Interpolating Silicon Photomultipliers

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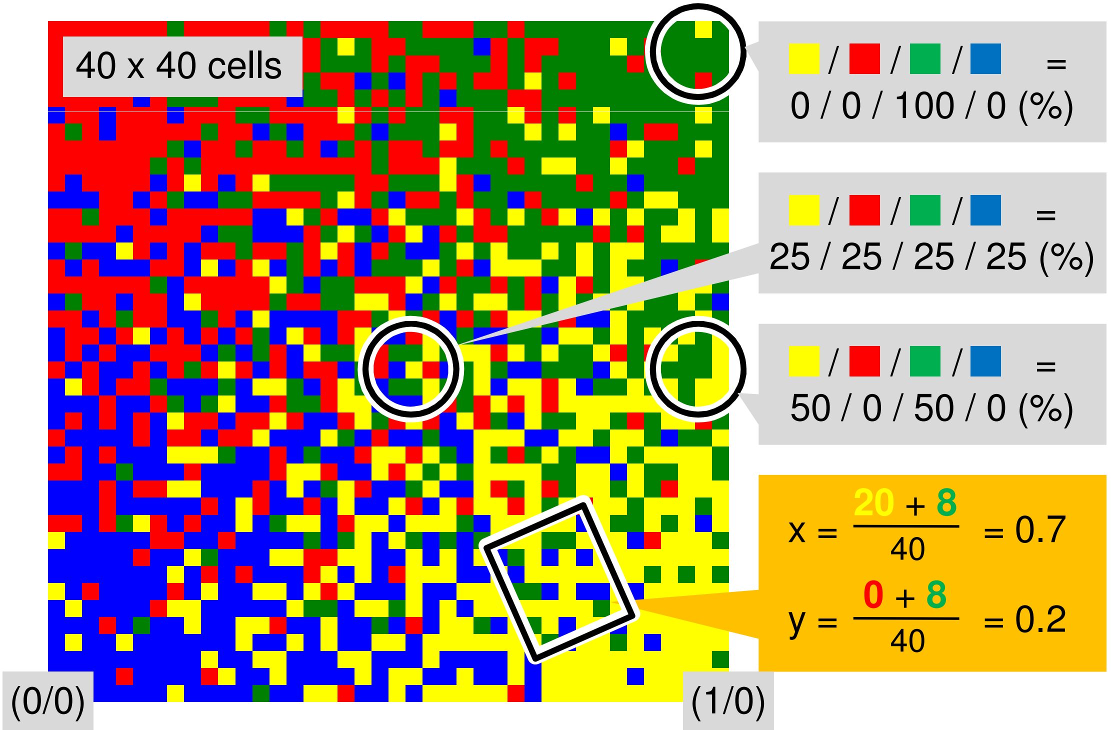
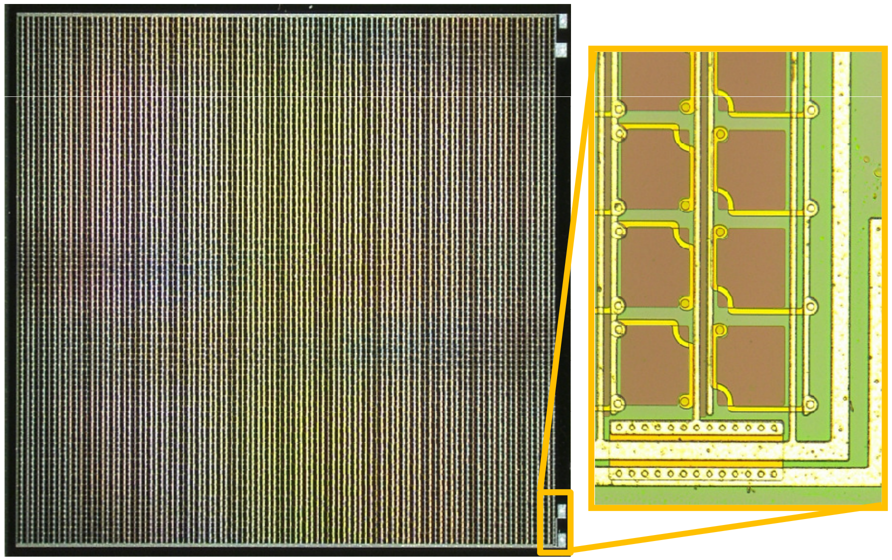
We present the novel **I**nterpolating **Si**licon **P**hoto**M**ultiplier (ISiPM) topology which provides the spatial position of photon clusters with high resolution. Individual APD cells of the ISiPM area are not connected to a *common* readout electrode, but each cell is connected to *one of several* output channels. The most straight forward embodiment is a rectangular device with four outputs located (conceptually) in the corners. The assignment of each cell to one of the channels is chosen such that the center of gravity of an arbitrarily shaped group of cells can be reconstructed as (for instance) the weighted sum of the corner signals. Due to the finite size of the cells, this exact goal can only be approximated and residual systematical errors remain. An algorithm is presented which produces fractal assignment maps with homogeneous reconstruction properties. Simulated limits of the expected spatial resolution as a function of cell size, cluster size, number of fired cells per cluster and readout noise will be presented. A first prototype device with 100×100 cells on a total size of 7.5×7.4 mm^2 has been fabricated at FBK and operated successfully. Individual LYSO crystals of ~2 mm width in a block array can be identified. The ISiPM concept offers good spatial resolution on large areas with a moderate number of readout channels so that it is a promising device for instance for PET detectors.

