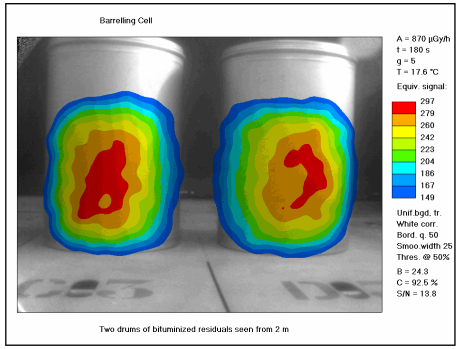


Visible image



Gamma image

Superimposed image



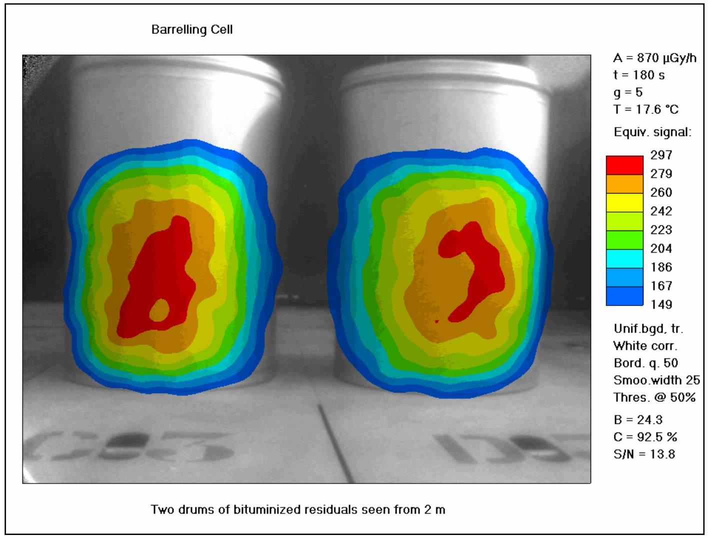
Design features (Cartogam):

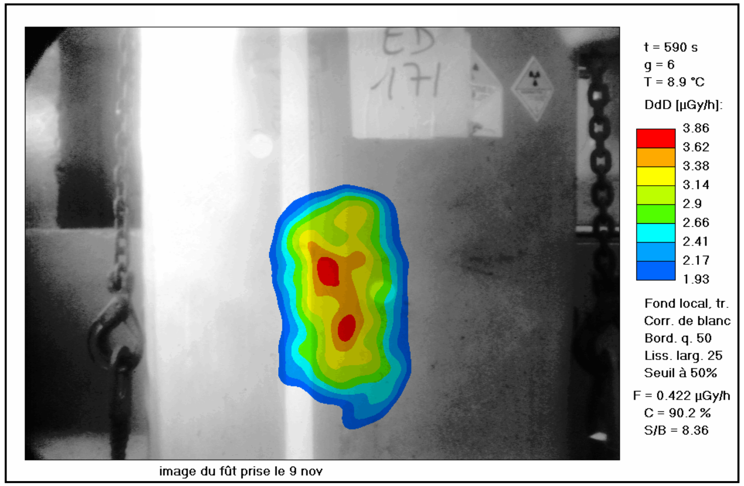
- **8 cm** in ext. diam. ; **16 kg**
- Working range:
  50 keV – 2 MeV ; **≤ 1 µGy/h – 1 Gy/h**
  (≤ 100 nGy/h in **"counting" mode**)
- Angular resolution: 1 ° to 4 °

Gamma-imaging systems developed at CEA

Examples of on-site images:

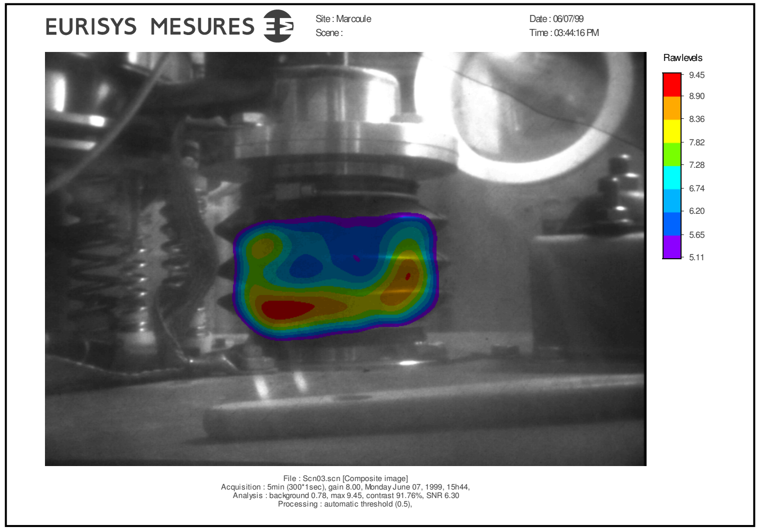
Bituminized waste drums
seen from 2 m (870 µGy/h)
Exposure: 3 min
(barrelling cell at **COGEMA/Marcoule**)





Irradiating case seen through its concrete container
Exposure: 10 min
(waste-container inspection at **CEA/Saclay**)

Accumulation of PuO_2 powder in bellows
Exposure: 3 min
(glove-box at **COGEMA/Marcoule**)



Development and tests of a camera with coded mask

Objective:

- Feasibility study of a **coded mask** fitted to the camera
- Expected gain: in **sensitivity**, also in **resolution**
- Difficulties: **miniaturisation** (holes and thickness), effect of **large sources** and of **sources out of the field of view**

