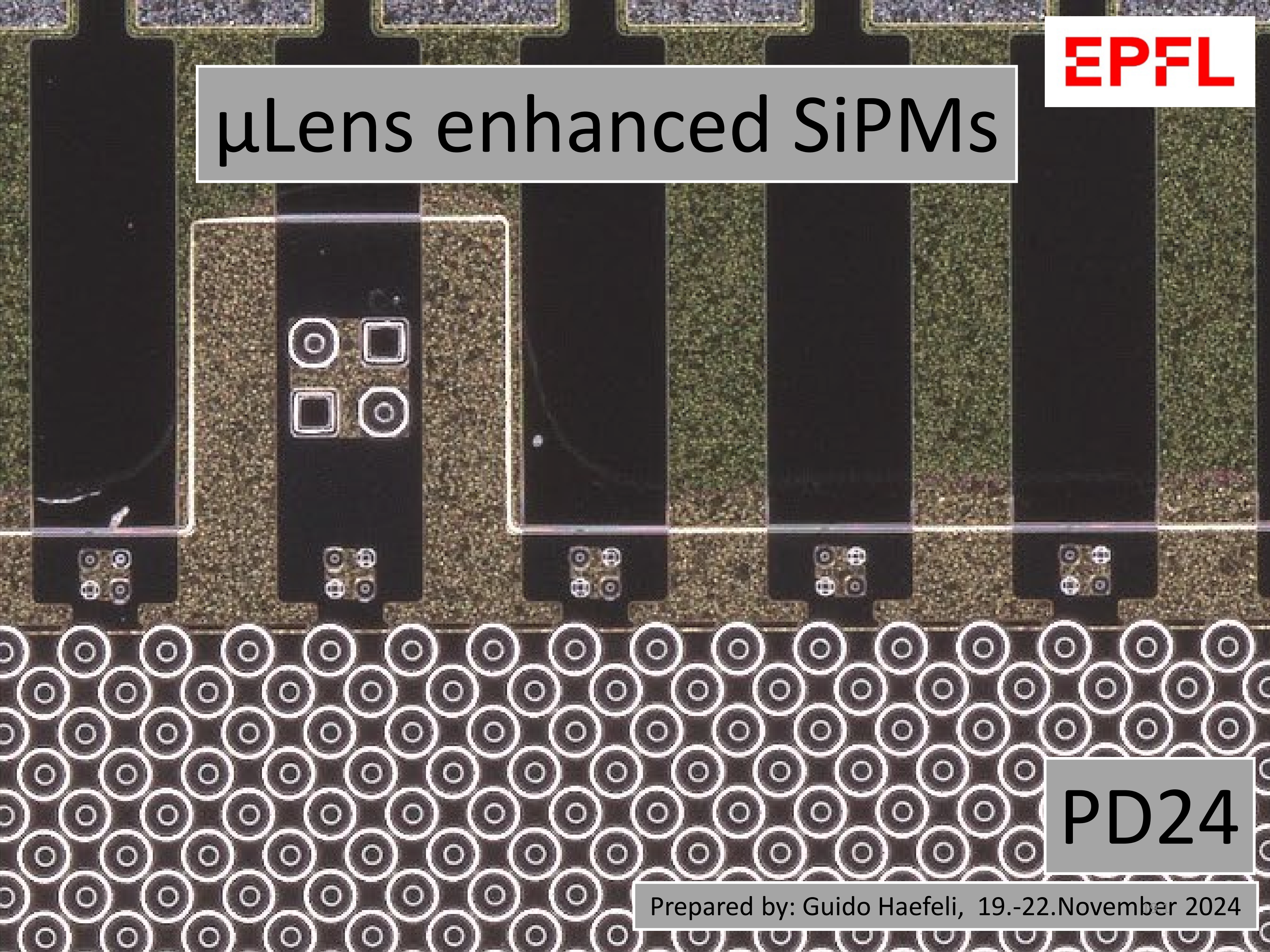
µLens enhanced SiPMs

EPFL

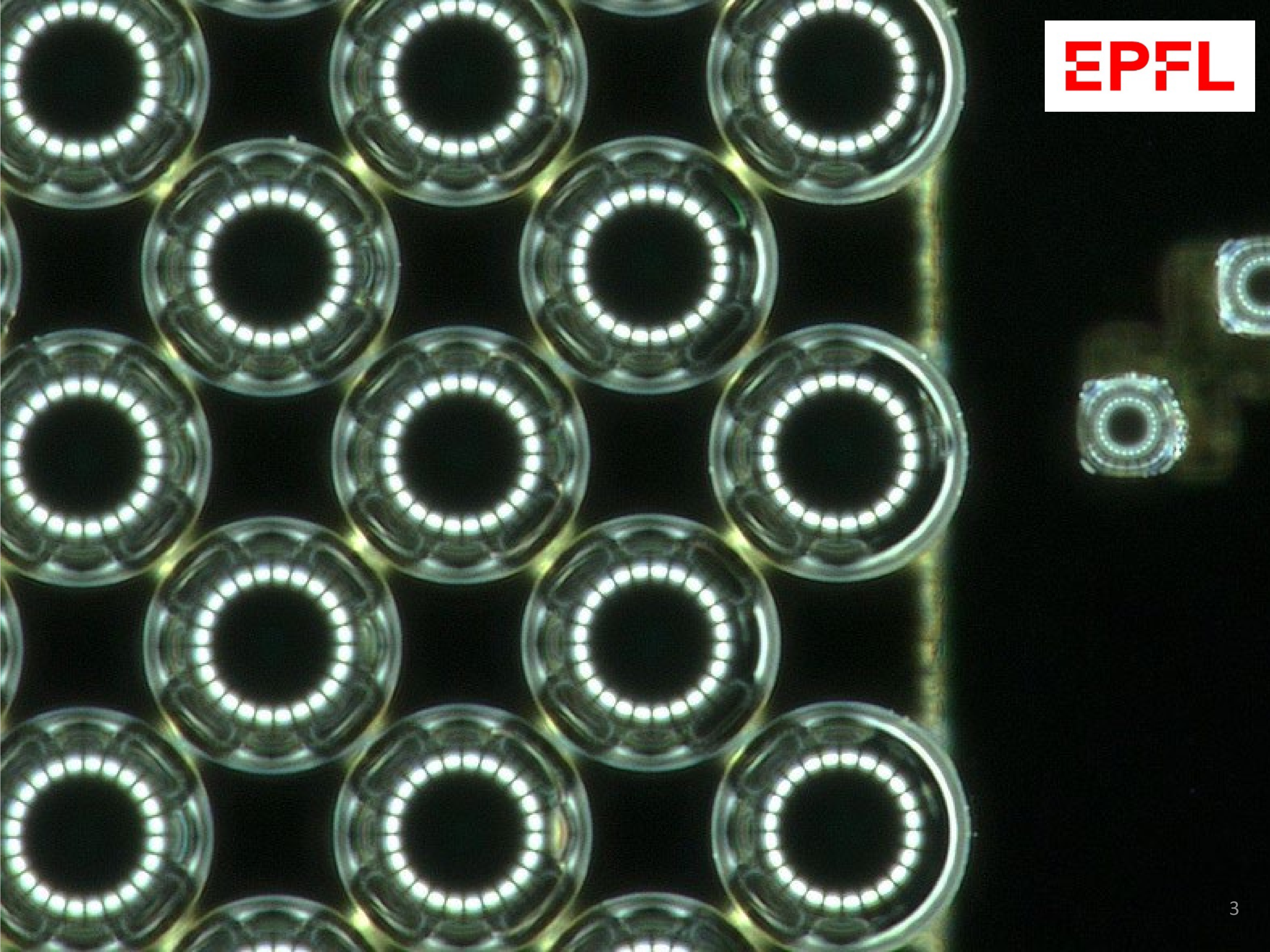


PD24

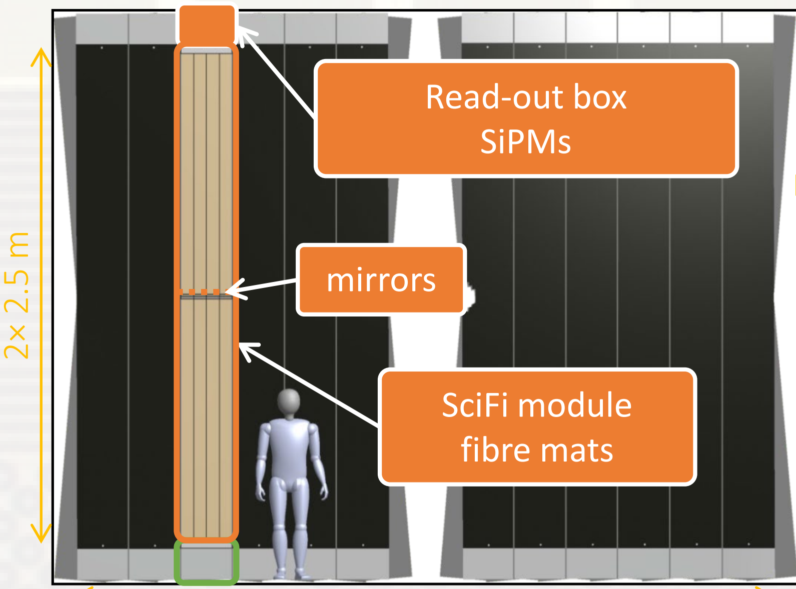
Prepared by: Guido Haefeli, 19.-22.November 2024

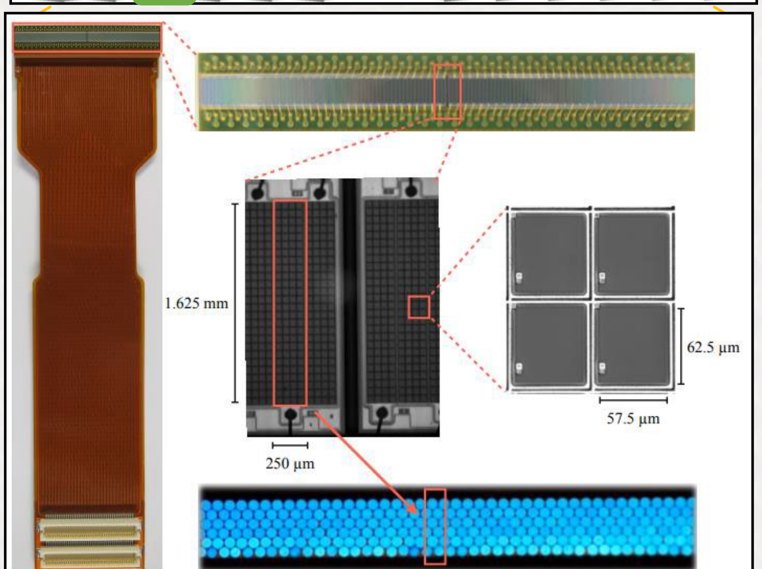
Outline

- Context the LHCb SciFi Upgrade II
- The concept developed for µLens arrays on SiPMs
- Simulation
- Measurements
  - PDE
  - Cross-talk
  - SPTR

