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spadRICH: Developing Digital Analog SiPMs as Candidate Photodetectors for Future RICH Detectors

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Motivation

Next generation of Particle physics experiments
- Increase in luminosity
  - **Increase in background radiation**
  - Upgrade of sub-detectors necessary

Ring Imaging Cherenkov Detectors (RICH)
- Critical sub-detector for particle identification
- LHCb [1], Belle II [2], ALICE 3 RICH [3]
- High requirements for photodetector performance

Silicon Photomultiplier (SiPM)
- Photodetector candidate for RICH upgrades
- Single-photon avalanche diode (SPAD) based photosensor
- Current limitation: **neutron radiation hardness**

LHCb RICH1

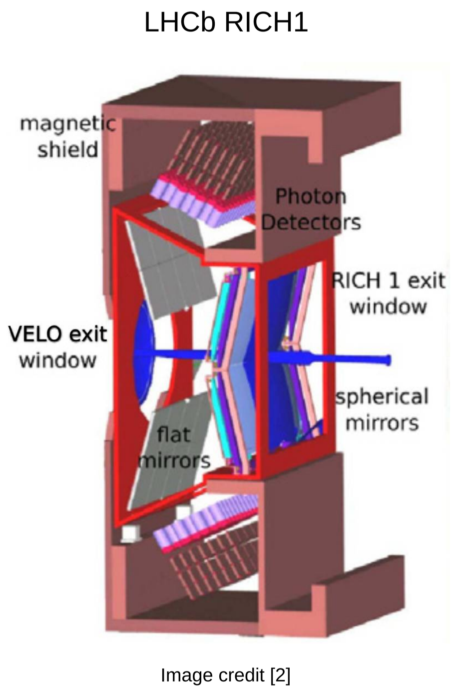


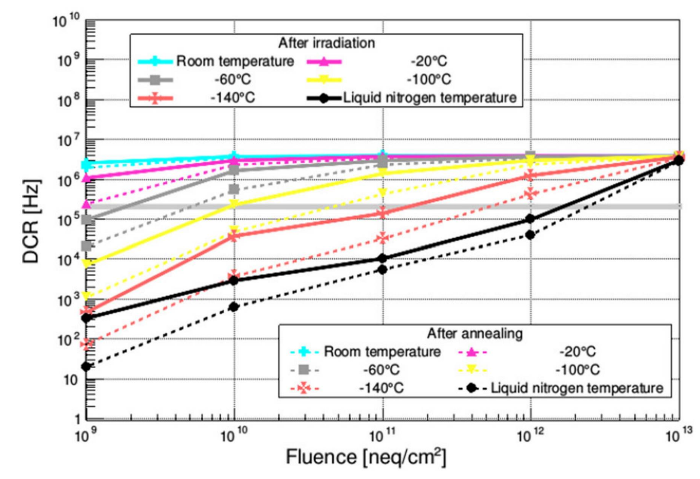
Image credit [2]

LHCb RICH Upgrade II photodetector requirements

Radiation hardness	**2 x 10^{13} 1-Mev neutron equivalent/cm²** 12 kGy TID 1 x 10^{13} HEH (>20 MeV)/cm²
Maximum occupancy	**30%** 1-photon hit probability / mm² /**25 ns**
Timing	100 ps FWHM SPTR few ns gate / 25 ns (40 MHz bunch-crossing)
Granularity	~ 1.4x1.4 mm²
Total area	1.5 m² (RICH1, 2 m² RICH2)
PDE	50% @ 400 nm
DCR	**~ 100 kcps – 1 Mcps/mm²**
Cooling	~ liquid nitrogen

Cryogenic opearation
- Neutron irradiation ➔ defects in SPAD ➔ increase in dark count rate (DCR)
- Cooling reduces DCR
- After 10^{13} n_{eq}/cm² cooling close to liquid nitrogen may be necessary [4]

Measured DCR of 1x1 mm² SiPMs at different irradiation levels, temperatures and with annealing (24h @ 80°C) [4]:

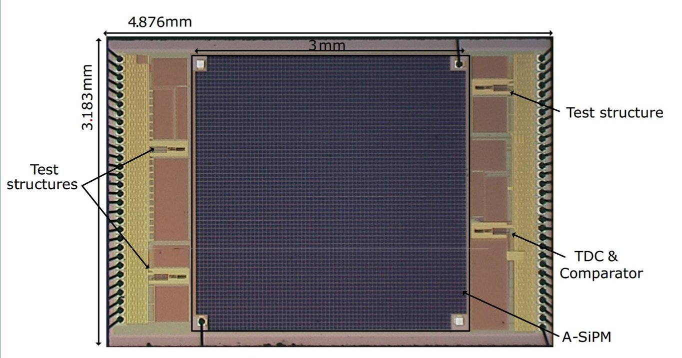


spadRICH Project

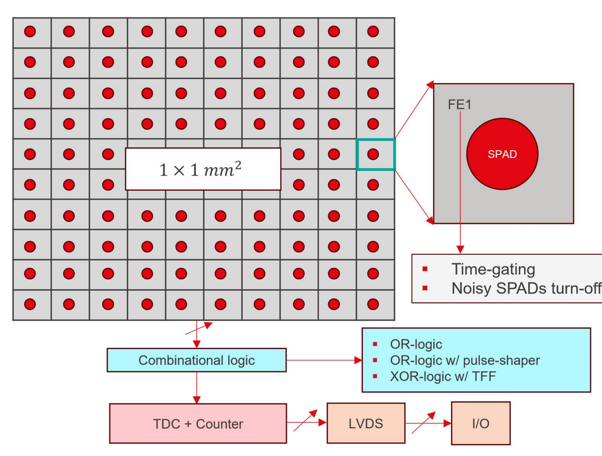
Develop radiation-hard photosensor optimized for RICH application

Based on SiPMs including reconfigurable electronics ➔ digital analog SiPM

Digital analog SiPM [5], demonstrating the feasibility of compensating electronics integration.