Example : coded mask
of the ***INTEGRAL telescope***
~ 1 m × 1 m; dist. ~ 3 m
Cf. presentation by F. Lebrun

Development in the framework of an INTAS (*) **Collaboration:**

- Partners: *CEA (Saclay + Marcoule)*
  Kurchatov Institute (Moscow)
  MEPHI (Moscow)
  SCK-CEN Mol (Belgium)
- End of the project: 2004

(*) *The* ***Int****ernational* ***As****sociation for the Promotion of Co-operation with Scientists from the New Independent States (NIS) of the Former Soviet Union*

Development and tests of a camera with coded mask

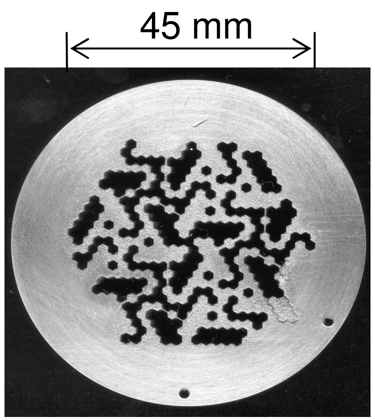
Principle:

- Replace the pinhole by **multiple holes**
- Hole positions according to **mathematical rules**

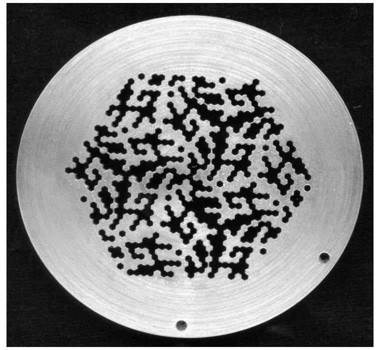
→ **Decoding algorithm**

$$d_{ij} = \sum_{kl} r_{kl} a_{k+i,l+j}$$

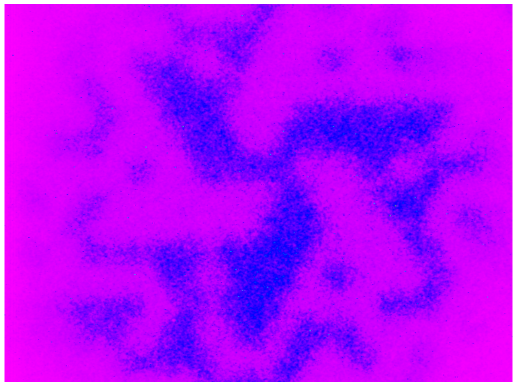
(correlation product) [1]



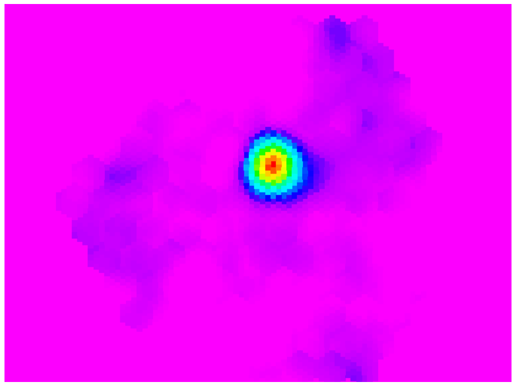
HURA of rank 6
Hole step = 1.85 mm
Thickness = 12 mm



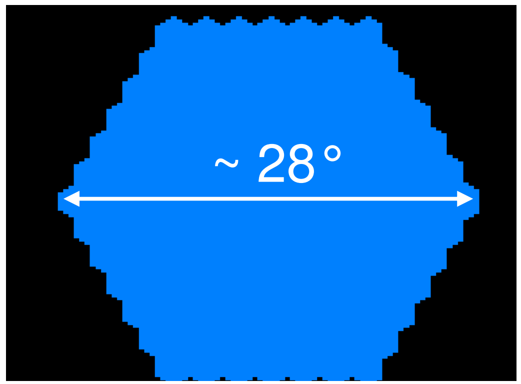
HURA of rank 9
Hole step = 1.26 mm
Thickness = 4 and 6 mm



Raw image



Decoded image



Field of view

[1] E.E. Fenimore and T.M. Cannon, *Applied Optics*, vol. 17(3), pp. 337-347 (1978)

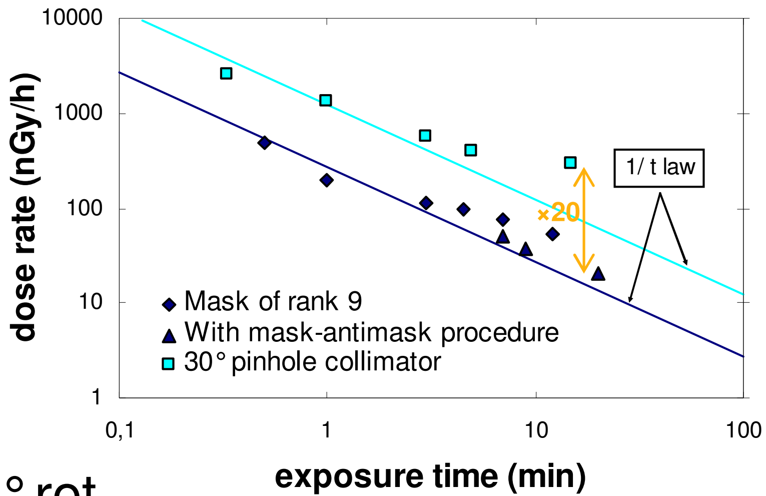
Development and tests of a camera with coded mask

Resolution limit:

- Varies little with γ energy (contrary to pinhole collimator)
- **Significant gain**, especially for ^{60}Co (1.25 MeV): 3° vs. 6.7°

