spadRICH project: digital SiPMs for RICH application

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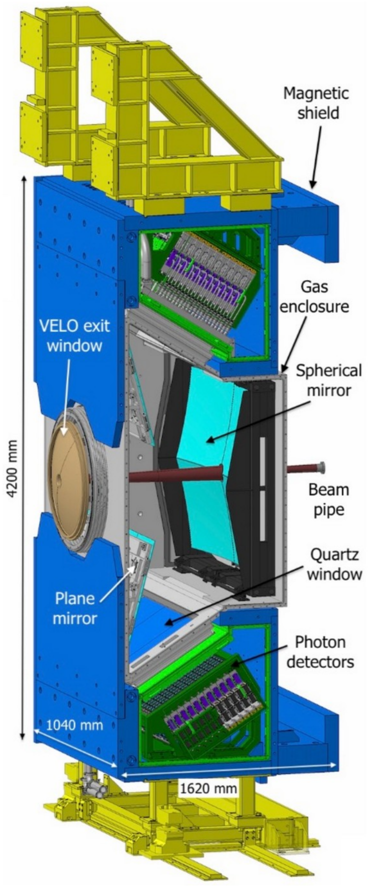
Overview

- **Ring imaging Cherenkov (RICH) detectors**
  - provide particle identification in high energy physics experiments
  - planned upgrades ➔ very high photodetector requirements
- Silicon photomultiplier (SiPM) could meet the requirements, except for **neutron radiation hardness (~ 10^{13} n_{eq}/cm^2)**
- **spadRICH project**
  - Develop radiation-hard photodetector optimized for RICH application
  - Based on SiPMs including reconfigurable electronics
  - Radiation hardness/RICH optimizations:
    - rad-hard SPAD and electronics design
    - integrated compensating electronics
    - smaller SPADs with microlenses (RICH ➔ limited photon N/A)
    - cryogenic operations

LHCb RICH1



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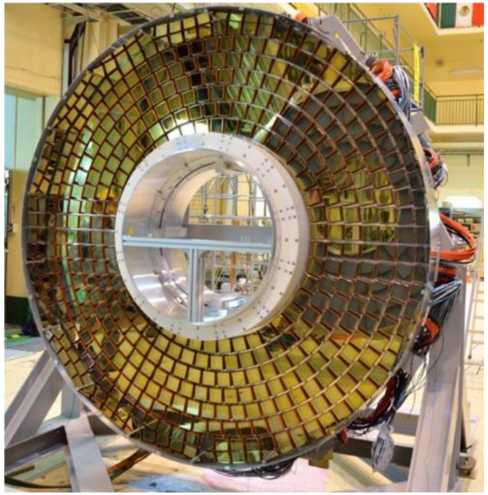
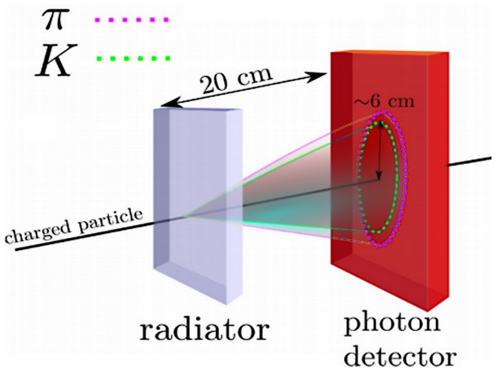
Belle II ARICH