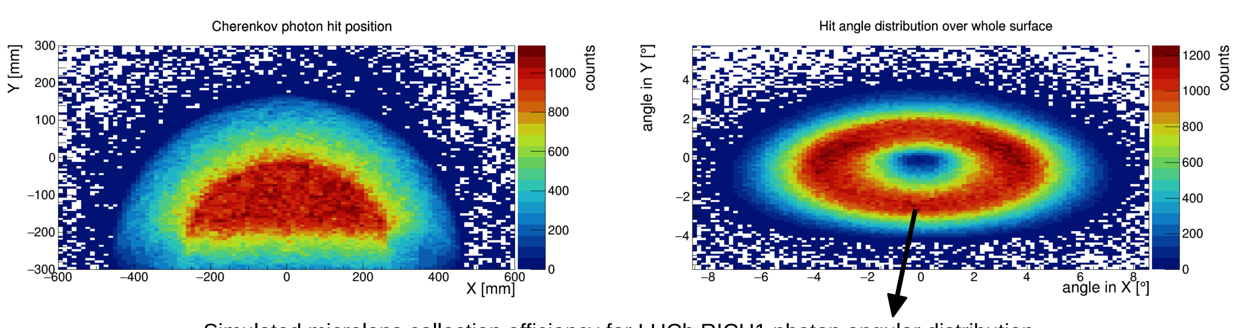
Proposed device architecture



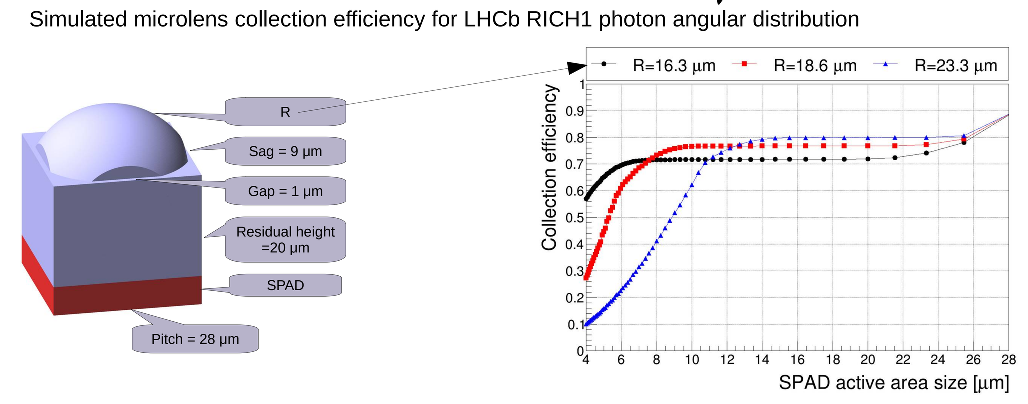
Radiation hardness achieved by means of:
- rad-hard design techniques at transistor and SPAD level
- integrated compensating electronics ➔ switch off noisy SPADs, employ active recharge and custom hold-off times
- microlenses ➔ smaller SPADs

Possible SPAD/architecture optimizations in a RICH detector scenario:
- limited photon angular acceptance (NA) ➔ reduce SPAD size (DCR↓), compensate with microlenses
- timing resolution, gated operation ➔ reduce DCR and data rates
- cryogenic (liquid nitrogen) operation ➔ reduce DCR, but potential increase in afterpulsing (irradiated samples)

Simulated photon spatial and angular distributions at the upper LHCb RICH1 photodetector plane



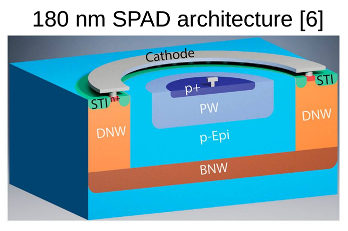
Simulated microlens collection efficiency for LHCb RICH1 photon angular distribution



Methods

Samples characterized
- 180 nm CMOS SPADs [6-9]
- 110 nm CMOS SPADs [10]
- 55 nm CMOS SPADs [11-15]
- Microlenses [16-18]

180 nm SPAD architecture [6]



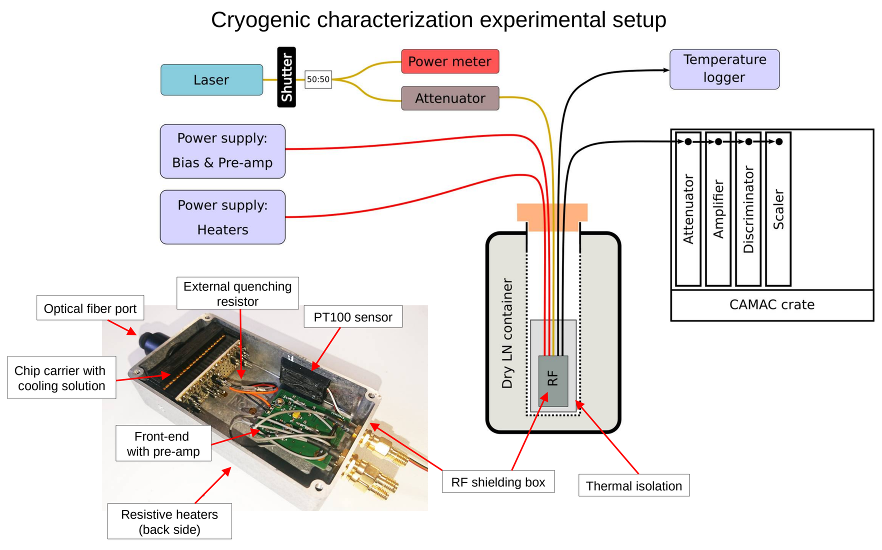
SPAD samples characterized

Type	Junction	D [µm]
55 nm	PN	10
		12
	NP	8
		9
		10
110 nm	P+/N	5
		10
	N+/P	5
		10
		25
180 nm	P+/N	25