Detection limit:

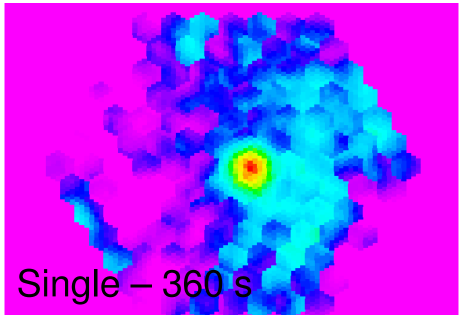
- The coded mask is at least **5 times as sensitive** as the pinhole collimator
  (**10 to 20 times** for small dose rates)

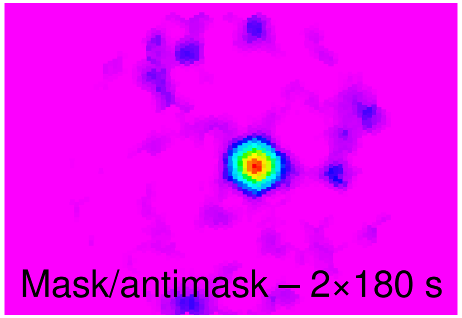


Background removal:

- Masks are **anti-symmetric** by 60° rot.
- Make 2 id° images with 60° rotation, decode the difference

Ex.: ^{137}Cs in high ^{60}Co ambiance



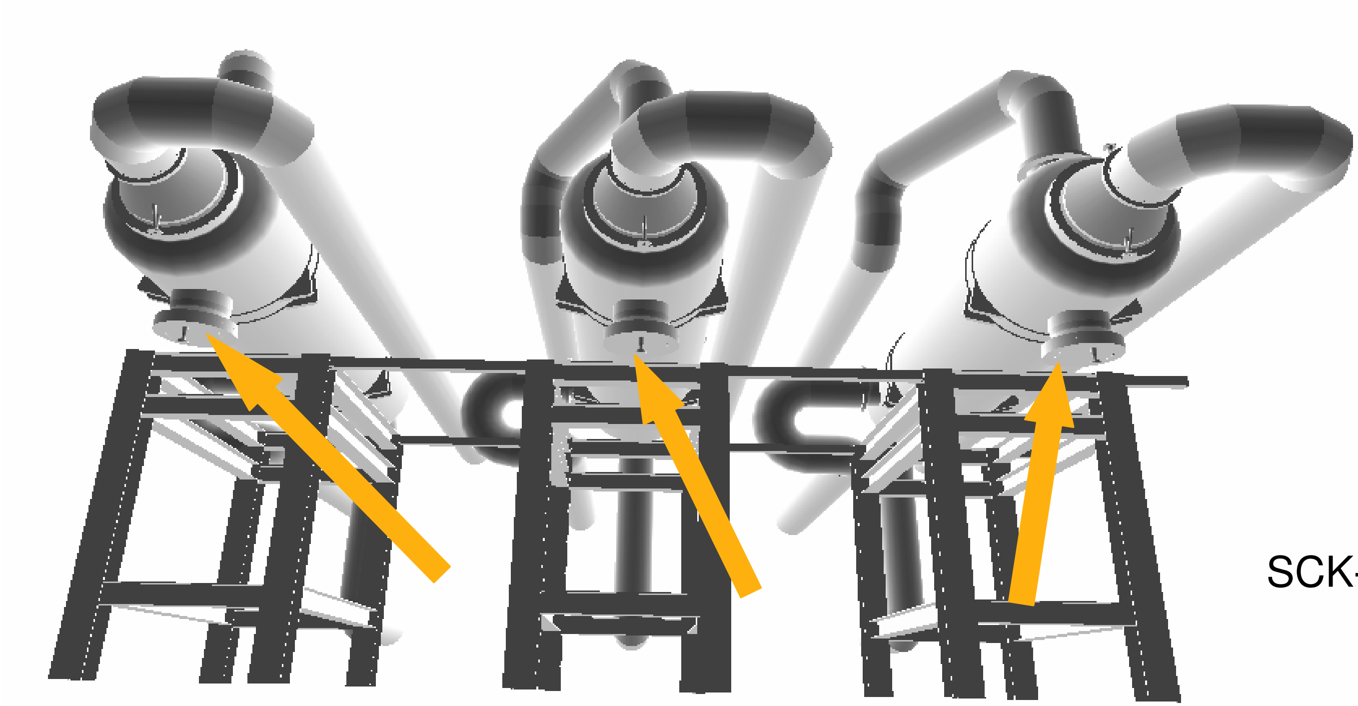


M. Gmar, O. Gal, C. Le Goaller, et al., *IEEE Trans. Nucl. Sci.*, vol. 51(4), pp. 1682-1687 (2004)

Development and tests of a camera with coded mask

Tests on site SCK-CEN, Mol (Belgium): (1)

- **One-week campaign** realized with the cameras *Cartogam* and *Aladin*.
- Search for **hot spots** on **heat exchangers**, in BR2 reactor.
- Comparison between collimator and coded mask configurations.