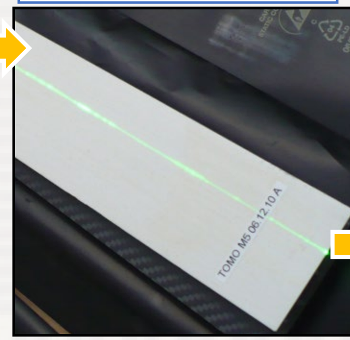


SciFi in LHCb Upgrade I and II

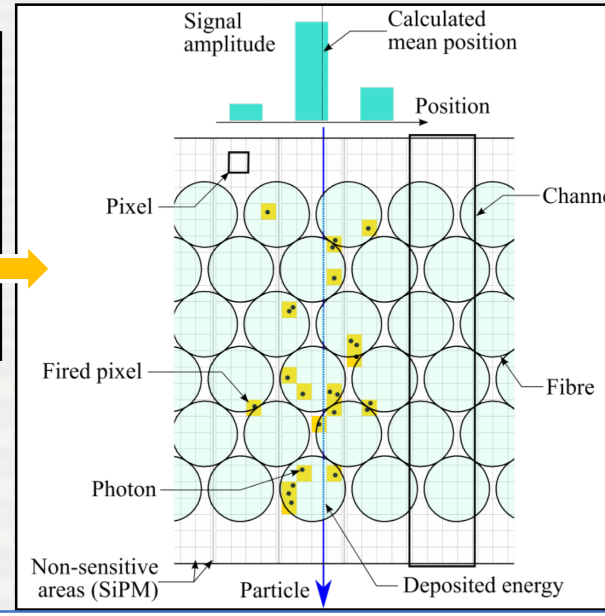




Light transport in fibre



- Low noise allows for high efficiency
- MIP=11PE distributed over 3 channels

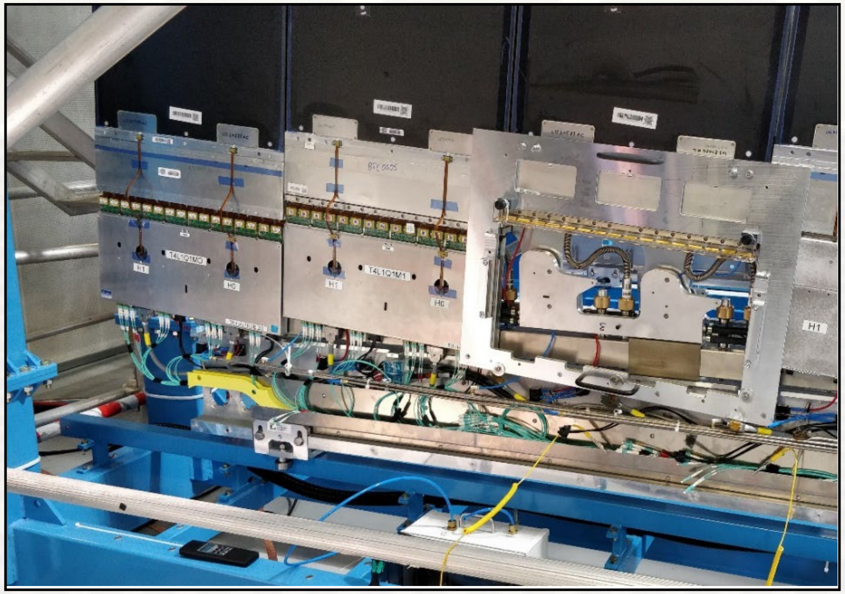


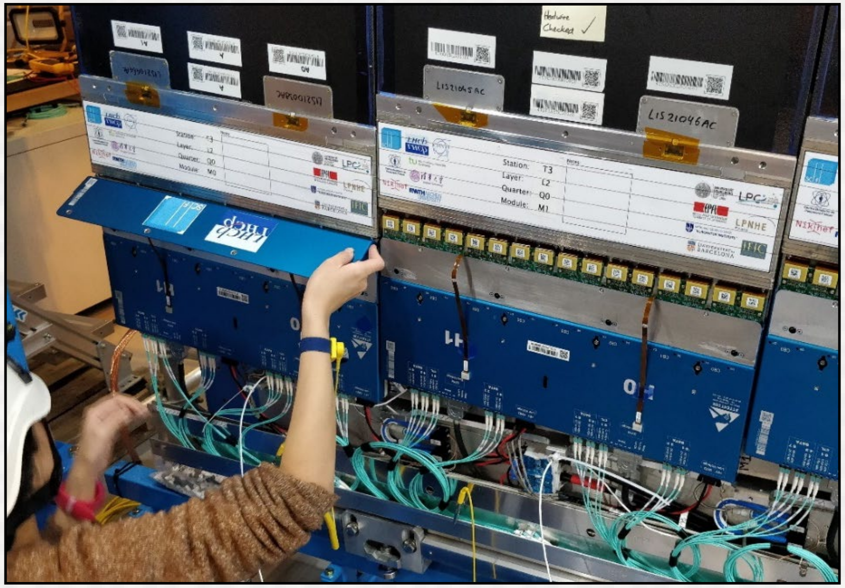
Requirements for the photo-detector:

- Custom geometrical dimension imposed by the SciFi fibre arrangement, segmentation of channels
- High PDE in blue to green asks for large pixels
- Low correlated noise (x-talk), low noise cuts
- Low DCR after irradiation ($3..30 \times 10^{11}\, n_{eq}/cm^2$)
- Thin entrance window (<100µm)
- High geometrical coverage (no gaps)

PhD thesis Olivier Girard PhD thesis Axel Kuonen

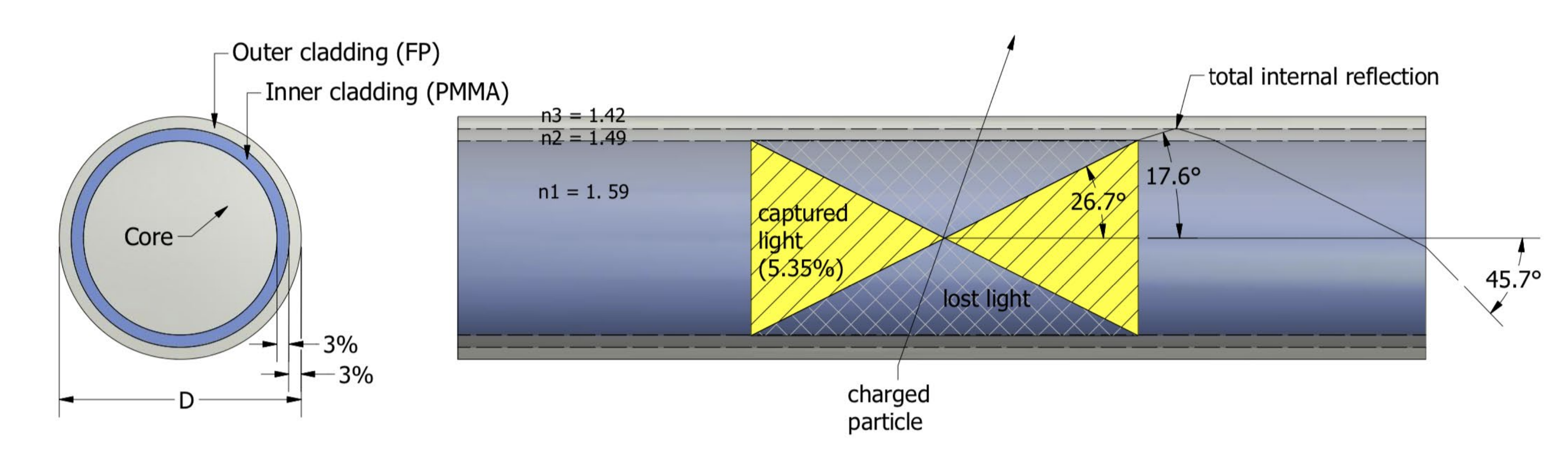
SciFi Tracker LHCb Upgrade I (2019)





Light source angular distribution (SciFi)

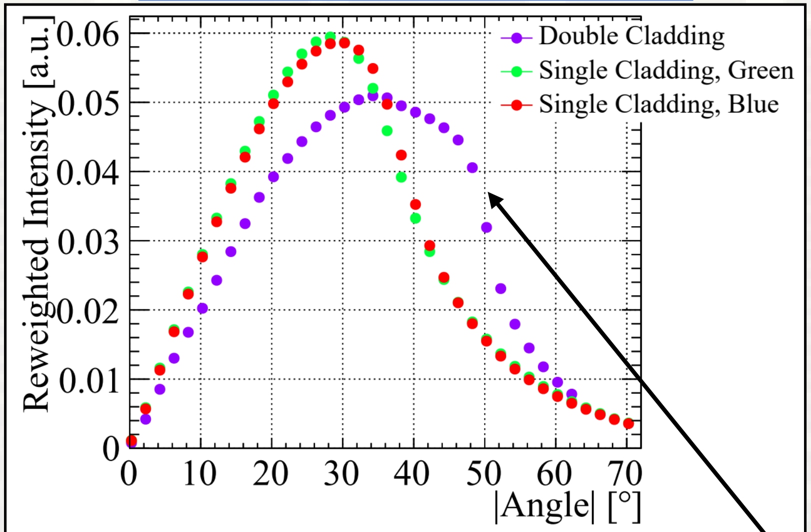
- Plastic optical fibre (POF) with 250µm diameter, double cladded multimode
- NA=0.72 =n sinΘ (numerical aperture)



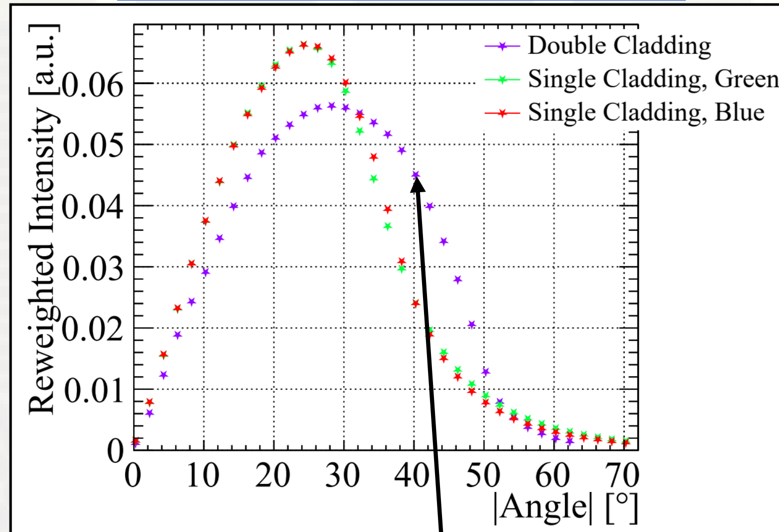
A narrow angular distribution (small NA) can lead to a performant optical focusing.
For this fibre, the lost photons at the production (only trapped 5.35%) introduces a angular selection
-> Narrow angular distribution is also true for (LHCb) RICH, LiDAR, camera sensors commercial CCD,CMOS
Not for applications where an optical dense material is directedly in contact with the SiPM silicon, LYSO readout TOFPET, LAr

Measured vs Simulation: Fibre exit angle distribution

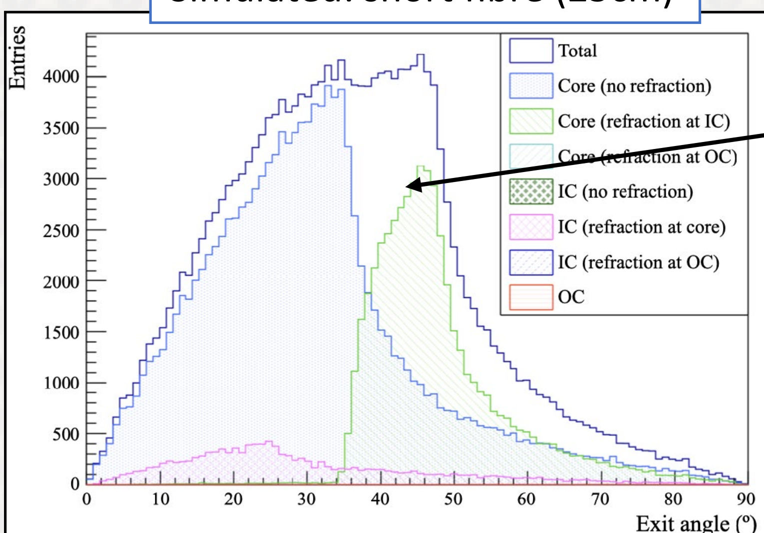
Measured: short fibre (25cm)



Measured: Long fibre (230cm)



Simulated: short fibre (25cm)