2 Summary Slides

The Interpolating Silicon Photo Multiplier (ISiPM)

- Idea:
  - Assign each cell of a large SiPM / MPPC to one of 4 ‘corner’ signals in a ‘fractal’ pattern
  - The relative densities are chosen such that the weighted sum yields the position (x/y)
- Properties:
  - When illuminating a *group* of cells, the *position can be reconstructed* as center of gravity
  - This allows, for instance, identification of scintillation crystals in *PET* or calorimetry



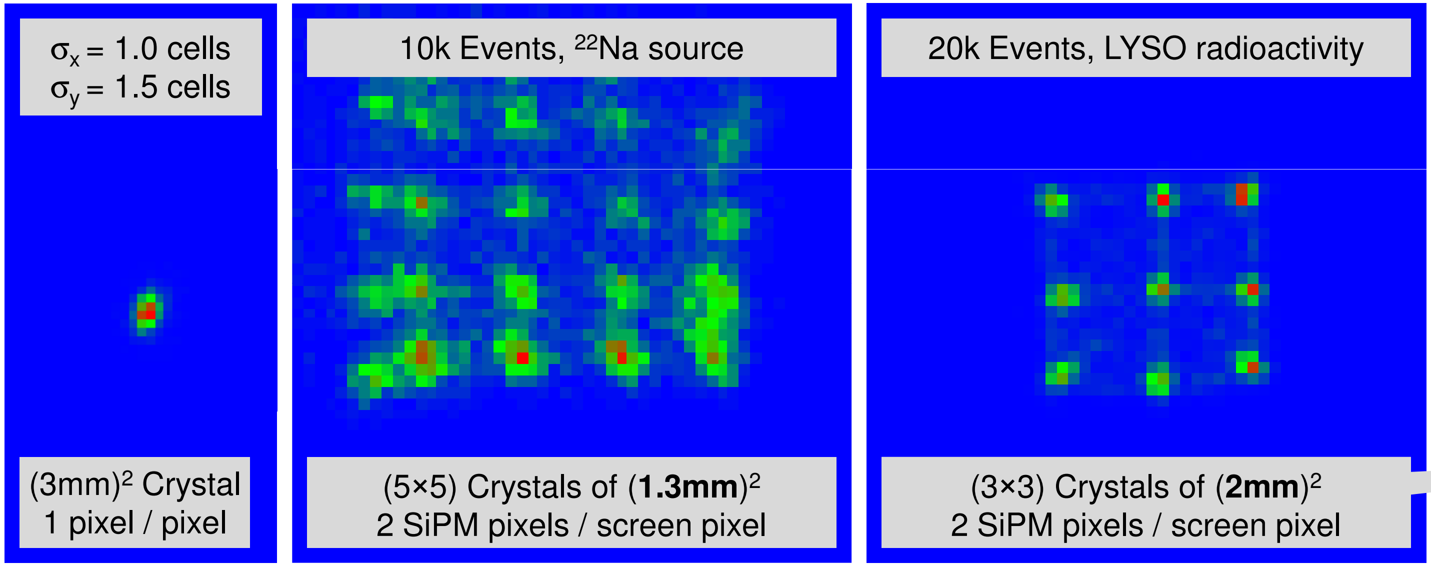


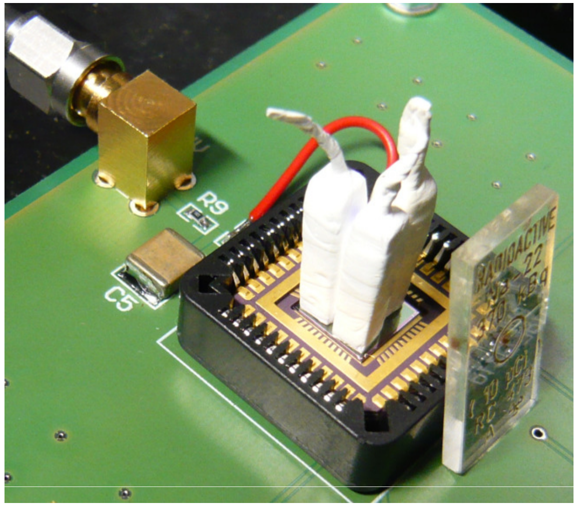
First prototype fabricated at FBK
100 x 100 cells, total device size ~7.4 x 7.4 mm^2