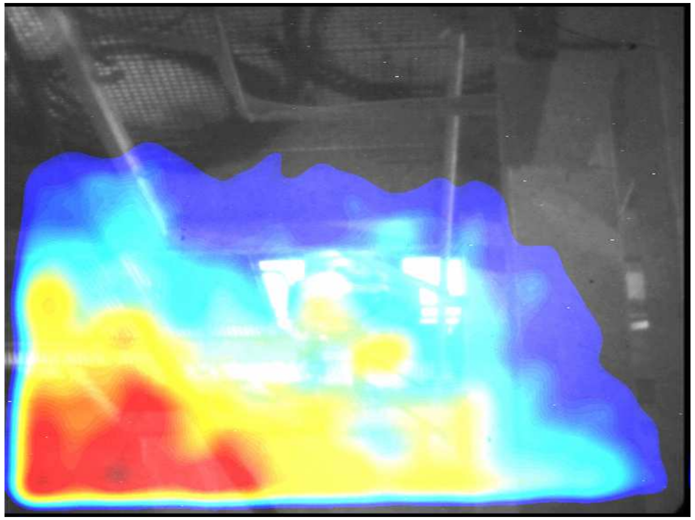
SCK-CEN / BR2

Development and tests of a camera with coded mask

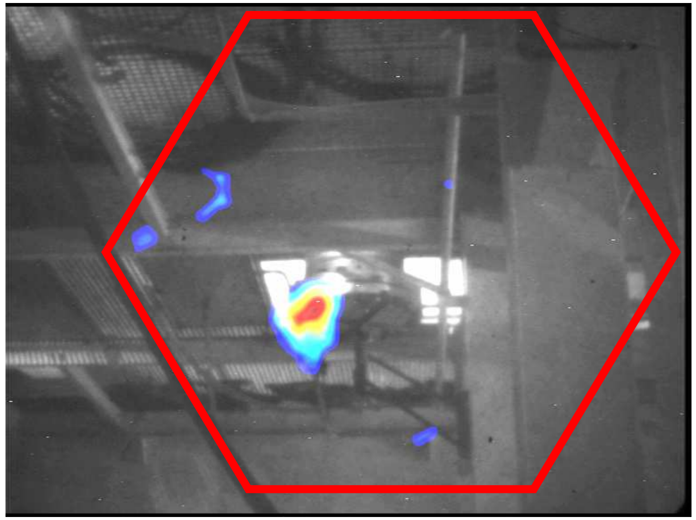
Tests on site SCK-CEN, Mol (Belgium): (2)

- Presence of **intense hot spots out of the field of view**, above the camera
- The camera was **often unusable** with the **pinhole collimator**
- **Background removal** very efficient with the **coded mask**

With 50° collimator



With coded mask

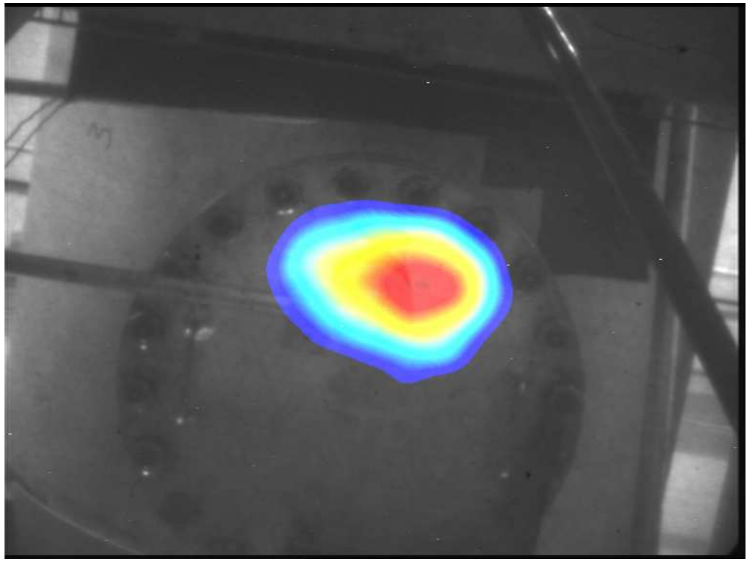


Development and tests of a camera with coded mask

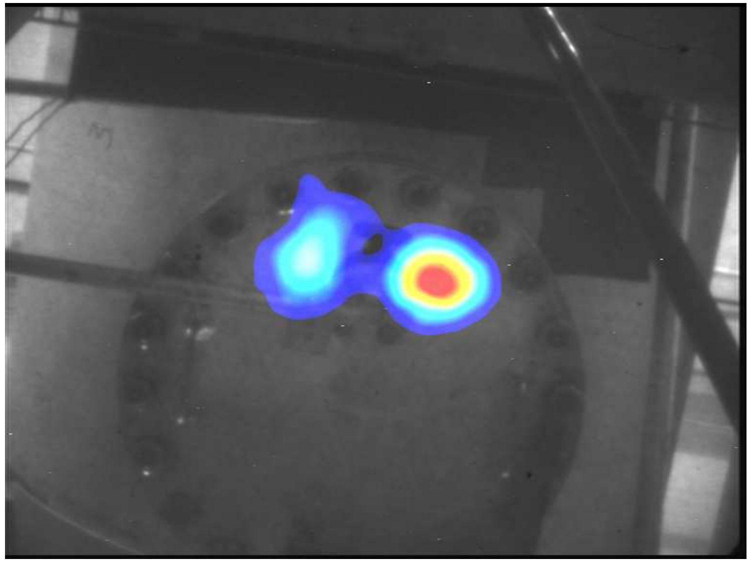
Tests on site SCK-CEN, Mol (Belgium): (3)

- **Gain in angular resolution** very significant in comparison with the pinhole collimator