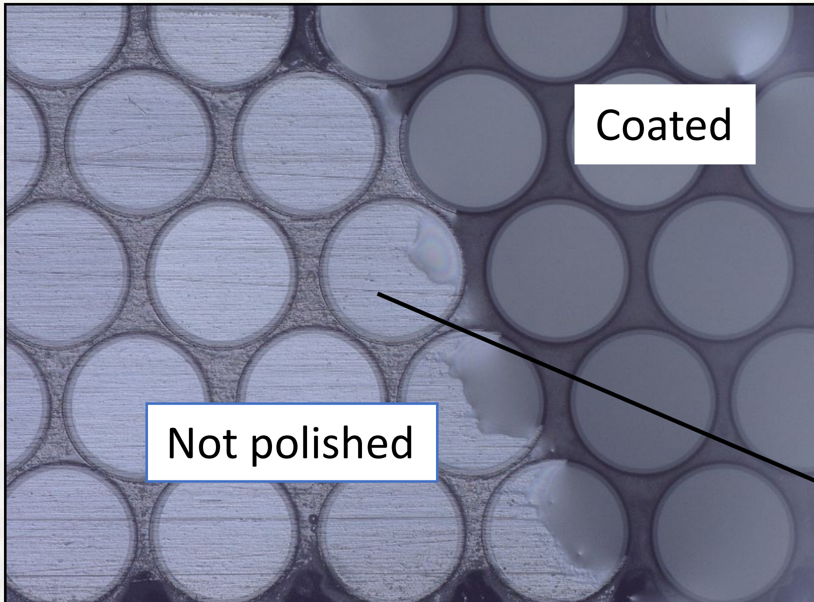


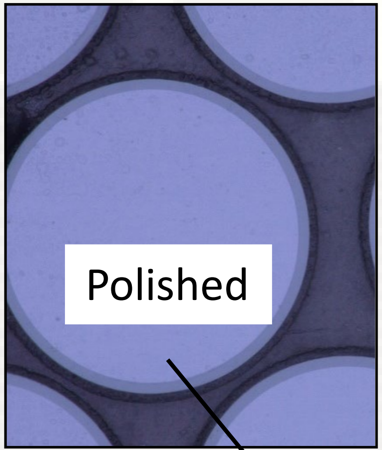
Double cladded fibre has a propagation mode that introduces a larger exit angle distribution.

After some distance (240cm) this mode is strongly suppressed and the exit angle distribution is narrower!

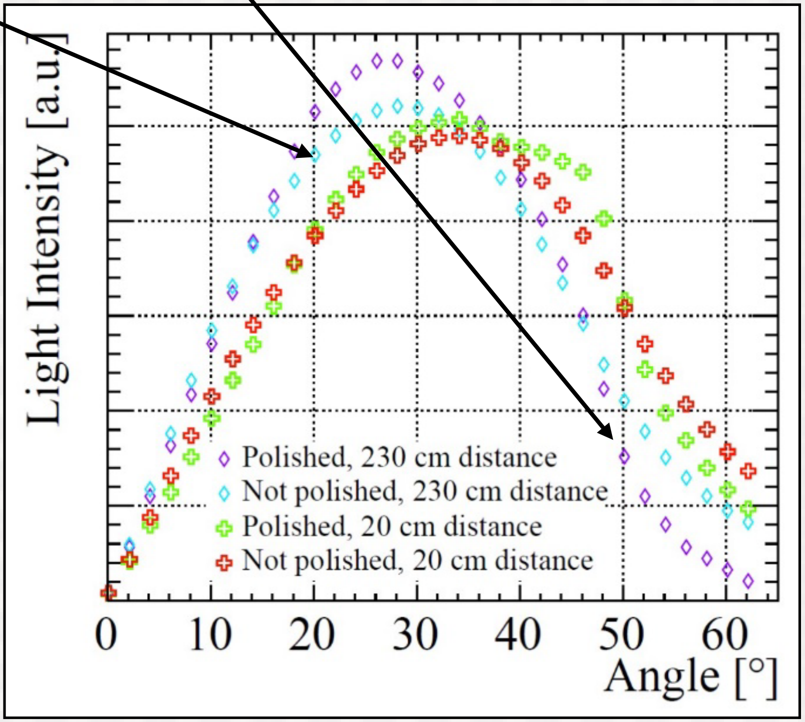
The simulation of the POF is difficult to tune to obtain to angular distribution at different propagation modes. Attenuation and surface quality is difficult to model. Base the studies on measurements.

Influence of the fibre surface

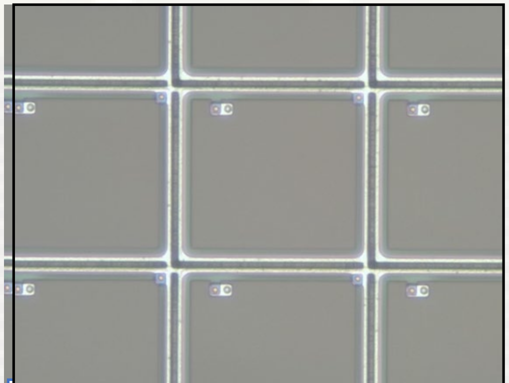




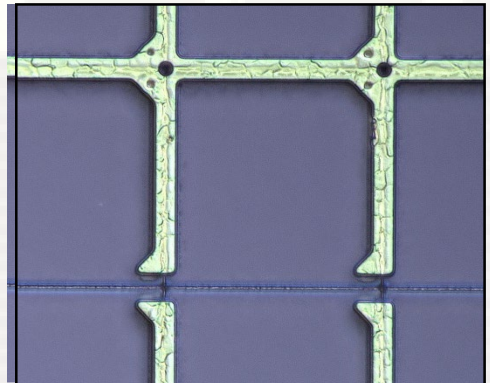
Polymer coating with an UV curable glue reduces the width and tail of the angular distribution



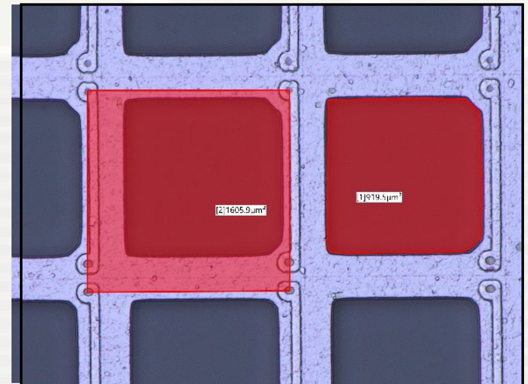
Pixel outline of a high density SiPM



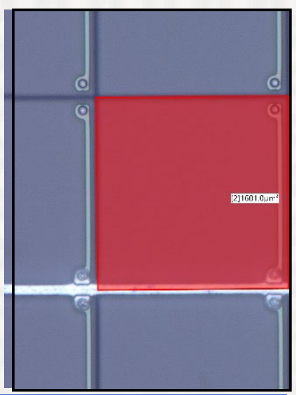
HPK, 62µm x57µm,
not square!
GFF=67%



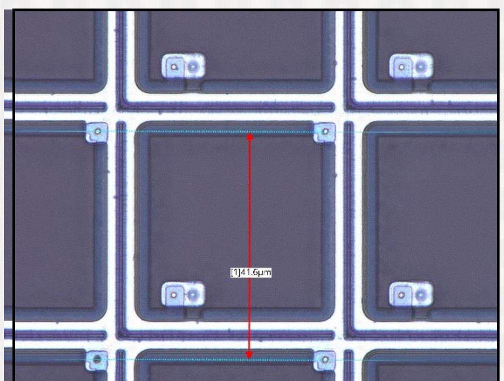
FBK, 42µm
GFF=81%



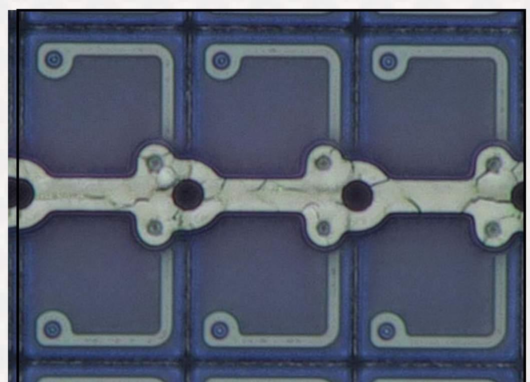
FBK, 40µm
GFF=57%



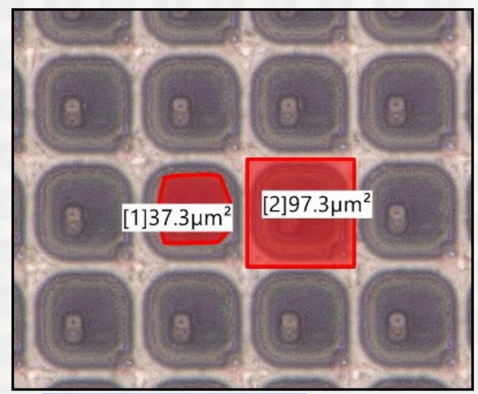
FBK, 40µm
GFF=87%



HPK, 42µm
GFF=68%



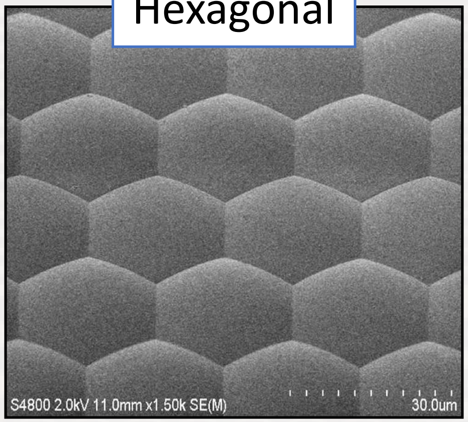
FBK, 16µm
GFF=43%



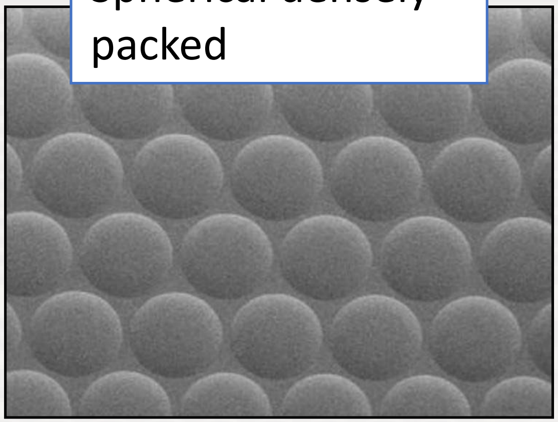
HPK, 10µm
GFF=33%

How can a refractive lens be used most efficiently ?