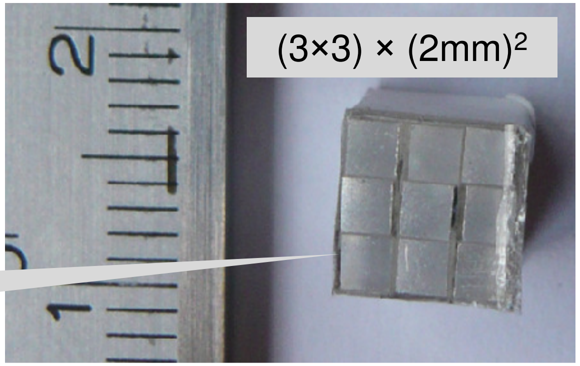
First Results

- LYSO Crystals & Arrays are standing on device, illumination with 511keV γ. Very first low-stat. results with *no* cuts / corrections:
  - Resolution < 100µm for 3mm single crystal
  - Can clearly resolve 2mm pitch crystals
  - Can still resolve 1.3mm pitch (low statistics)

  } $(7.4mm)^2$ 4 ch device







- Advantages:
  - High spatial resolution with few channels. No problems at SiPM/crystal edges. Works with arbitrary crystal geometries & orientations!

8 ‘Poster’ Slides

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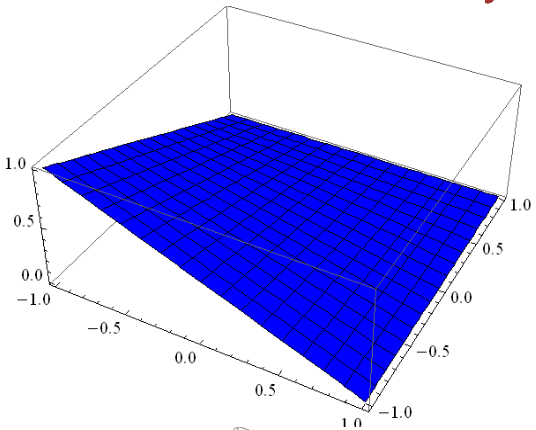
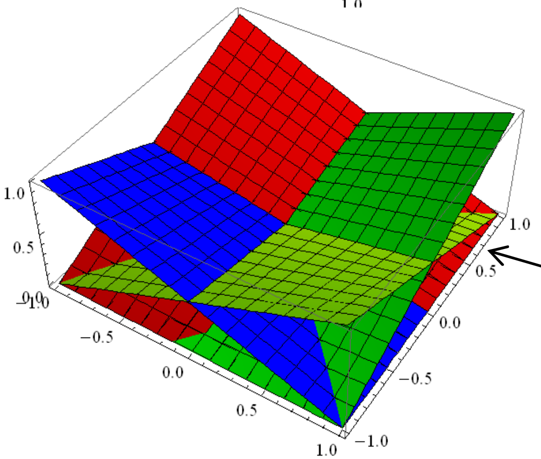
Idea

- Assign SiPM cells to one of N = 4 corners (■, ■, ■, ■)
- Chose local density of cells such that center of gravity of the 4 signals = position