With 50° collimator



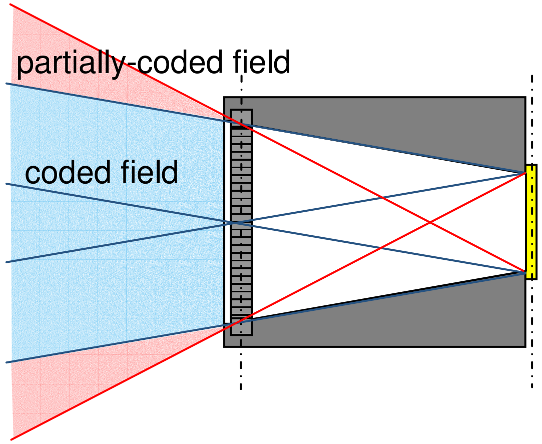
With coded mask

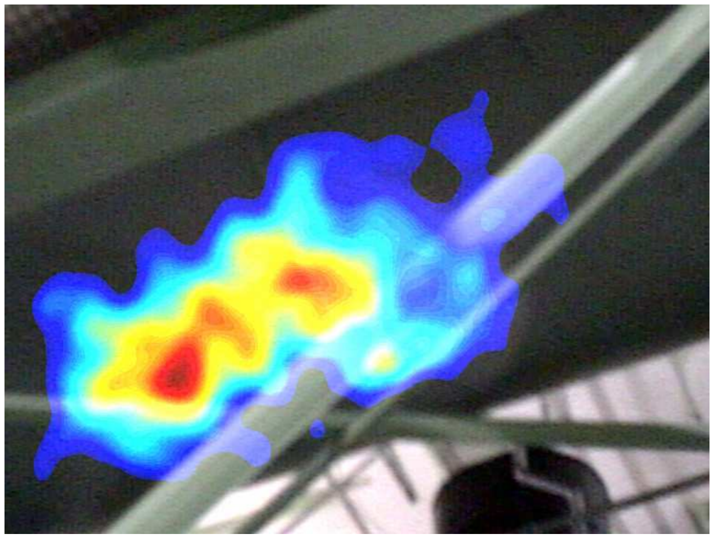


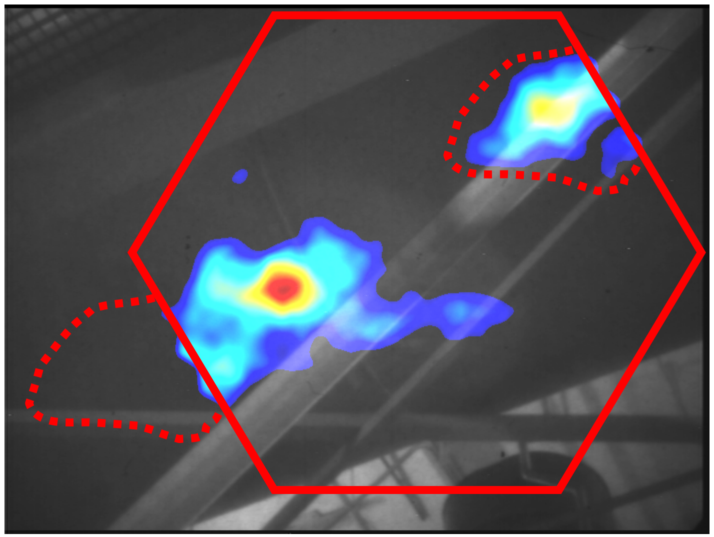
Tests on site SCK-CEN, Mol (Belgium): (4)

Problem of the **partially-coded sources**:

- Produce **artefacts** in the image, shifted by one mask period.
- Study of **correction algorithms** is under way.







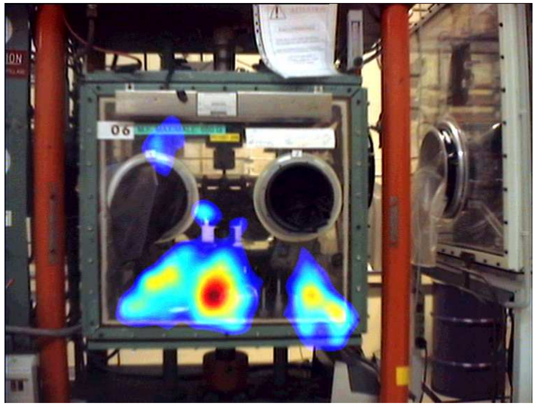
Development and tests of a camera with coded mask

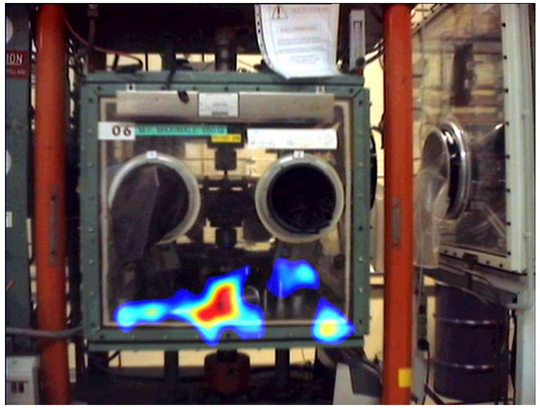
Other images (50° pinhole collimator vs. coded mask):

Pu contamination in a glove-box

Exposure: **30 min** vs. **20 s**

(CEA/Cadarache)