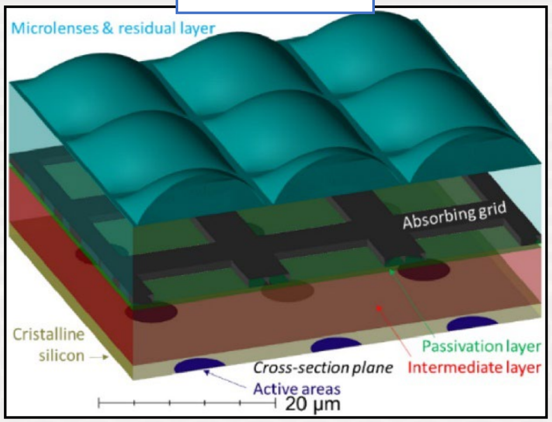
Hexagonal



Spherical densely packed

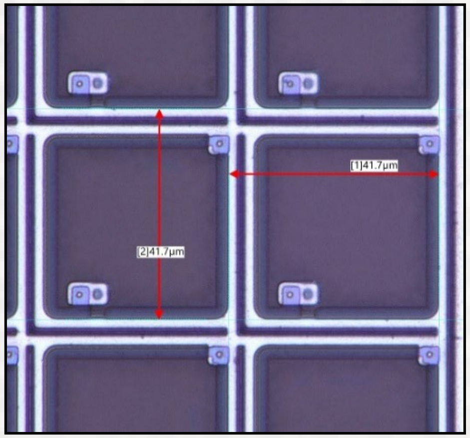


Square

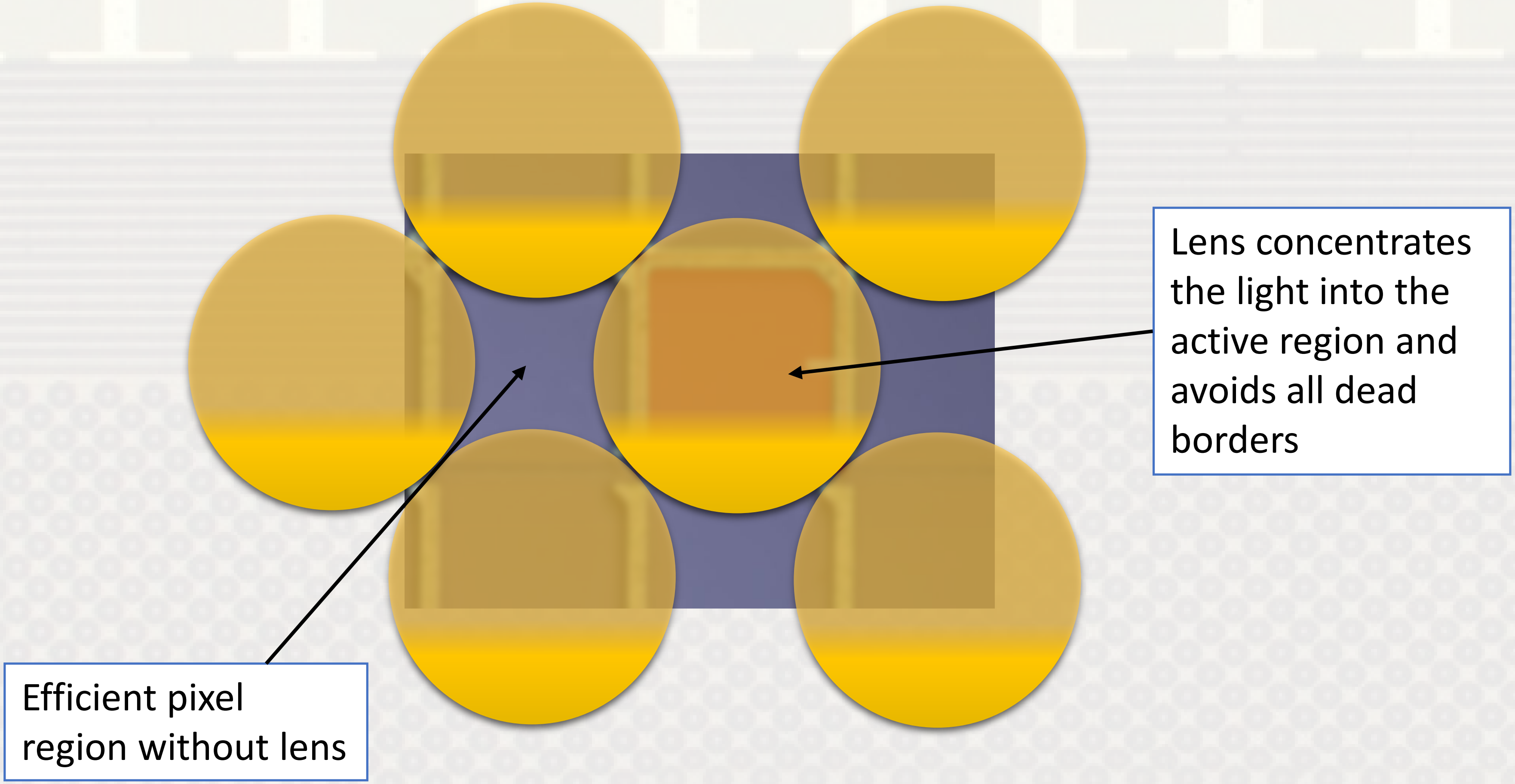


Require both new pixel layout, connectivity?

Are inefficient where the dead regions are.

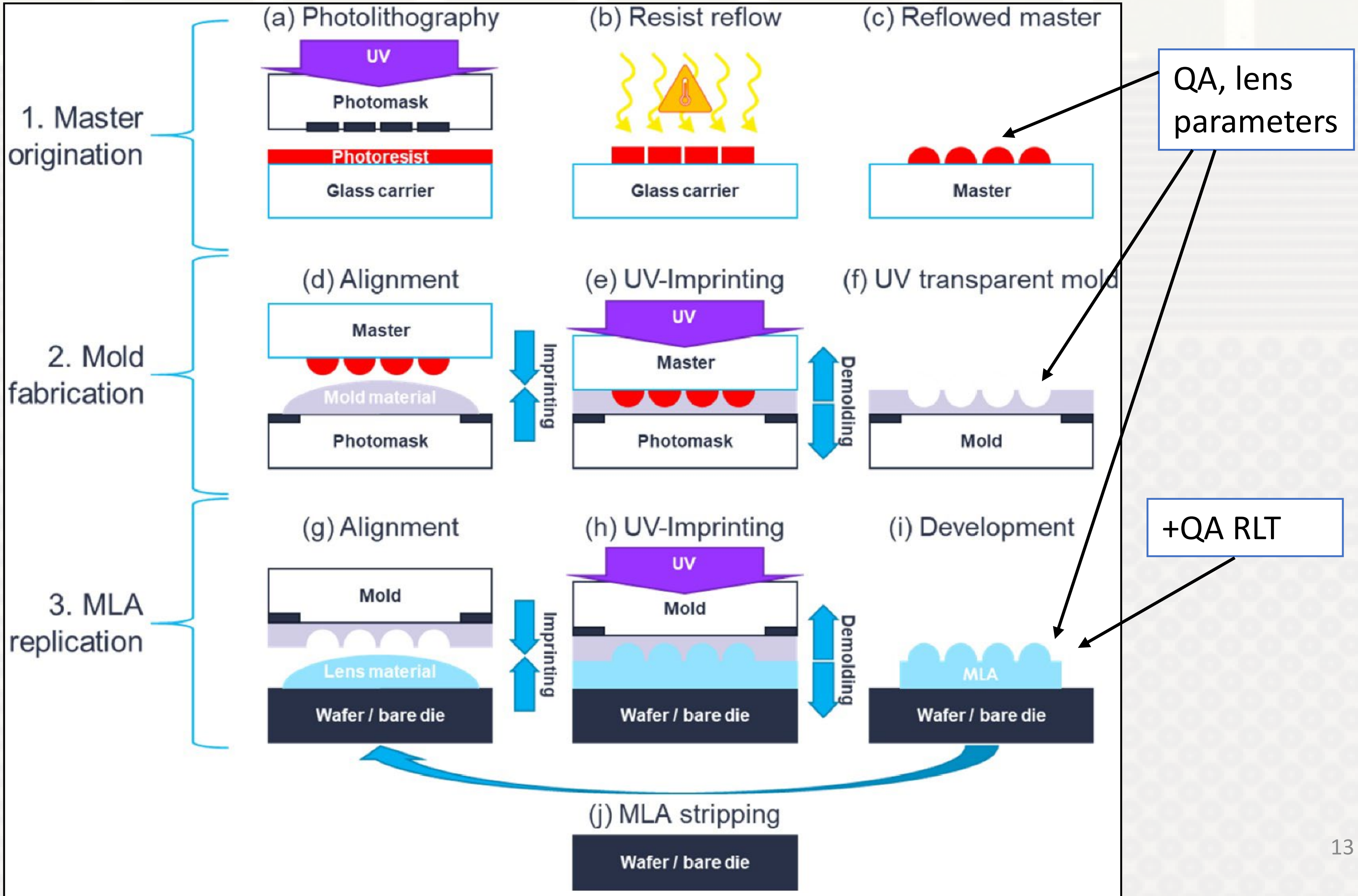



Spherical lenses one-in-two "checkerboard structure"



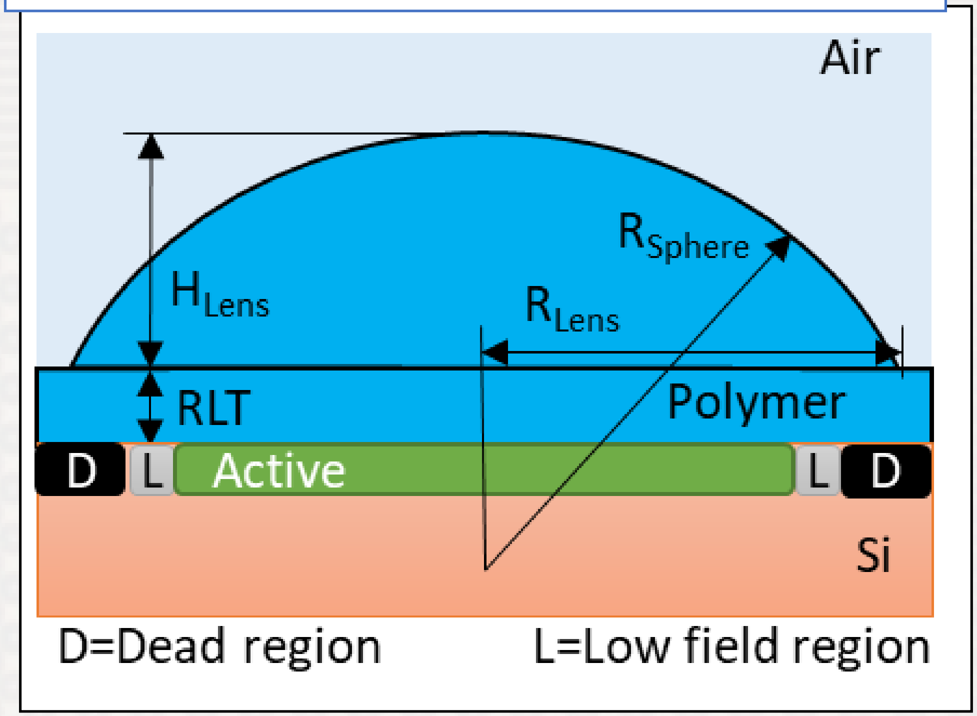
- High GFF SiPMs will profit less from the MLA eg. (GFF=81.5% -> 100%)
- To reach maximal PDE, don't reduce the GFF of the SiPM, decrease the dead region illumination