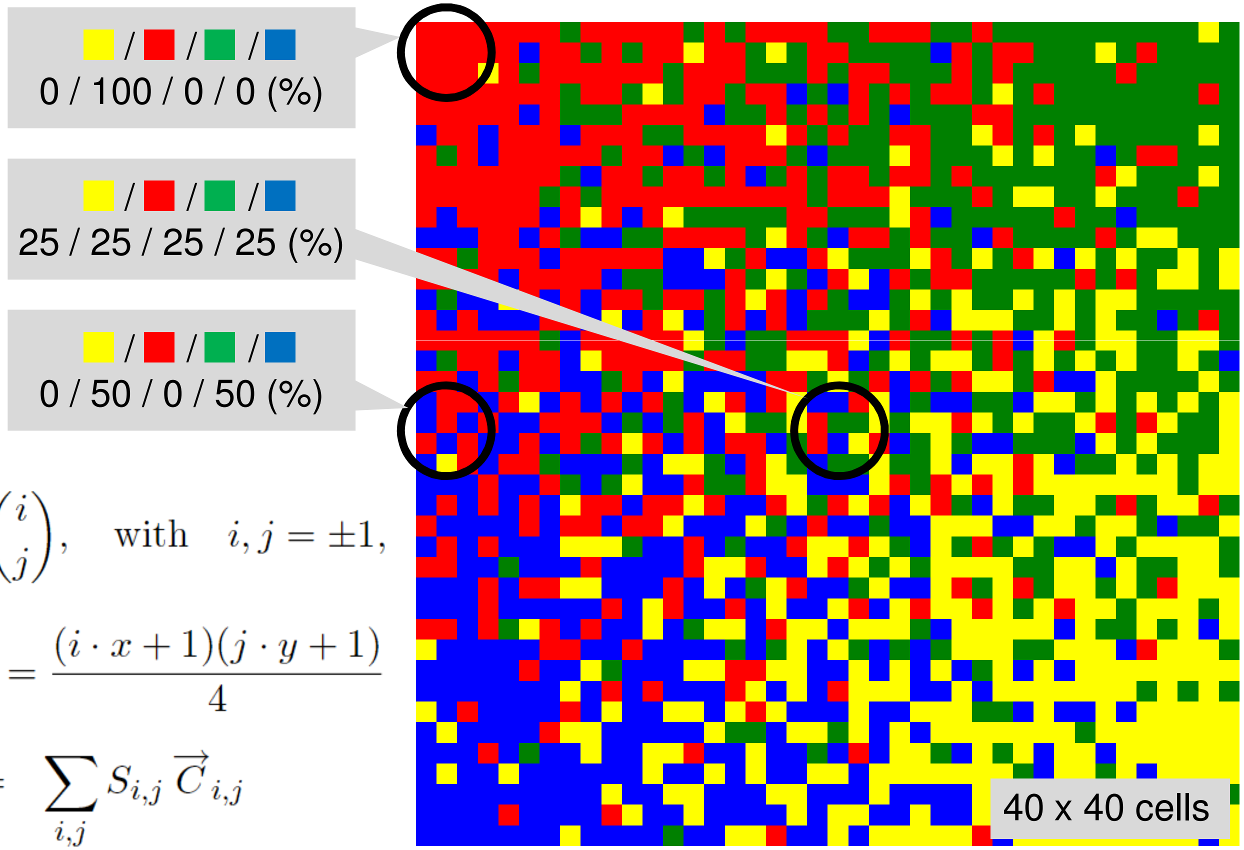




$$\vec{C}_{i,j} = \begin{pmatrix} i \\ j \end{pmatrix}, \quad \text{with} \quad i,j = \pm 1,$$

$$S_{i,j}(x,y) = \frac{(i \cdot x + 1)(j \cdot y + 1)}{4}$$

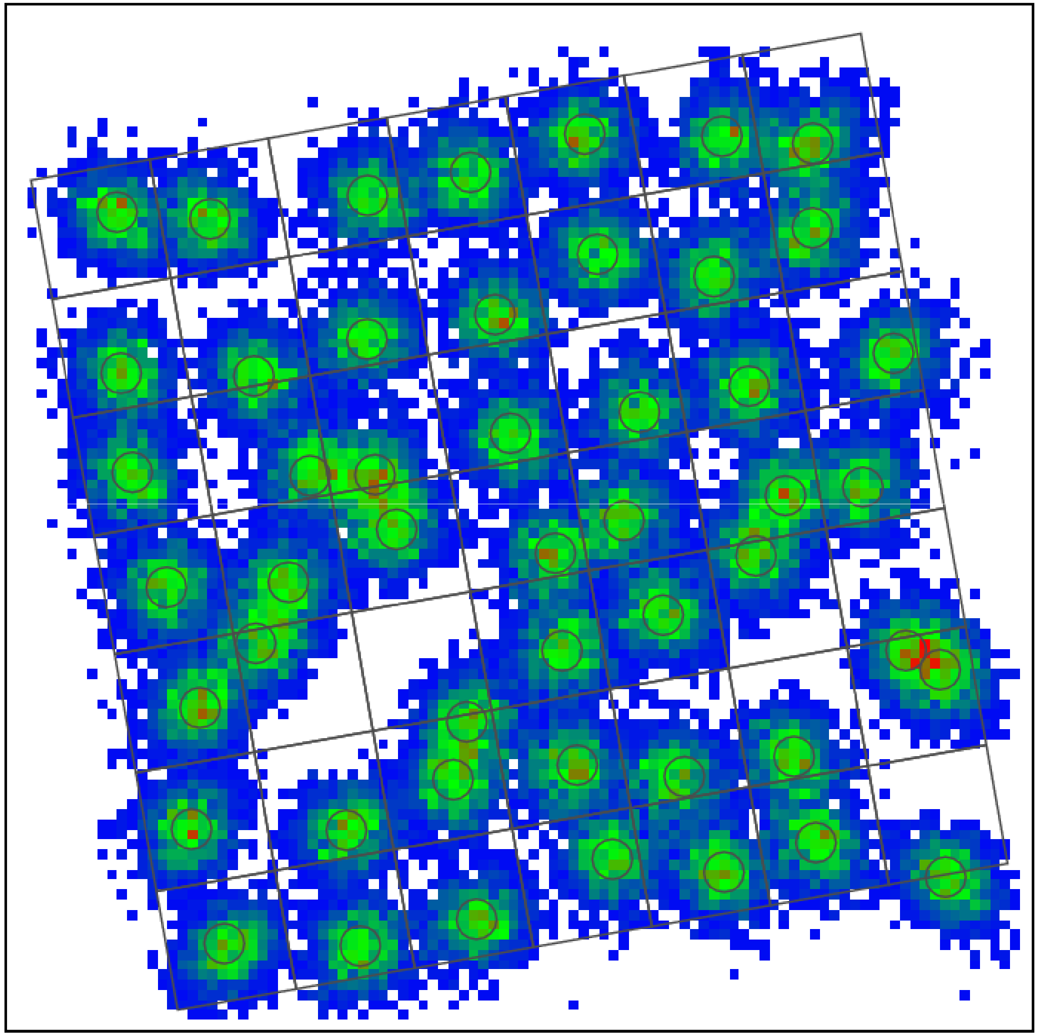
$$\vec{r}_{rek} = \sum_{i,j} S_{i,j}\, \vec{C}_{i,j}$$