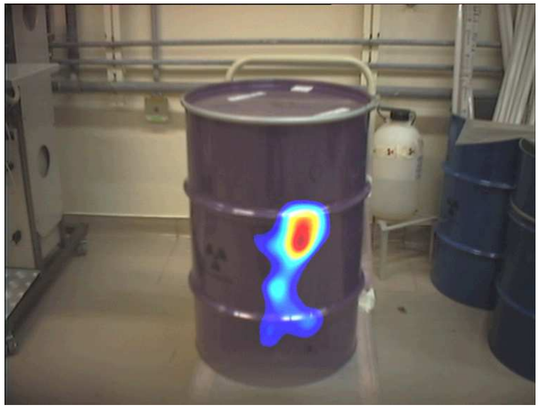


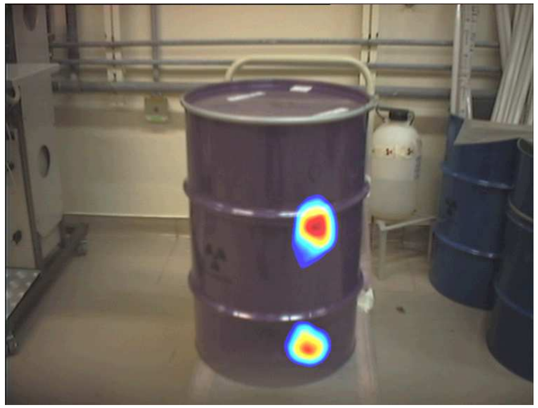
50° pinhole collimator | coded mask

Pu sources (~1 g) in a waste drum

Exposure: **30 min** vs. **7 min**

(CEA/Cadarache)



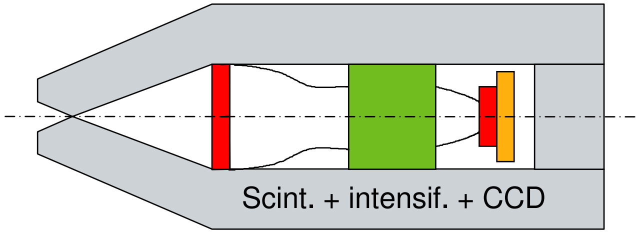


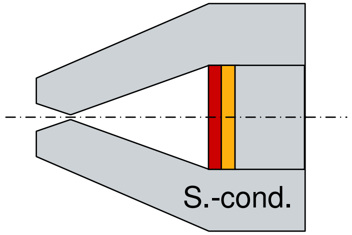
Gamma imaging with a semi-conductor pixel detector

Principle:

- Objective: replace the multiple conversion stages by a **direct conversion**, in photon-couting mode
- Advantages: sensitivity (SNR), **compactness (camera < 10 kg)**
- Difficulty: **pixels** of ~100×100 µm^2

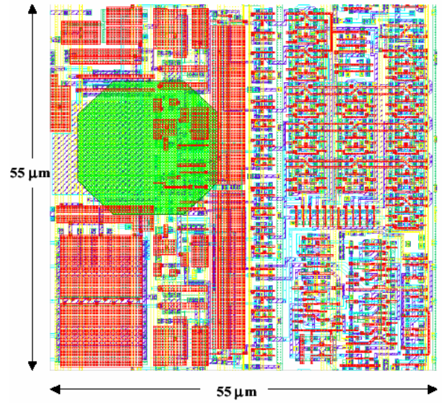
➡ **ASIC, hybridization**





Participation in the *Medipix Collaboration* (*) for the ASIC develoment

- **The Medipix2 chip:**
  14 mm × 14 mm
  256×256 pixels of **55 µm**
  2 thresholds + 1 counter per pixel (13 bits)
- **Substrate** (for high energy) :
  at least **1 mm of CdTe**, preferably **4 mm**



Pixel CAD scheme

(*) http://www.cern.ch/MEDIPIX/

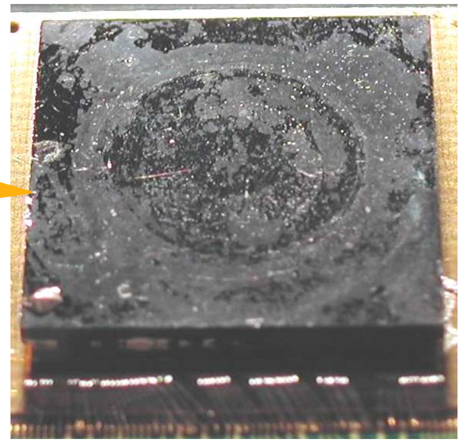
Results:

- First detectors hybridized on **CdTe (1 mm)** delivered in **June 03** and **November 03**
  - pixelated CdTe substrate: *Acrorad* (Japan) – THM CdTe:Cl
  - hybridization: *AIT* (Hong Kong) – Indium bump-bonding

M. Chmeissani, C. Fröjdh, O. Gal, et al., *IEEE Trans. Nucl. Sci.*, vol. 51(5), pp. 2379-2385 (2004)

+ Presentations by M. Maiorino (Session 2) and C. Fröjdh (Session 5) + Poster P23 (M. Maiorino)

Medipix2 chipboard (4 cm × 7 cm)