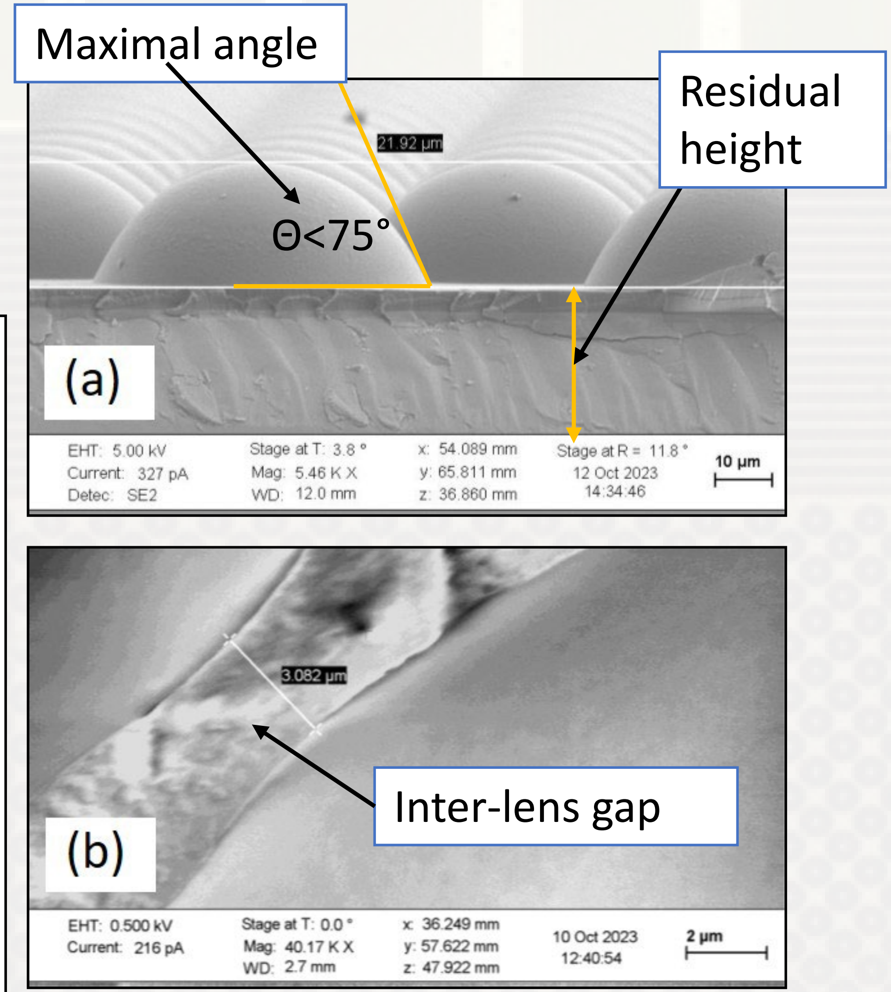
µLens production steps, limitations



The lens implementation (parameters)

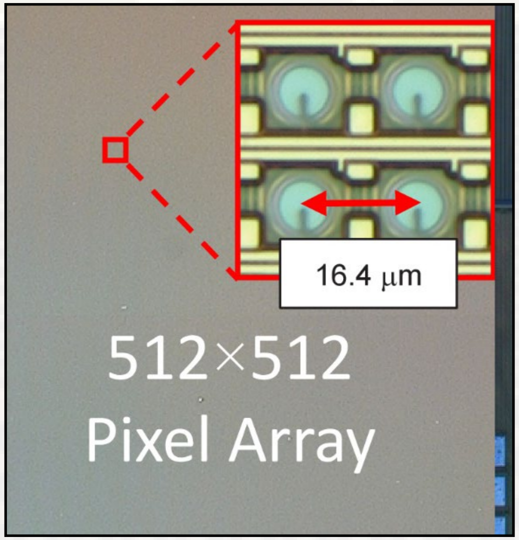
- Lens radius R_{lens}
- Sphere radius introduced by the lens height H_{Lens}
- Residual layer thickness RLT





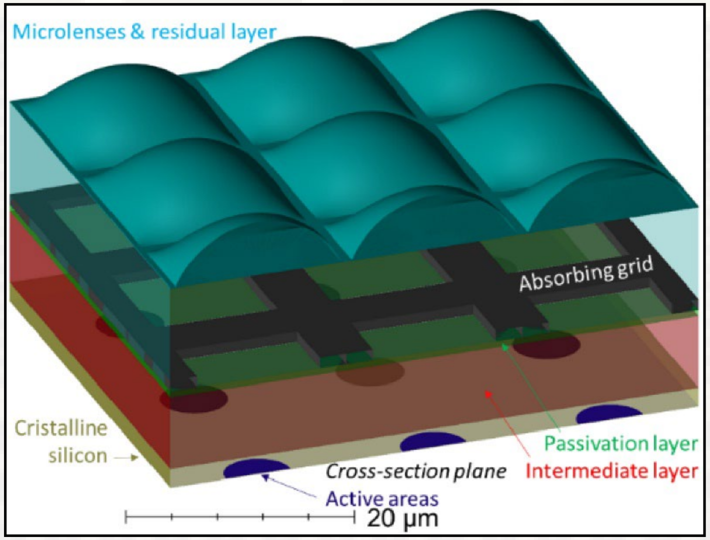
- Inter-lens gap >1µm
- Ratio Lens height / Lens radius (80%) for demolding angle < 75°
- Residual layer thickness > 10µm (depending on the total surface)
- Alignment precision >1µm

µLens on SPADs

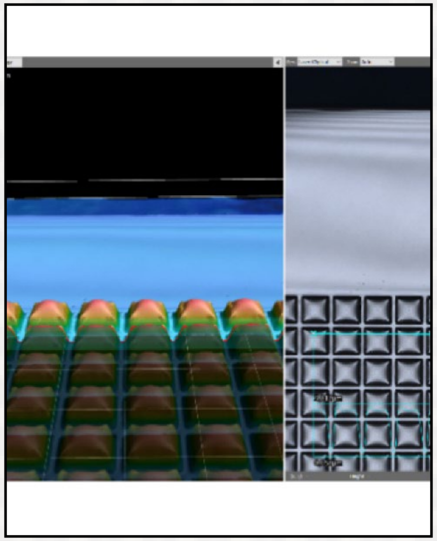


- Low fill factor (10.5%)
- Can potentially concentrate light by factors as high as 20

- A µLens is placed on top of every SPAD cell
- Square base surface is used



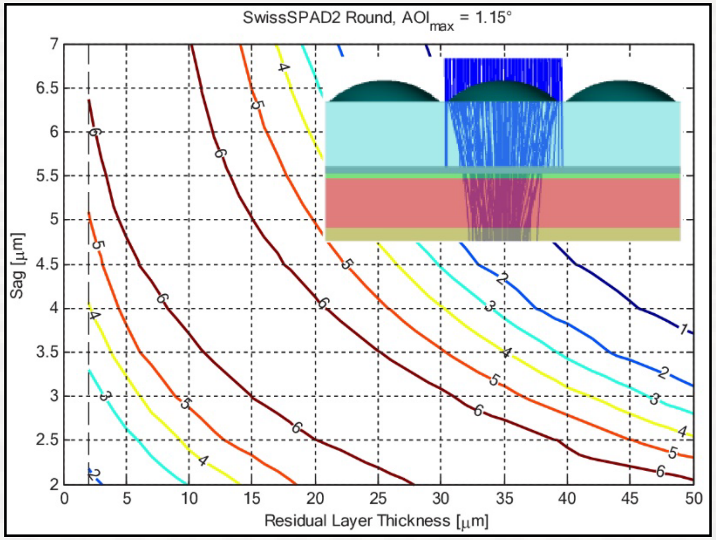
Critical to reach a minimal distance between lenses, 1µm is equivalent to $(39/40)^2=0.95$ -> 5% area loss



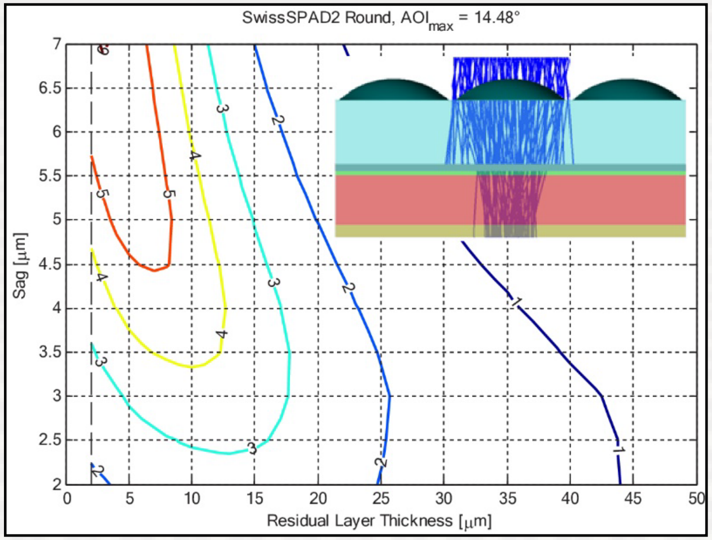
C. Bruschini, I. Antolovic, F. Zanella, A. Ulku, S. Lindner, A. Kalyanov, T. Milanese, E. Bernasconi, V. Pešić, and E. Charbon, "Challenges and prospects for multi-chip microlens imprints on front-side illuminated SPAD imagers," Opt. Express 31, 21935-21953 (2023).

µLens on SPADs: Concentration factor

Normal incident light NA=0.02



Normal incident light NA=0.25



- Lower concentration factor with larger NA
- Thinner residual layer is required for larger NA
- Largest possible lens sag is ideal

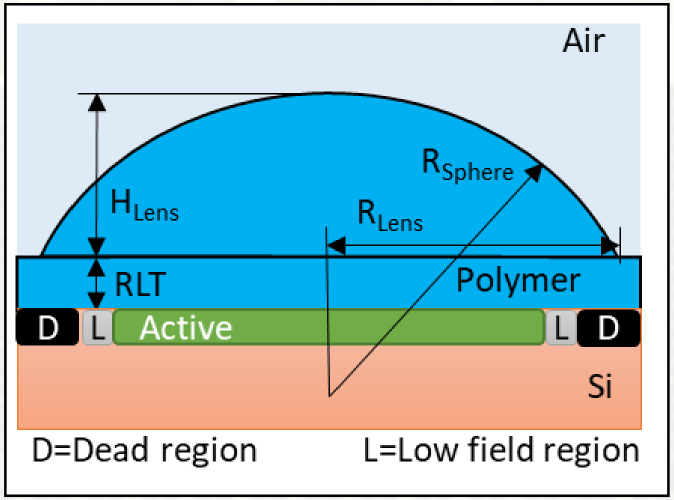
Implementation of MLAs for this design reaches PDE of +100%

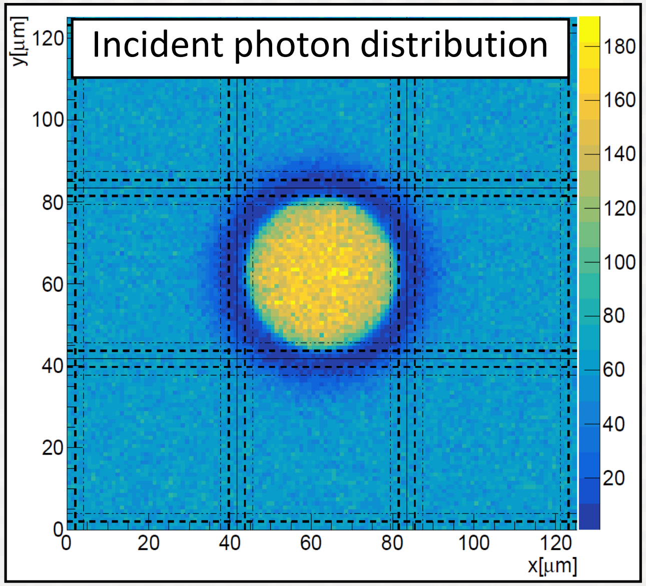
C. Bruschini, I. Antolovic, F. Zanella, A. Ulku, S. Lindner, A. Kalyanov, T. Milanese, E. Bernasconi, V. Pešić, and E. Charbon, "Challenges and prospects for multi-chip microlens imprints on front-side illuminated SPAD imagers," Opt. Express 31, 21935-21953 (2023).