spadRICH project & planned continuation

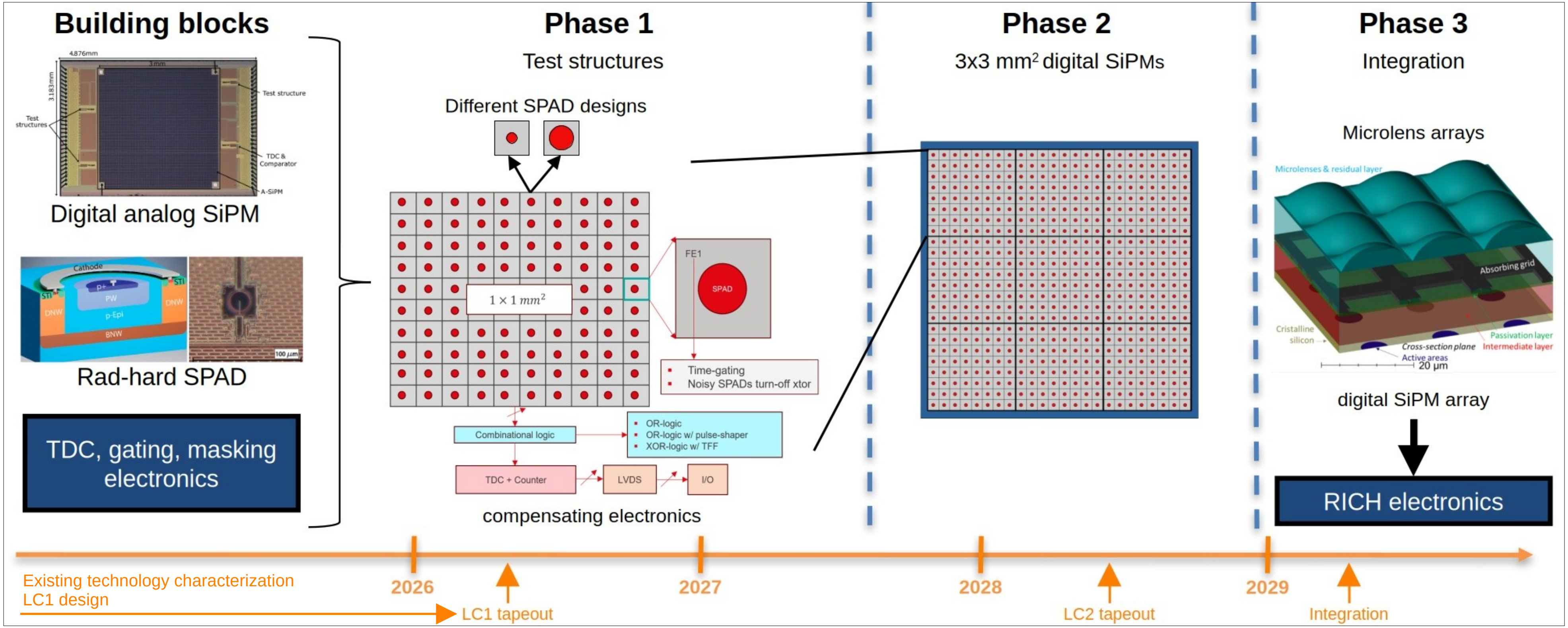
aqualab
EPFL

Swiss National Science Foundation

Institut "Jožef Stefan" Ljubljana, Slovenija

aris Slovenian Research and Innovation Agency

weave Research funding without borders

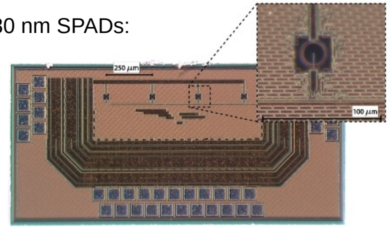


Characterization of existing technologies

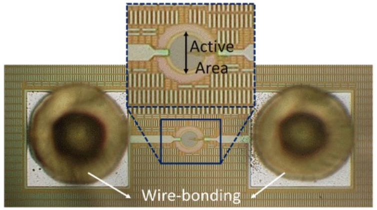
SPAD	Junction	Label	Diameter [µm]	Max. irradiation [1-MeV n_{eq}/cm^2]
180 nm	P+/N	-	25	10^{12}
110 nm	P+/N	108005	5	10^{12}
		115005	5	
		1015	10	
	N+/P	523005	5	
		527	10	
55 nm	PN	101	10	10^{12}
		102	10	
		103	12	
	NP	331	8	
		333	9	
		335	10	

Microlens polymer	Label	Thickness [µm]	Max. irradiation [1-MeV n_{eq}/cm^2]
Lumogen	L	120	10^{14}
Ormostamp	OS	500	10^{14}

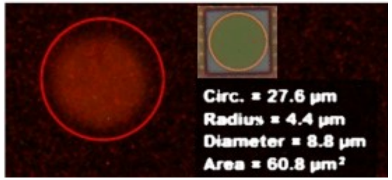
180 nm SPADs:



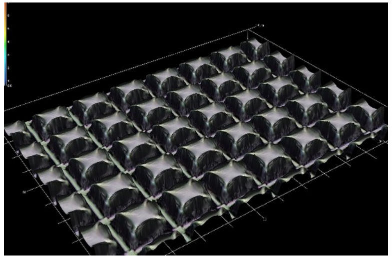
110 nm SPADs:



55 nm SPADs:



Microlenses:



180 nm SPAD results:

doi.org/10.1109/NSSMICRTSD49126.2023.10337871

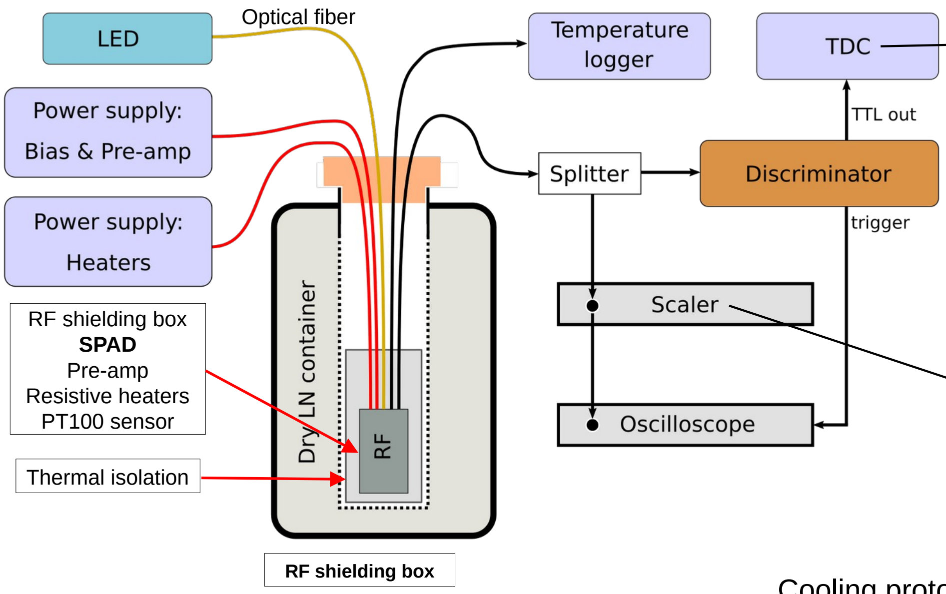
55 nm abd 110 nm SPAD results:

doi.org/10.1088/1748-0221/20/06/P06052
doi.org/10.48550/arXiv.2602.24045
doi.org/10.1016/j.nima.2026.171538

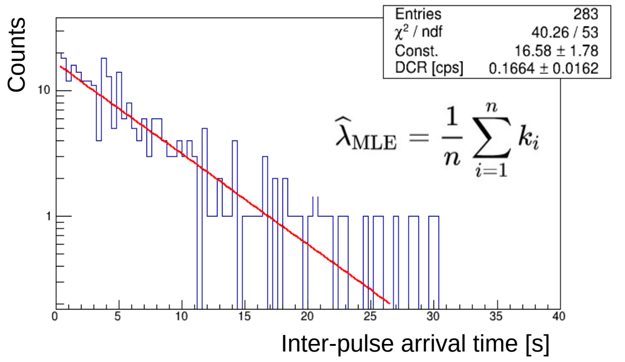
Microlens irradiation results:

doi.org/10.1117/12.3041096

Methods

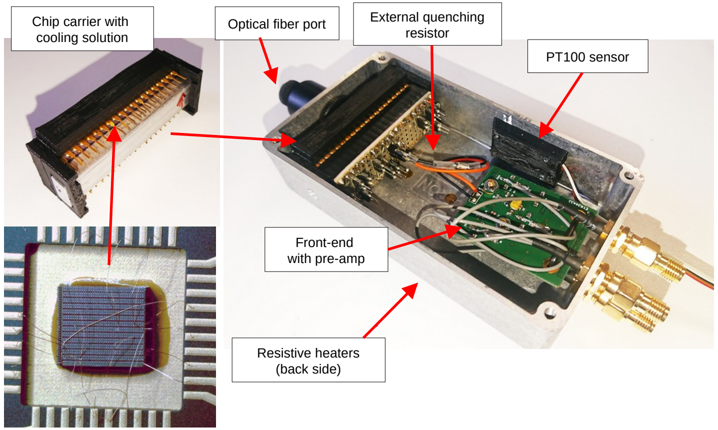


Inter-pulse arrival time ➔ DCR < 1 cps from fitting or most likely expectation value for Poisson distribution