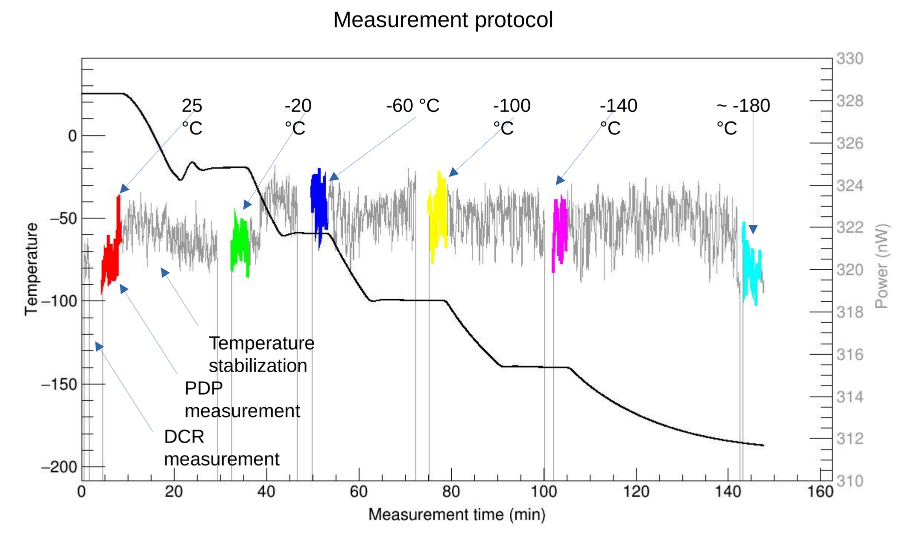
Neutron irradiation
- TRIGA Mark-III nuclear reactor [19]
- Irradiated in TOK2 channel between **10^9 n_{eq}/cm² and 10^{13} n_{eq}/cm²** (microlenses up to **10^{14} n_{eq}/cm²**)

SPAD Characterization
- Stabilized in steps between room and liquid nitrogen temperatures
- Dark count rate (DCR)
- Afterpulsing probability (APP)
- Response to single photon level illumination