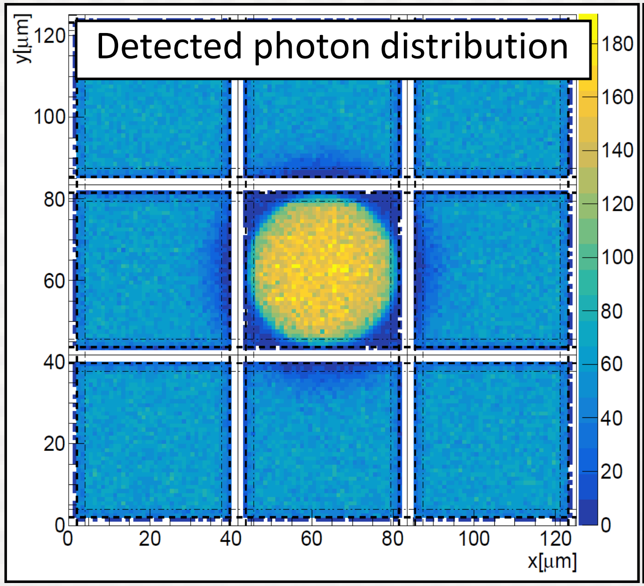
Simulation

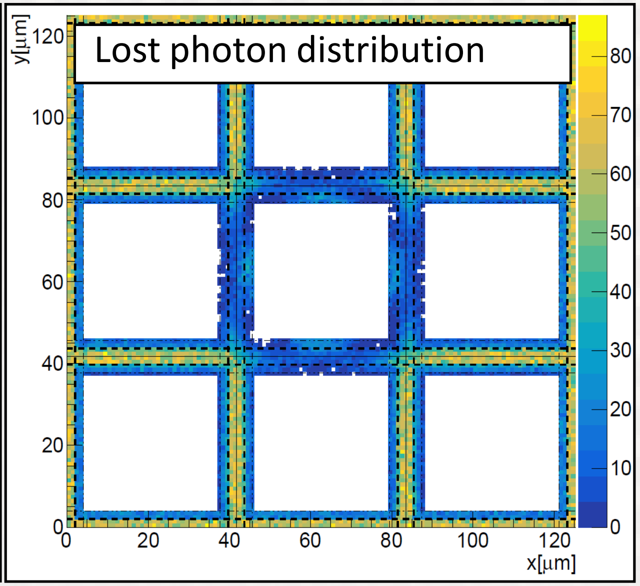
What are the best values for the lens?

- Simulate a surface of 9 pixels but only 1 lens
- Introduce light source exit angle distribution
  - SciFi NA=0.72
  - Normal incident light source with NA=0.05
- Ray tracing simulation in a ROOT framework, calculate diffraction and Fresnel reflection
- Introduce geometry of the pixel active and dead regions
- Optimise R_{lens} H_{Lens} RLT









Simulation results I

EPFL

- The quantity to optimise is the ratio between detected and incident photons, without lenses it is proportional to “GFF”, with lenses it is called “EGFF” (effective)
- We calculate the enhancement in light detection “LY_{enh}”

Best values for a pixel size of 41.7µm are:

- R_{lens} is best at 95% of the maximal radius resulting in an inter-lens gap of 2.95µm
- H_{Lens} is best when the lens has the maximal height (Θ=75° or 22µm)
- RLT is critical and is the free parameter during the lens replication (not defined at the master production) best at 12.5µm

GFF=81.5% but no low field region)

FBK, pixel size 41.7μm, GFF=81.5%, light source SciFi		
$H_{Lens}[°]$	$RLT[\mu m]$	$LY_{enh}[\%]$
65	10	13.35
	12.5	15.15
	15	15.52
	17.5	15.13
70	10	15.88
	12.5	17.22
	15	16.83
	17.5	16.29
75	10	18.17
	12.5	**18.59**
	15	17.12
	17.5	16.12

EGFF=96.7%

Low field region, 2µm with 60% efficiency
GFF=75.5%

FBK, pixel size: 41.7μm GFF: 81.5%, light source SciFi	
$RLT[\mu m]$	$LY_{enh}[\%]$
10	24.54
12.5	**24.57**
15	23.68
17.5	22.11

EGFF=94.1%

Simulation results different light source

- Simulation with SciFi and Narrow light
- Simulation for different pixel size and GFF

Set:

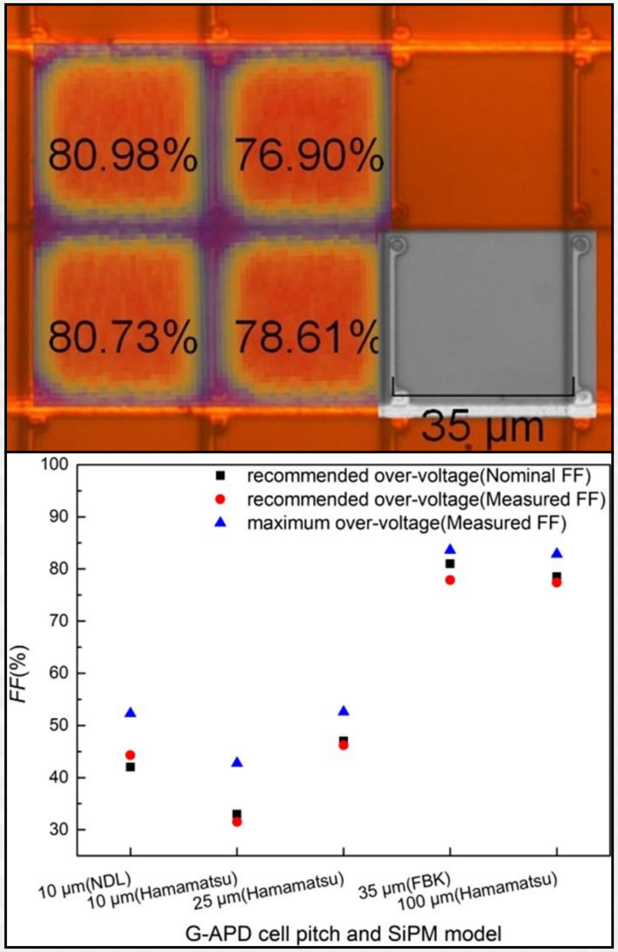
- H_{Lens} maximal height (Θ=75°)
- R_{Lens} = 95% lens radius
- RLT = 12.5µm for 41.7µm pixel
- RLT = 10µm for 31.3µm pixel
- Low efficient region, 2µm at 60%

$GFF[\%]$	Light source	$LY_{enh}[\%]$
FBK, pixel size: $41.7\mu m$		
81.5	SciFi Narrow	24.57 27.91
HPK, pixel size: $41.7\mu m$		
68.5	SciFi Narrow	38.98 45.93
FBK, pixel size: $31.3\mu m$		
77.7	SciFi Narrow	27.51 39.87

EGFF=94.1%
EGFF=96.7%

EGFF=88.2%
EGFF=92.7%

EGFF=89.6%
EGFF=96.3%



Chen Zhang et al, "Methodology for measuring the fill factor of silicon photomultipliers", https://doi.org/10.1016/j.measurement.2023.112720.

The implementation

Custom silicon from FBK (NUV-HD)

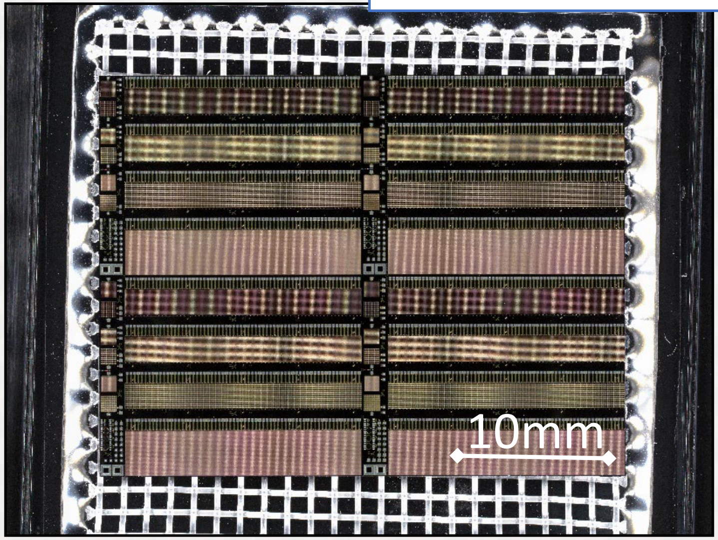
- Pixel size 41.7µm
- 64-channel, segmentation to 1.6mm x 0.25mm=0.4mm^2

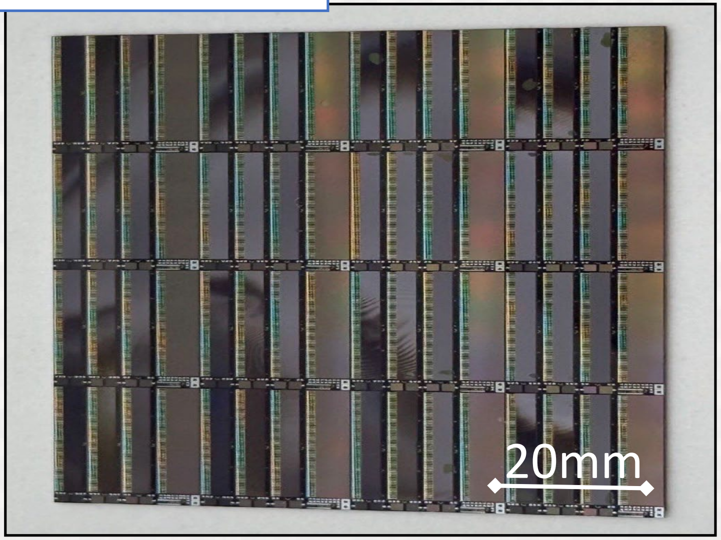
(we should use the segmentation to check uniformity of the MLA)

Lens parameters nominal:

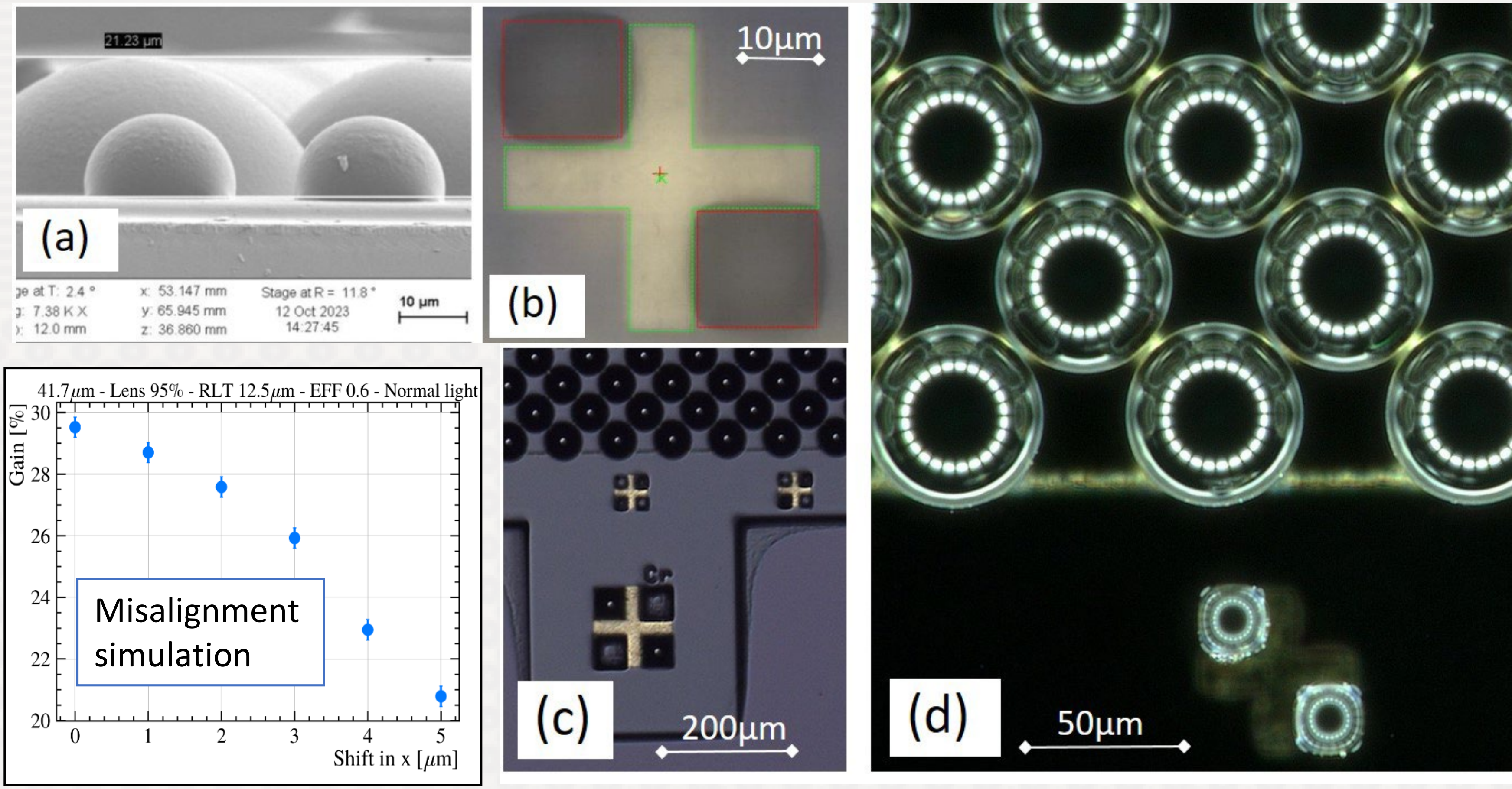
- H_{Lens} maximal height (Θ=75°) (22µm)
- R_{Lens} = 95% lens radius
- RLT = 12.5µm