- Other weighting functions and number of corners can be used

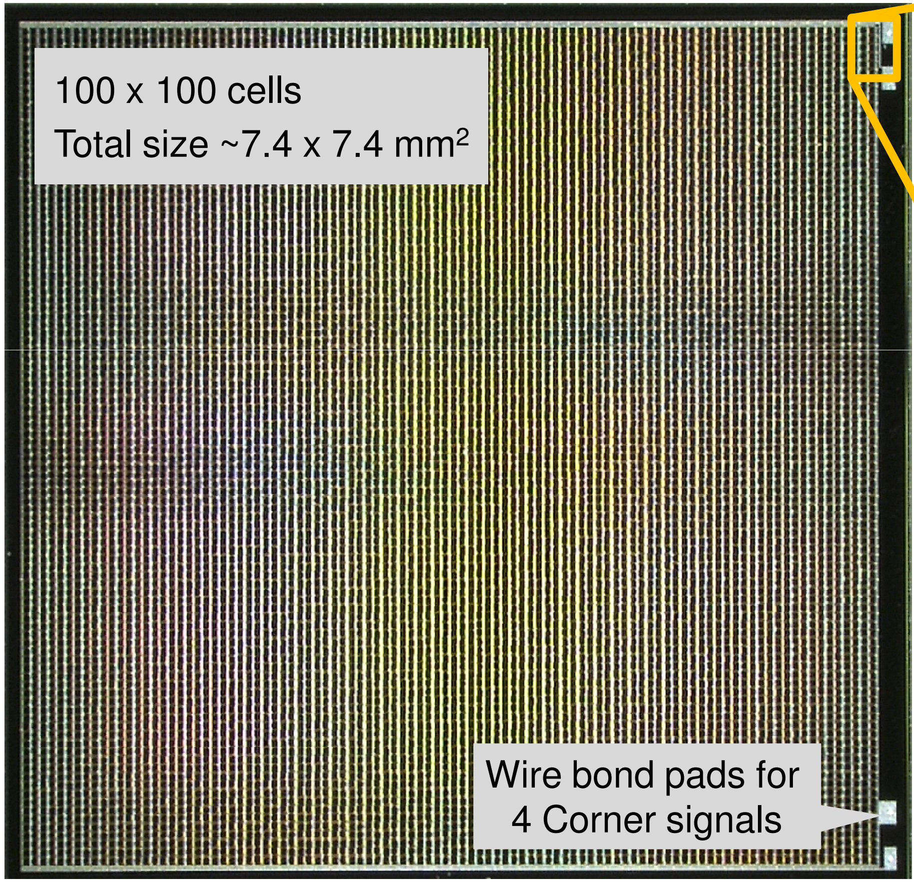
Simulation

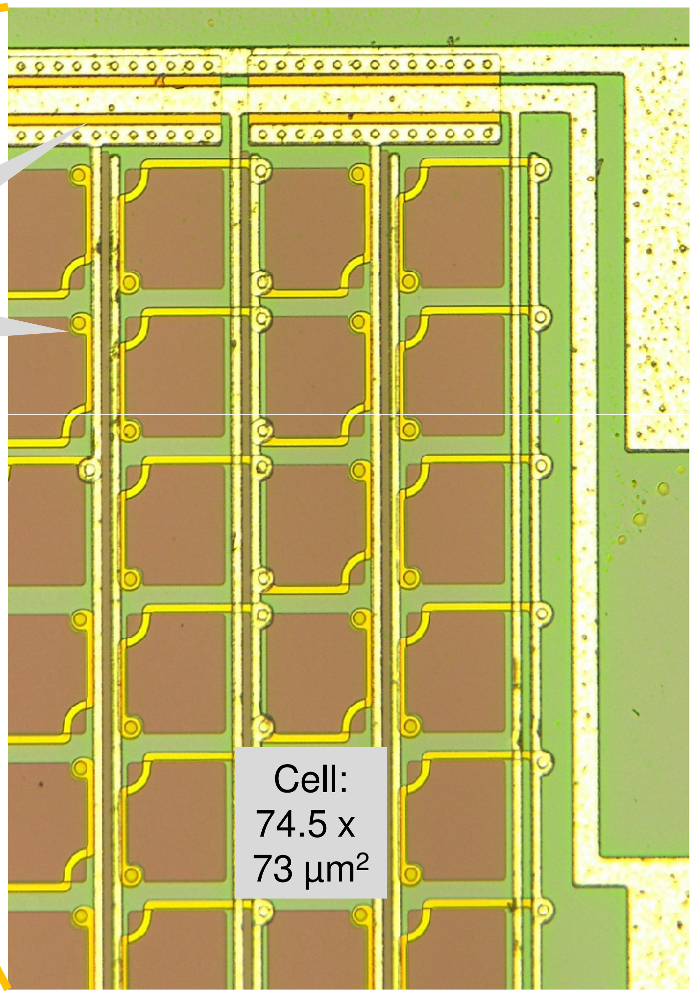
- Example for device simulation:
  - ISiPM with 100 × 100 cells
  - Array of 7 × 7 crystals (boxes)
  - Tilted on purpose to show flexibility
  - Each crystal has size of 12 × 12 cells (~1 mm^2 for Prototype device)
  - 250 randomly fired cells / crystal
  - noise per corner signal: 2 cells (rms)
- Reconstructed position is compared to (systematically shifted) center positions (circles)
- Only 7% of hits are associated to wrong crystal (offset by 1)