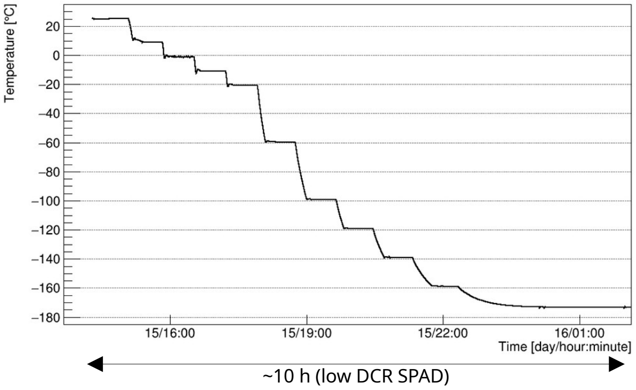


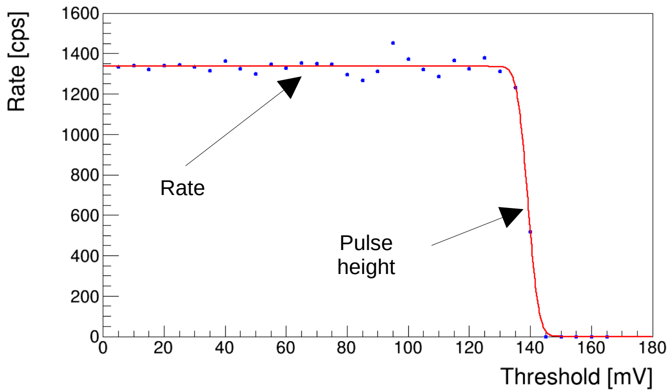
$$\widehat{\lambda}_{\mathrm{MLE}} = \frac{1}{n} \sum_{i=1}^{n} k_i$$

Threshold scans ➔ DCR > 1 cps, pulse heights for breakdown voltage estimation



Cooling protocol



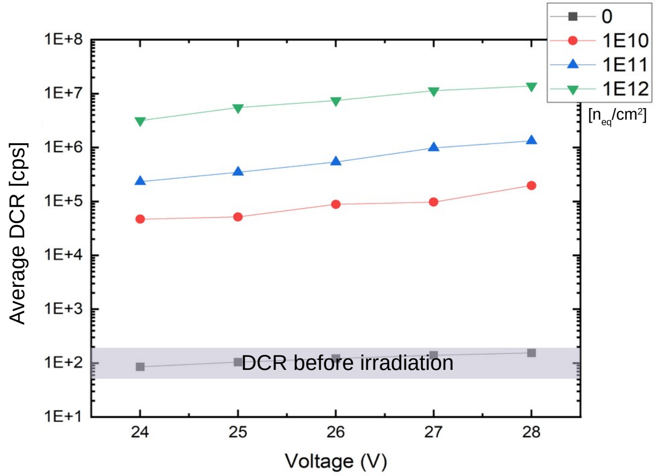


Experimental results: Dark count rates

- Studies of existing SPAD technology performance
  - 180 nm CMOS SPADs
  - 110 nm CMOS SPADs
  - 55 nm BCD SPADs
- For planned RICH detector environment
  - neutron irradiated
  - cryogenic temperature