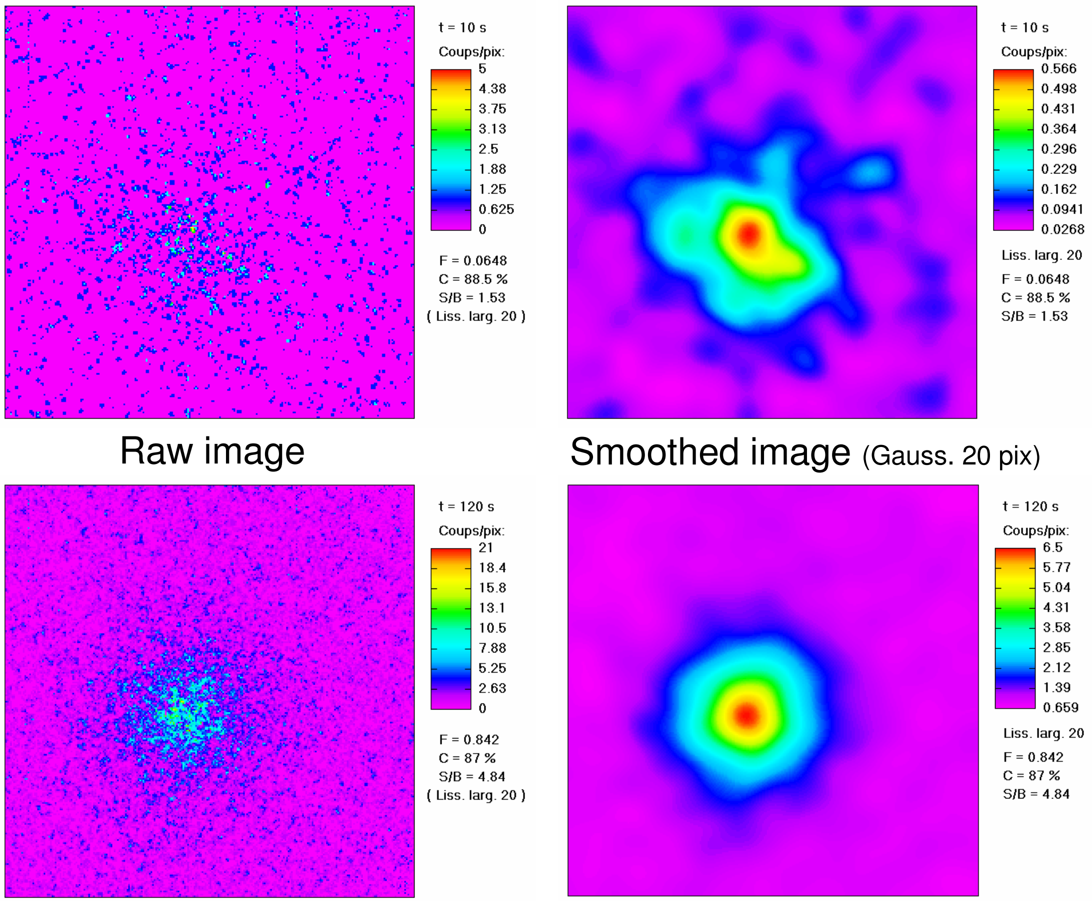
CdTe detector (1 mm thick)

Measurements at high energy with the CdTe detector – 1 mm:

- **^{137}Cs source** (662 keV)
- 90 µGy/h ($8 \cdot 10^3$ ph/cm²/s)
- Efficiency: **4.5%**
- 50° pinhole collimator

10 s

120 s



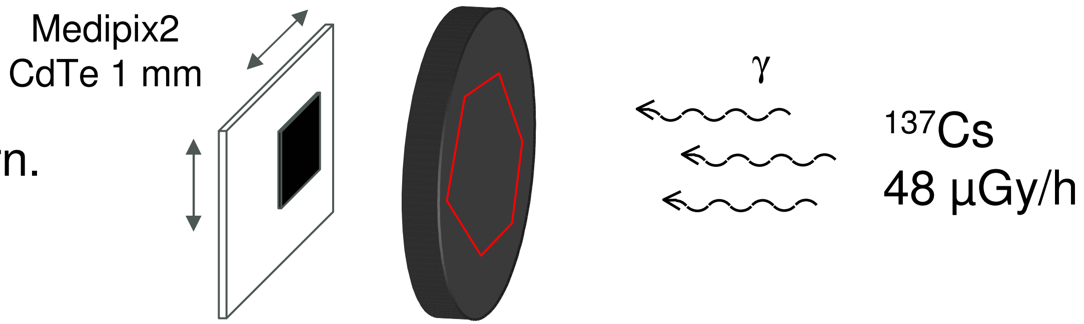
→ **More sensitive** than the present camera, at equal exposure

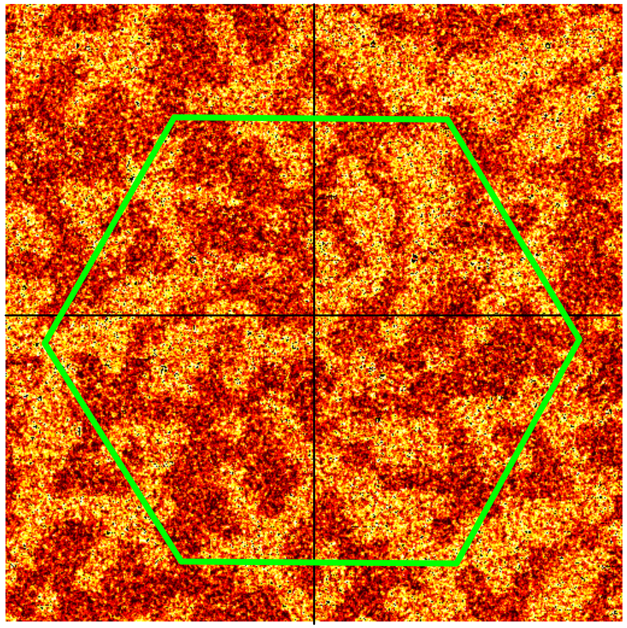
→ **Detection limit** much lower, for long exposures (230 nGy/h in 15 min)