Prototype

- A first prototype has been fabricated at FBK, Trento, Italy (one metal layer)

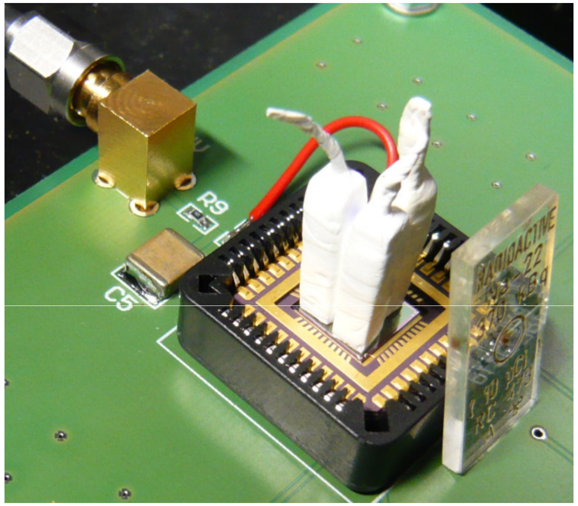


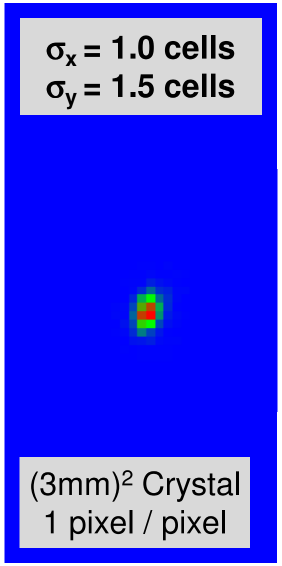


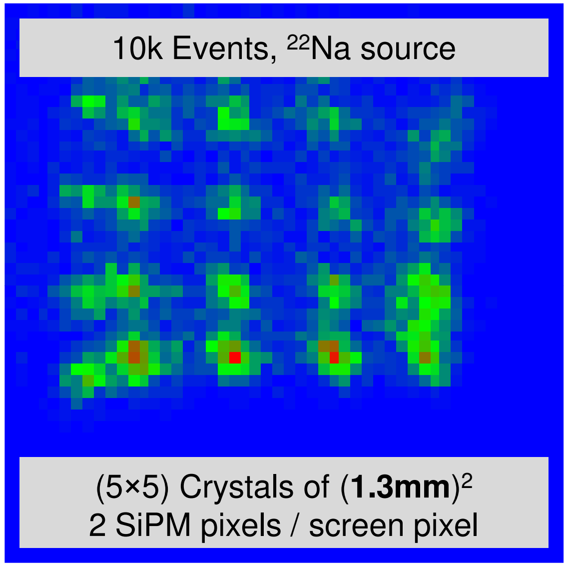
Results

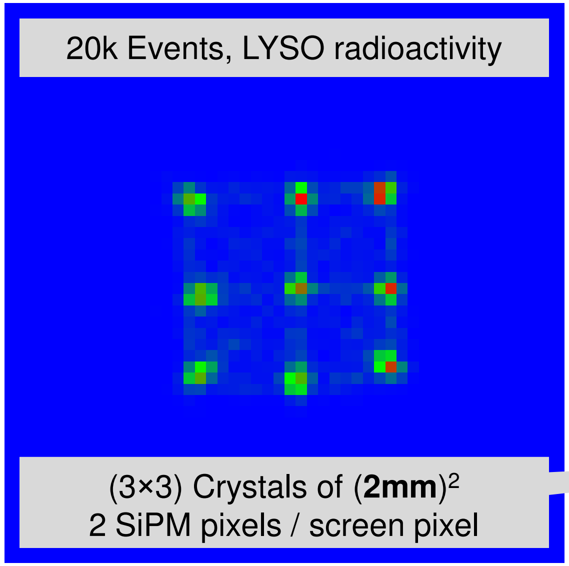
- ISiPM has been read out by 50 MHz Oscilloscope (‘peak’ measure)
- LYSO Crystals & Arrays are standing on device, illumination with 511keV Gamma
- All data plotted (no corrections / cuts):
  - Resolution < 100µm for 3mm single crystal
  - Can clearly resolve 2mm pitch
  - Can still resolve 1.3mm pitch (low statistics)