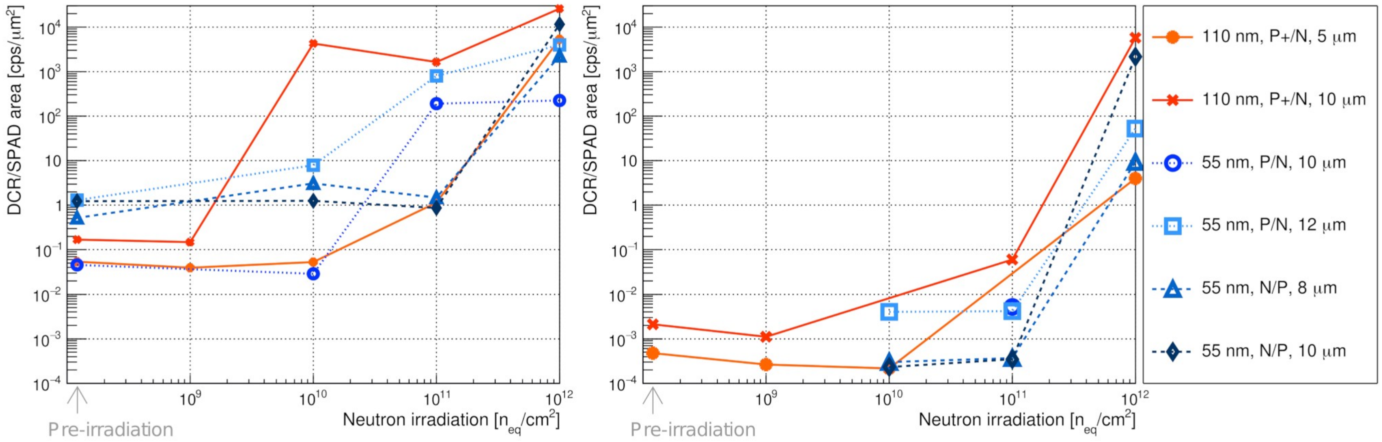
110 nm & 55 nm SPADs

180 nm SPADs



doi.org/10.1109/NSSMICRTSD49126.2023.10337871

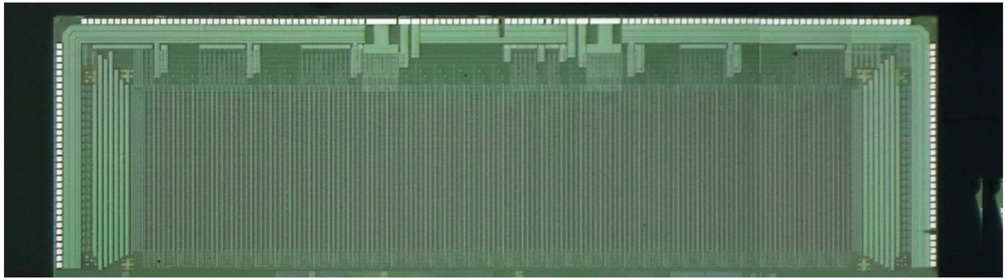
+ 25 °C **-160 °C**

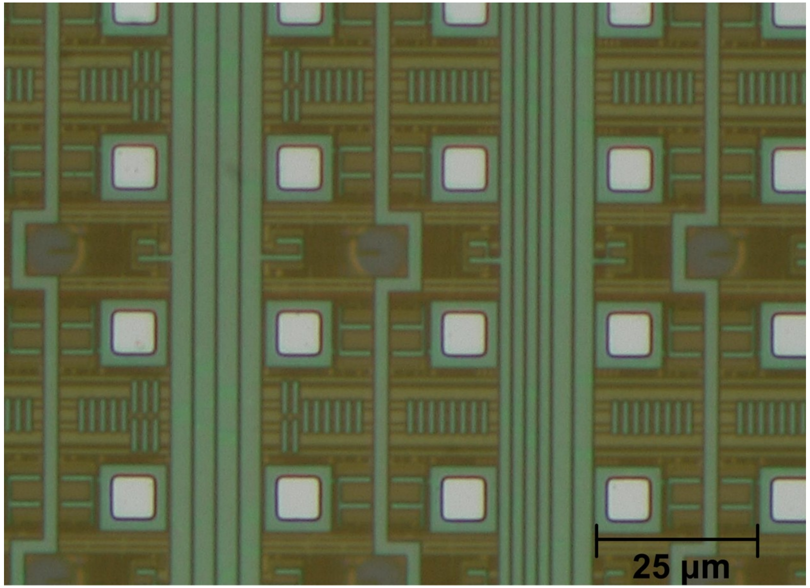


doi.org/10.48550/arXiv.2602.24045

Phoenix3 SPAD Array

- 144x32 arrays (=4608 pixels) of SPADs designed in same 110 nm CIS technology as individual samples
- 5 µm active diameter SPADs at 25 µm pitch
- 9 samples (chips) available
- Binary frame readout doi.org/10.1364/OE.585267
  - rolling shutter with passive quenching
  - 32 kHz rate
- DCR measurements:
  - at room temperature
  - after neutron irradiation up to 10^{13} n_{eq}/cm^2
  - after thermal annealing (100°C – 160°C in 20°C steps for 1 h) doi.org/10.3390/s22082919