Super reticles for lens replication 2x2 and 4x4





Alignment between silicon structure and MLA

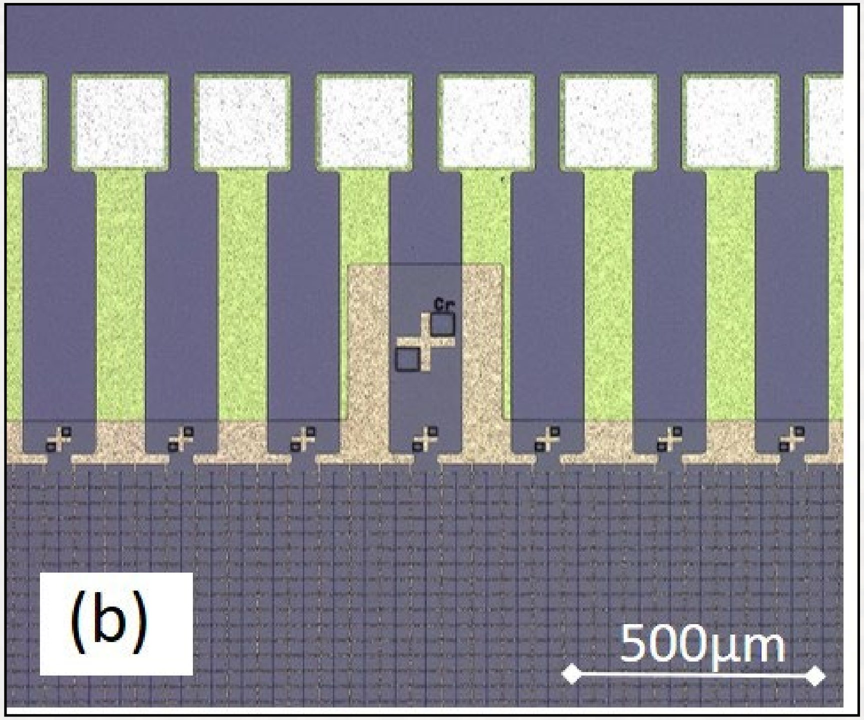


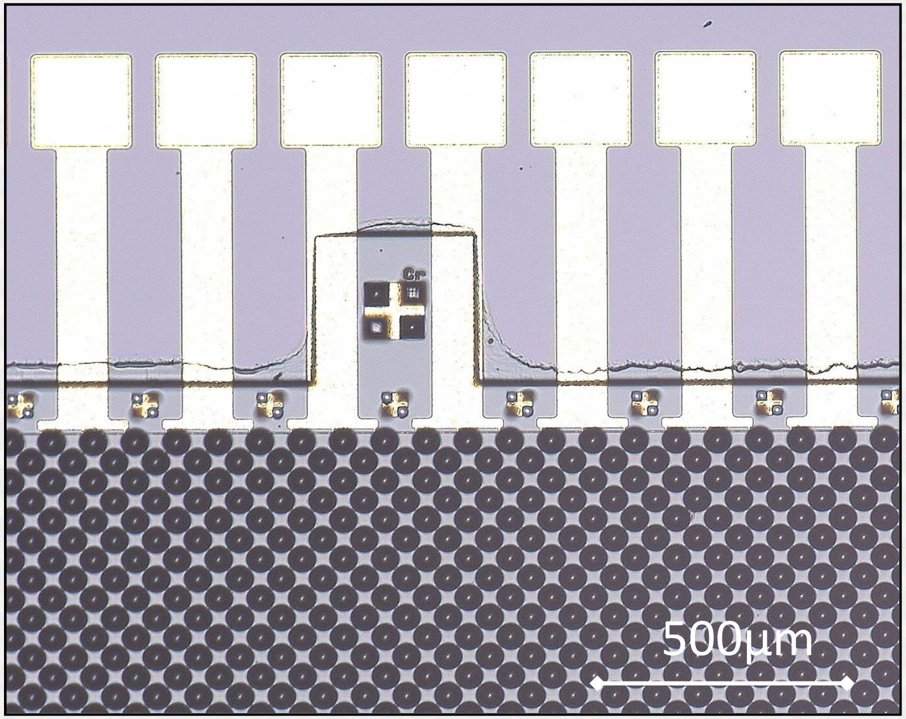
Alignment QA is performed with the relative position of small lenses placed at the alignment markers on the silicon

Obtained 1-2µm deviation in x or y direction

Flat layer coating for reference and comparison with MLA

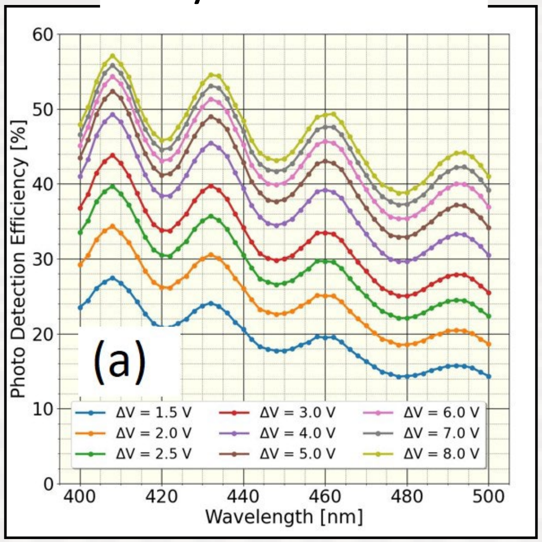
To compare a conventional polymer coating, a flat layer with same polymer as MLA is produced.



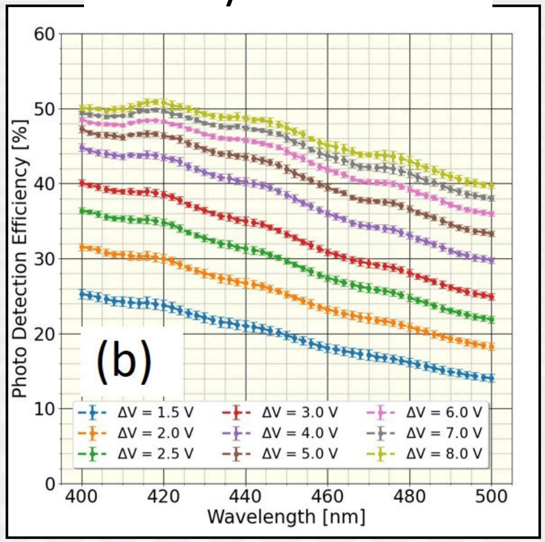


PDE with low NA<0.05 light source

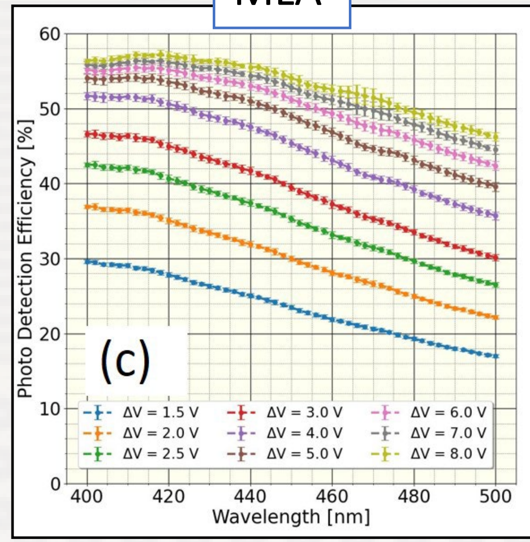
Only ARC on Si



Flat layer coated Si



MLA



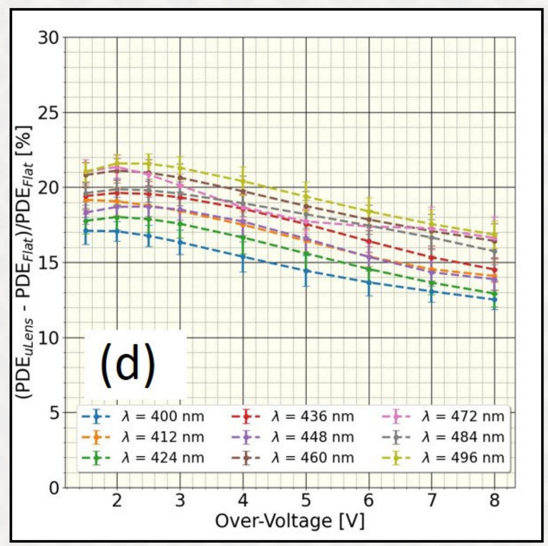
- PDE increase is at its maximum at low over-voltage -> confirms the low field region at the pixel boarders are less illuminated

Over-voltage 2V:

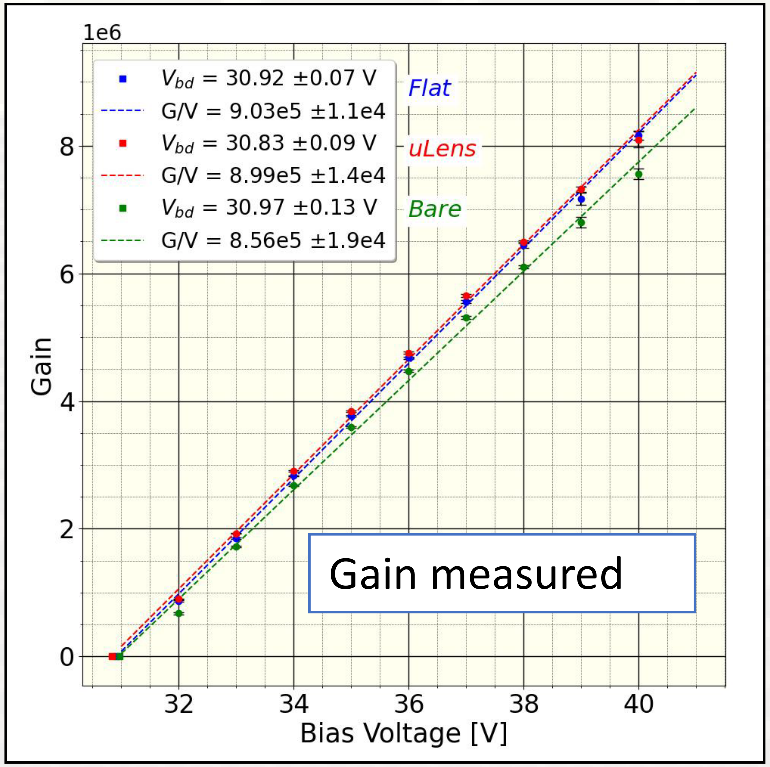
- Simulation (27.9%) vs measurement (22%)