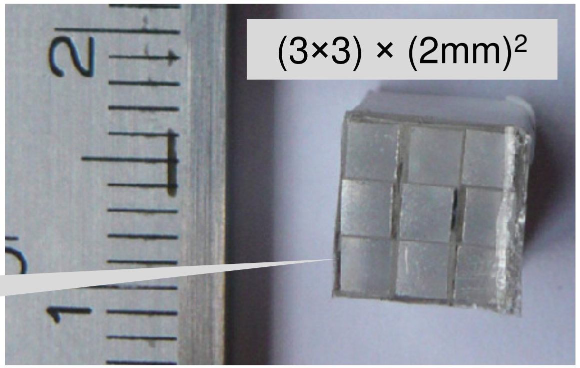
  } $(7.4\text{mm})^2$ 4 ch-device!







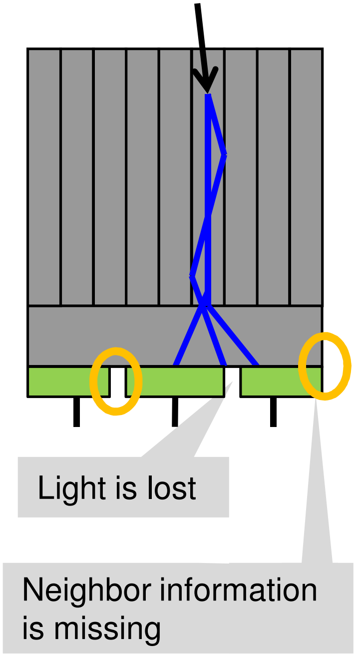




Advantages & Applications

- ISiPM determines center of gravity of clusters of any shape
- No restrictions on position / size / orientation of crystal or light spot!
- High spatial resolution with few readout channels

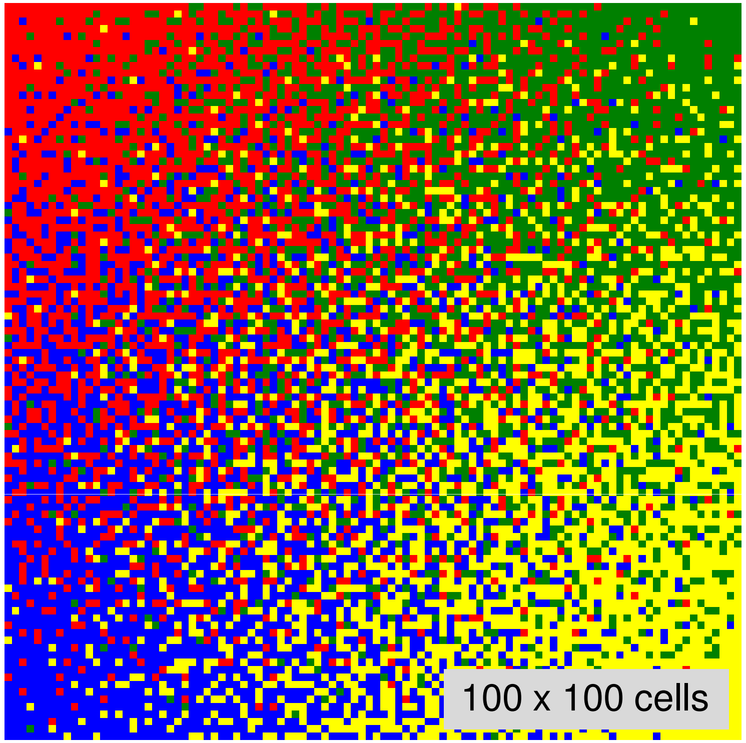
- Ideal for *crystal readout* in *calorimetry* or *PET*

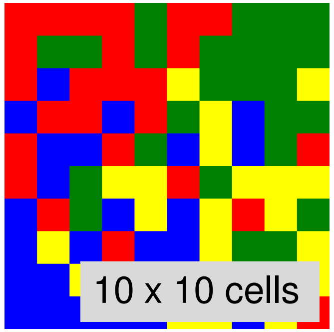


- Advantages compared to traditional light sharing:
  - Avoid problems of light loss *between* SiPM dies
  - Avoid *edge* problems (no neighbor information)
  - Better SNR because signal is confined to N=4 electrodes only
  - Simple neighbor logic sufficient
  - No fundamental problem for small crystals (becomes difficult with light sharing because light spreader must follow SiPM pitch)

Algorithm

- For each SiPM cell, calculate the *ideal* corner assignments according to the desired weighting function. (The sum of these four values is one.)
- Assign all cells to *no* corner, to start with.
- Set CLUSTERSIZE = 2
- Process all blocks of CLUSTERSIZE × CLUSTERSIZE SiPM cells, starting at a corner, stepping by CLUSTERSIZE. For each block:
  - Calculate the sum of *ideal* corner assignments for each corner I(ix,iy)
  - Calculate the number of *already fixed* assignments to each corner F(ix,iy)
  - As long as any of the I(ix,iy) > F(ix,iy) + 1, we can be sure that an assignment to corner (ix,iy) in this block is missing. Pick a *random* free position in the block and assign it to corner (ix,iy).
- Double CLUSTERSIZE and repeat the last block until all cells are assigned