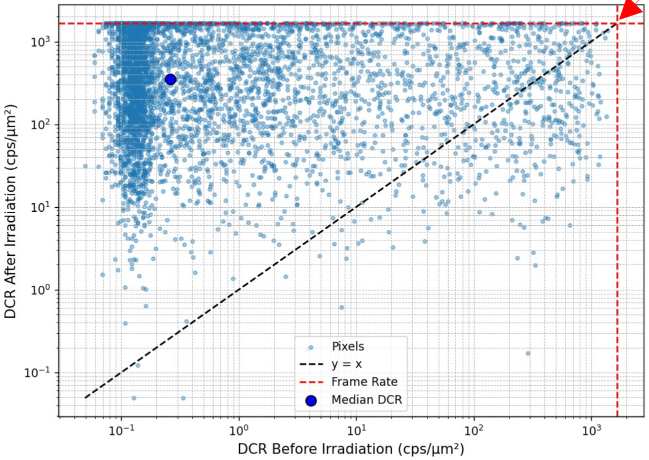
H.K. Yildirim et al., “A 3D Stacked 288x64 InGaAs/InP Gated SPAD Array with Coincidence for SWIR Imaging”, presented at ISSW 2026 conference, 1-4 June 2026, South Korea.

Results: Phoenix3 SPAD arrays

- DCR scatter plots
  - before (BI) vs. after (AI) irradiation
  - after (AI) irradiation vs. after annealing (AA):