Gamma imaging with a semi-conductor pixel detector

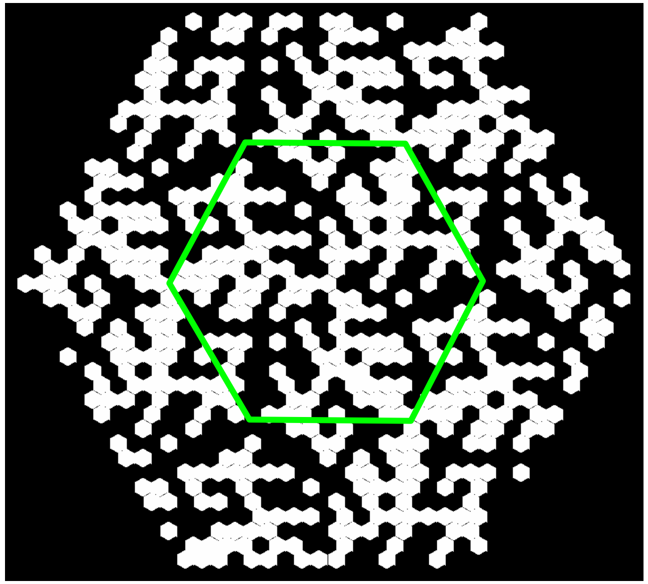
First tests of Medipix2/CdTe with a coded mask: (1)

Detector should be **translated** to cover the mask central pattern.





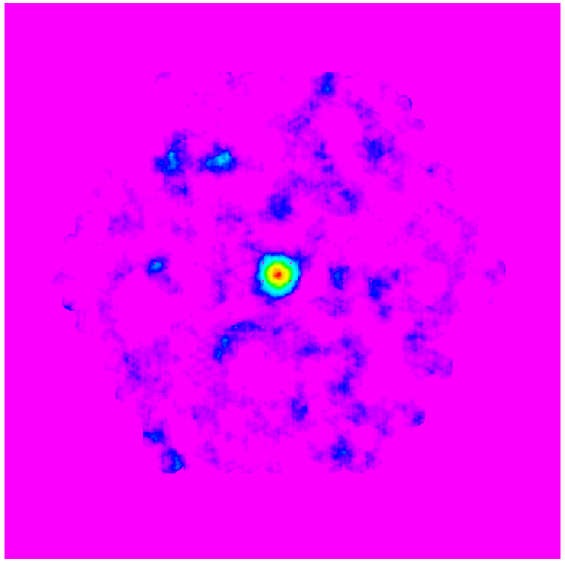
Assembly: surface equivalent to 4 images (180 s exposure).



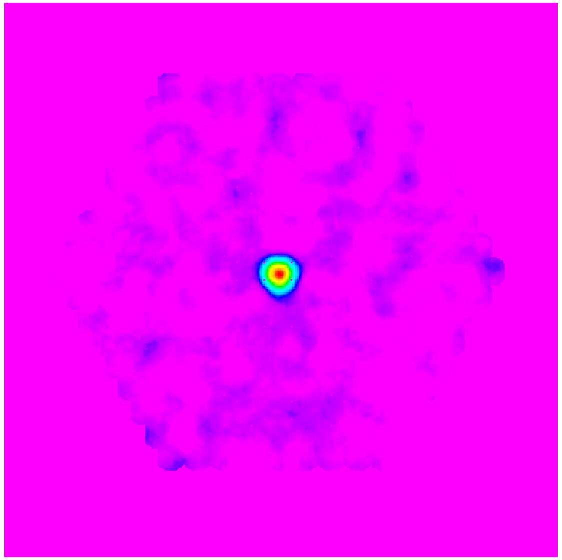
Mask of rank 9

First tests of Medipix2/CdTe with a coded mask: (2)

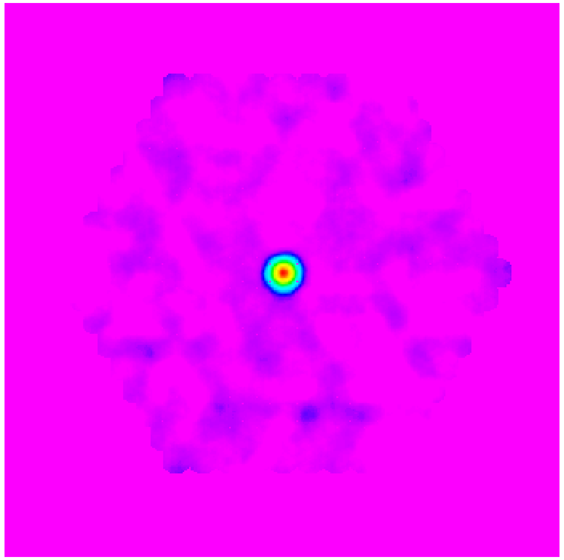
- **Decoded images**, for ^{137}Cs – 48 µGy/h



15 s



60 s



180 s

- **Image quality** is very encouraging, particularly the **resolution**
- Some ***systematic errors***, possibly due to misalignments in the assembling, mask rotation, sensitivity inhomogeneities…

Conclusions

- Use of **miniaturized coded mask** for **gamma imaging** brings important gain in **sensitivity** (up to 20 times) and in **angular resolution** (especially at high energy), allows **background removal** by the **mask-antimask procedure**.
- Performances quantified in laboratory tests and verified on site.
- The next stage is the realization of a **motorized prototype** in order to make on-site operation easier.

- At longer term, the use of **Medipix2/CdTe** instead of scintillator + intensified CCD will increase sensitivity and compactness.
- The association of a **Medipix2/CdTe** detector with a **coded mask** could lead to very significant improvements:
  - a factor of 2 on **mass**
  - a factor $\geq$ 10 on **sensitivity**
  - a better **angular resolution**
- For that, **Medipix2/CdTe detectors** of **greater surface** and **greater thickness** would be preferable.