Reconstruction Errors

Reconstruction Error from:

1. Binning effect due to finite cell size:

- Are Systematic
- Can be corrected for partially
- Depend details of corner assignment

2. Cell *hit statistics*

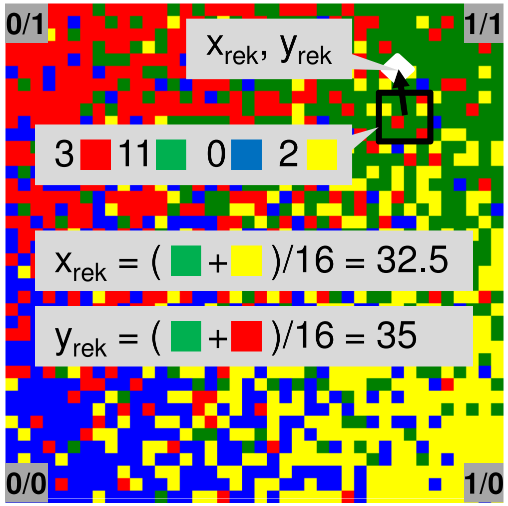
- Better for more photons

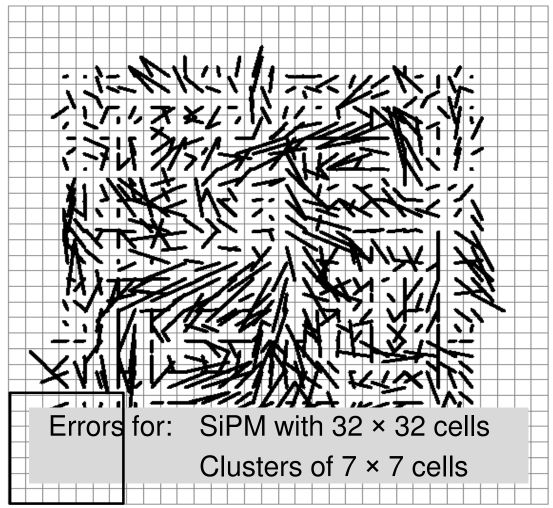
3. Readout noise

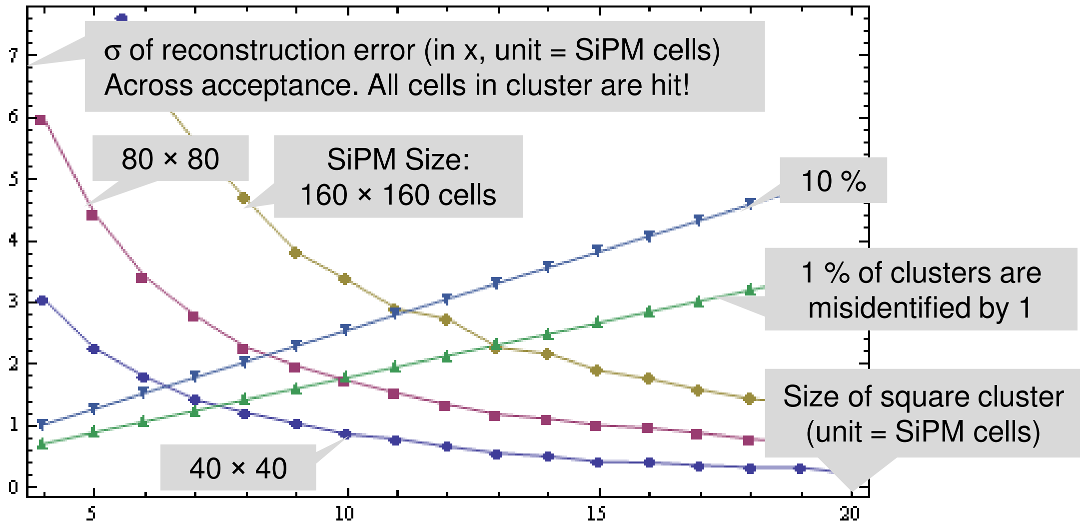
- Better for more photons

Errors become smaller for larger spots

- Better cell statistics (1)
- More photons (2)
- Better SNR (3)







Problems & Future

- Problems with *present* test devices:
  - no surface protection → shorts introduced by touching
  - Parallel busses generate crosstalk → correction required (under study)
  - Serial resistances high → signals depend on impact point
- Problems with setup
  - Acquisition slow → poor statistics
  - Triggering on one channel → corner crystals preferred
  - Tiny arrays not flat → unwanted light sharing
- Next steps
  - New devices with higher fill factor & less crosstalk
  - New setup with ADC under development
  - Implement sum trigger
  - Implement correction algorithms
  - Provide flat crystal arrays