rate limits due to 32kHz frame readout

chip 5, $\mathbf{10^{12}\ n_{eq}/cm^2}$, 2 V excess bias



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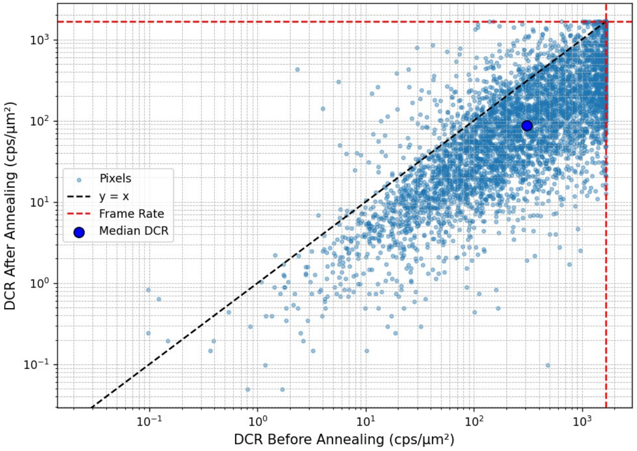
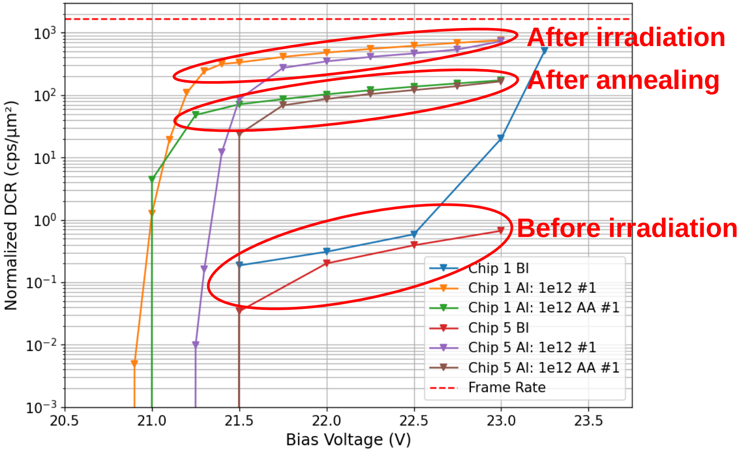
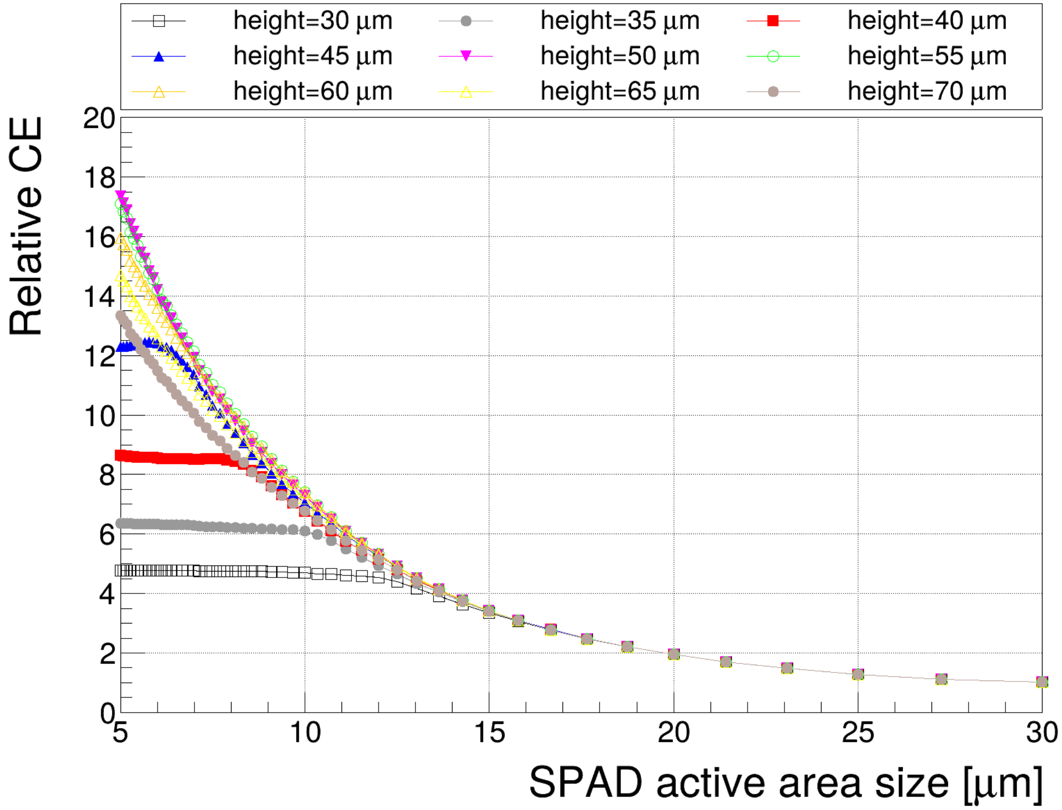
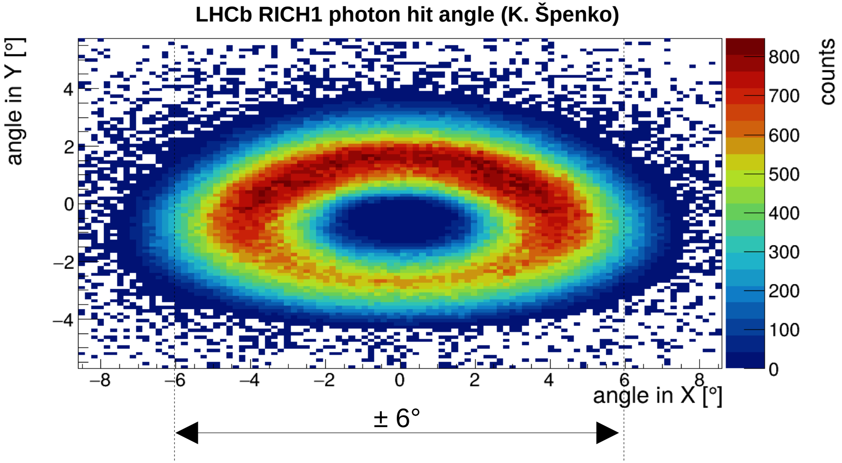