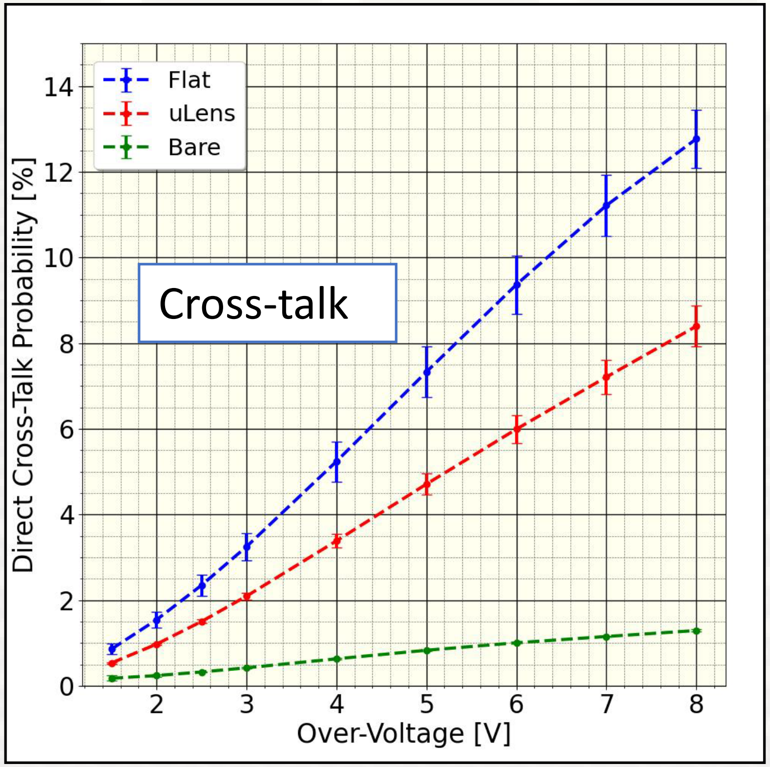
Over-voltage 8V:

- Simulation (24.6%) vs measurement (17%)



Gain and cross-talk

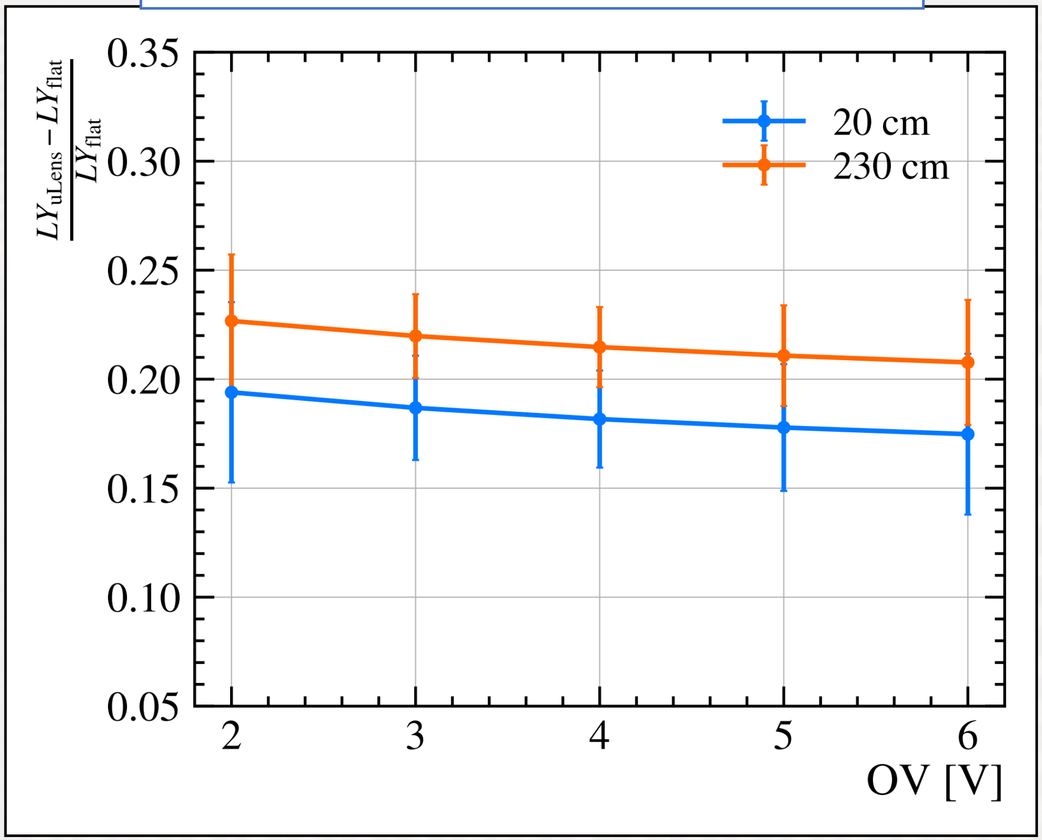


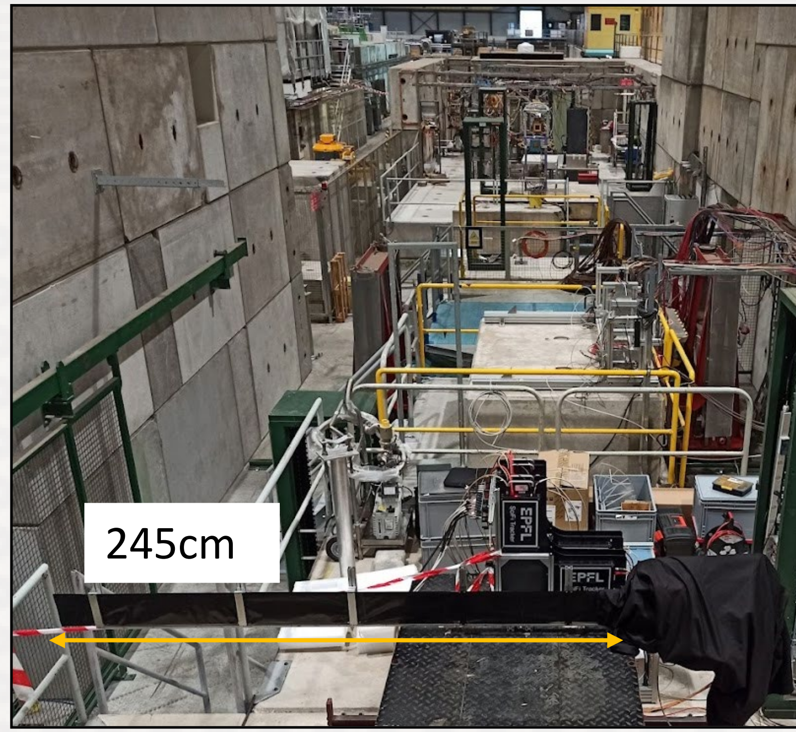


- Gain remains constant
- X-talk is reduced by 40% , µLens surface is reducing external cross-talk

LY with fibre module Scifi angular distribution

With SciFi, increased LY due to uLens enhanced detectors.

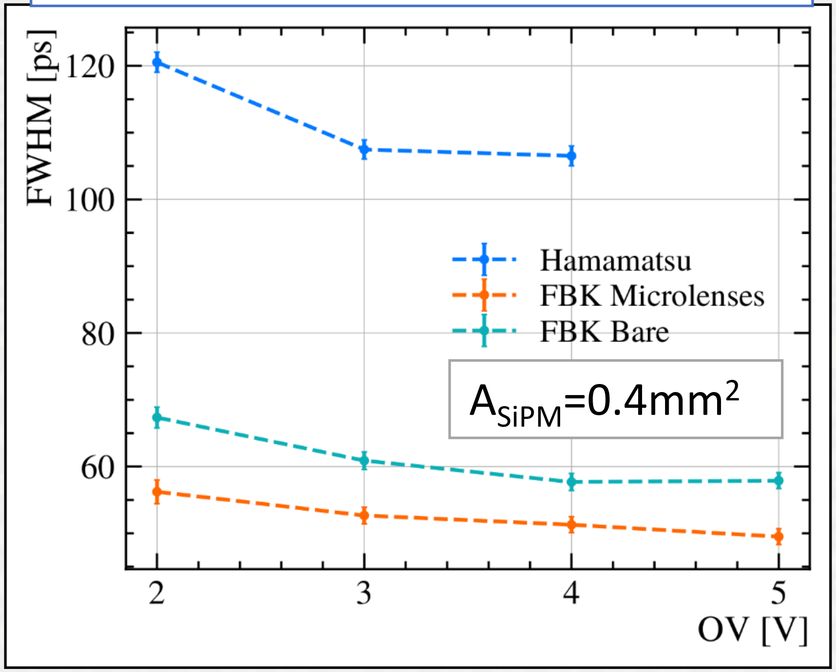




- Short (20cm) 20%
- Long (230cm) measured 23% vs simulation 24.6%

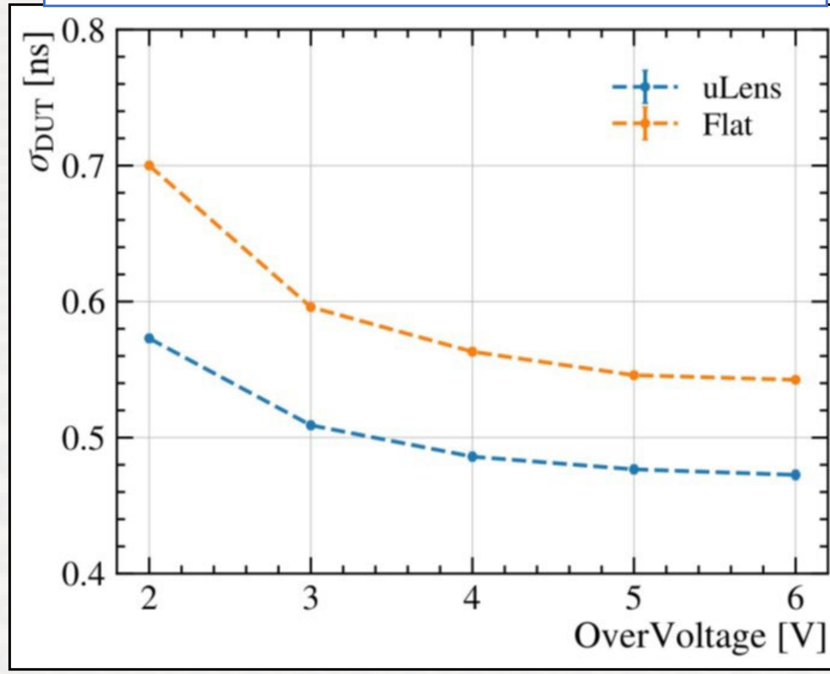
SPTR and time resolution improves with MLA

Only SiPM with laser source, three detectors with identical surface.



- SPTR measured with oscilloscope, single photon signal only
- Corrected for amplitude induced time walk (CFD)
- Scan of best timing threshold
- Detector on Kapton flex PCB

With SciFi, increased LY enhances time resolution dominated by scintillator.



The uLens acts like a mask around the pixel boarders. Better SPTR has been reported.

Gundacker, S., Borghi, G., Cherry, S., Gola, A., Lee, D., Merzi, S., Penna, M., Schulz, V. & Kwon, S. On timing-optimized SiPMs for Cherenkov detection to boost low cost time-of-flight PET. Physics In Medicine And Biology. 68 (2023,8)

Summary

- High GFF SiPMs have been enhanced with MLAs and an improvement of 22% for low over-voltage (2V) and 17% for high over-voltage have been measured.
- MLAs can also improve SPTR, cross-talk and are particularly useful for operation with radiation as the best PDE improvement is at low over-voltage.
- The light source of SciFi (NA<0.72) is sufficiently small to have a large improvement similar to a very narrow normal incident light source.
- Critical for the implementation are RLT control (limit of the technology 10µm) and the alignment precision during the replication should be better than 2µm.
- Moving to larger mold is desired, large quantity replication at low cost when wafer level replication can be performed.