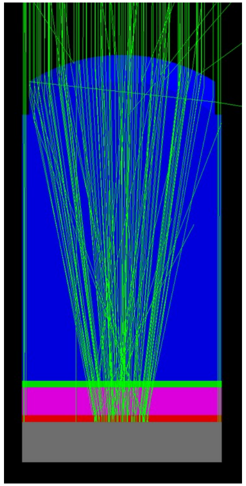


Simulation studies of microlenses for RICH

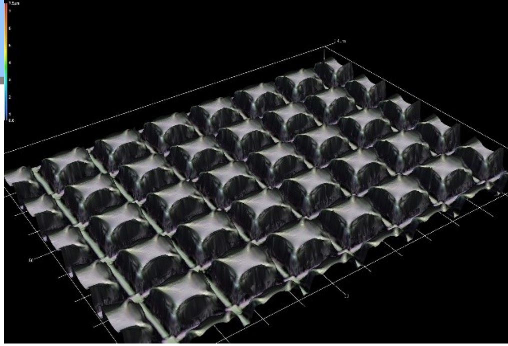
- Limited photon N/A (≈ 0.1 / f ≈ 5) in RICH
  ➔ microlenses perform very well
- Collection efficiency with microlenses vs. without (for 30 μm pitch):





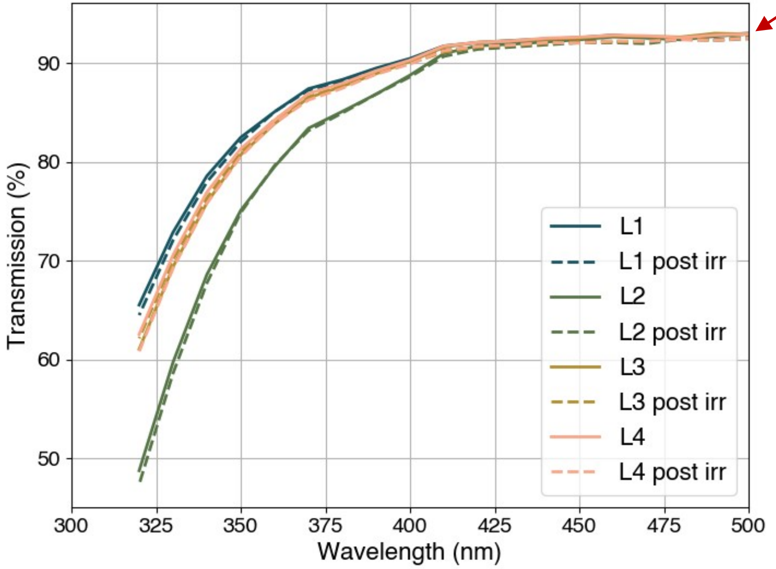


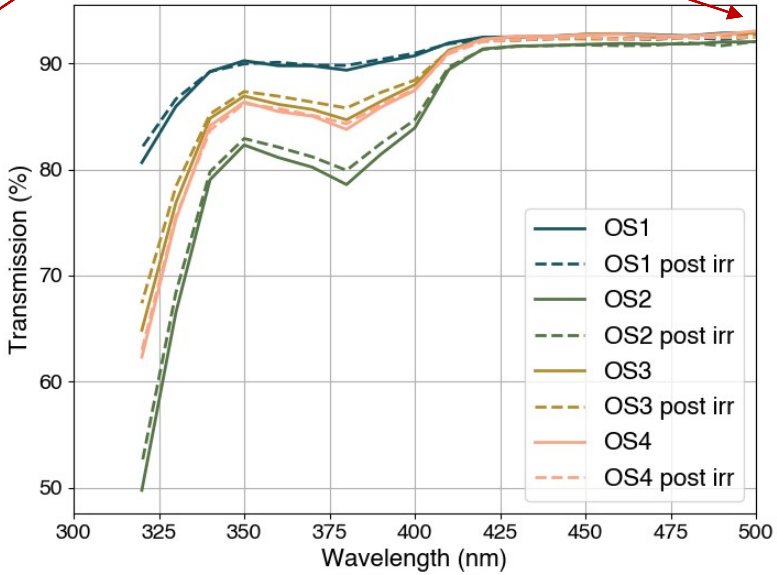
Microlens material radiation hardness study



- Irradiated two commercial microlens process polymers on quartz substrate
  - Lumogen - L, 120 µm
  - Ormostamp – OS, 500 µm
- No observable difference was observed even for 10^{14} n/cm^2

Measured to 1000 nm, flat response after 500 nm.





L1/OS1: 10^{11} n_{eq}/cm^2
L2/OS2: 10^{12} n_{eq}/cm^2
L3/OS3: 10^{13} n_{eq}/cm^2
L4/OS4: 10^{14} n_{eq}/cm^2

doi.org/10.1117/12.3041096

Summary

- Future RICH detectors ➔ require highly performing, rad-hard photodetector
- spadRICH project: developing SPAD-based, rad-hard photosensor optimized for RICH application
- Guide sensor design by characterization of existing CMOS SPAD technologies:
  - neutron irradiation ➔ increases DCR up to 5 orders of magnitude, larger SPADs seem more affected
  - cooling to LN ➔ recovers up to 3 orders of magnitude in DCR
  - technology comparison: 55 nm BCD samples seem to fare better than 110 nm CMOS SPADs
- Simulations of LHCb RICH1 Cherenkov light distribution & optical propagation in the microlens:
  - microlenses can efficiently concentrate light in RICH application
  - small SPAD active area possible to improve rad-hardness
- First dedicated CMOS digital SiPMs currently in production (tapeout in April 2026, expected in October 2026)
  - different 32x32 SPAD arrays of approximately 1x1 mm^2
  - exploring effects of different SPAD sizes, readout architectures and array geometries for future addition of microlenses
  - included electronics functionalities: time gating, fast quenching, hit SPAD addressing
- Design started for next digital SiPM iteration, including integrated TDC

spadRICH collaboration & Acknowledgements

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