Cryogenic characterization experimental setup



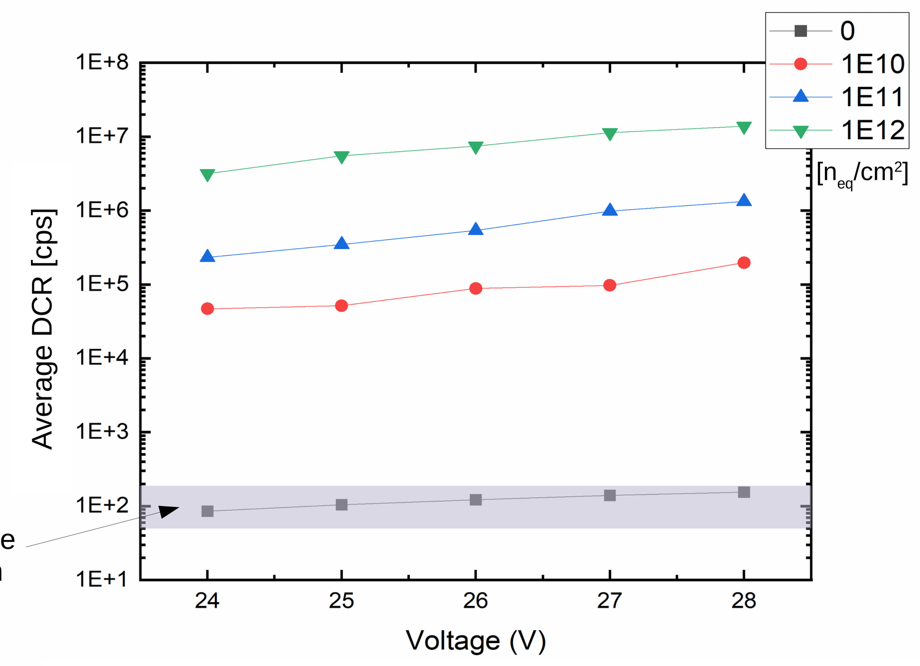
Measurement protocol



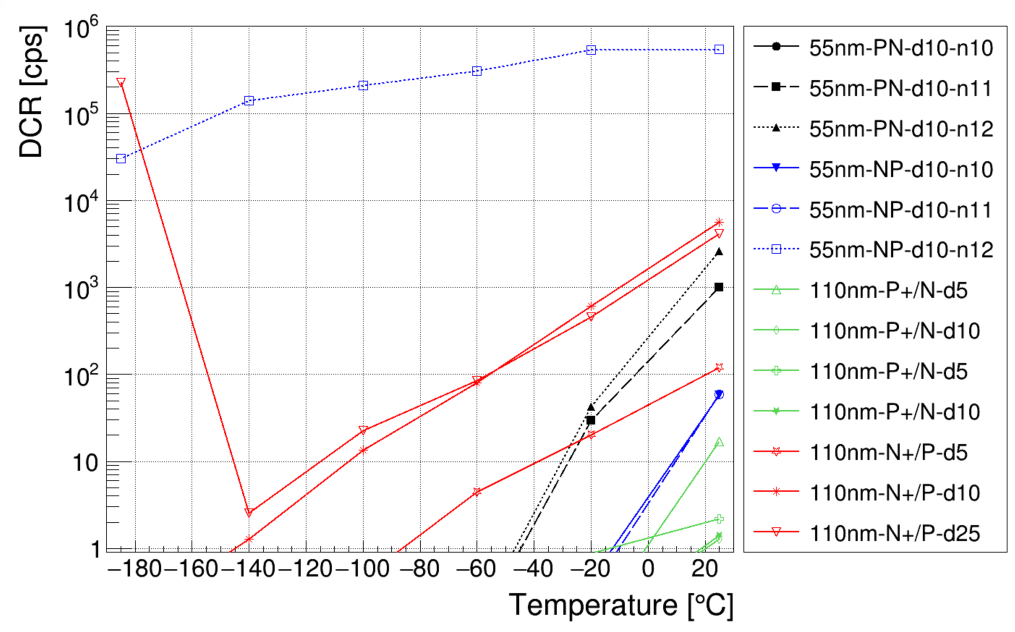
Results

180 nm CMOS SPADs:

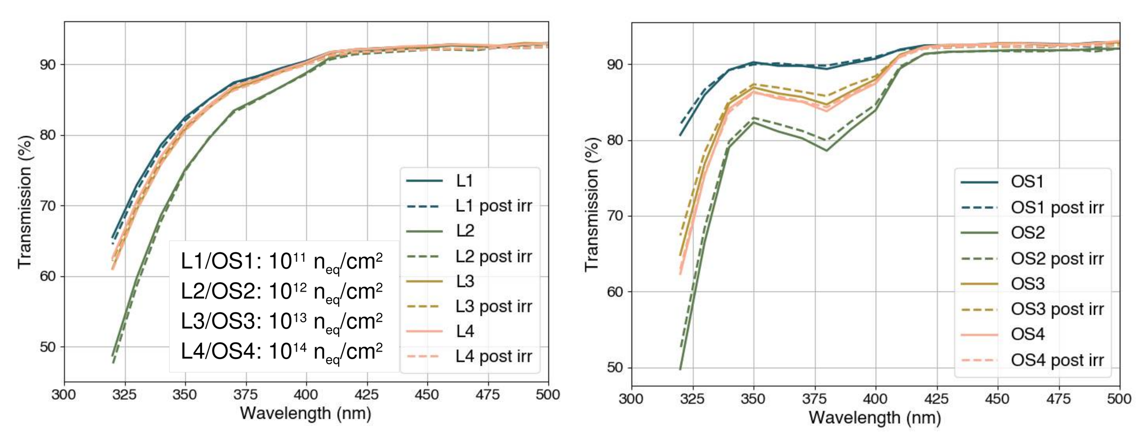
- 4 SPADs per irradiation step
- The dark count rates averaged over the 4 SPADs were measured before and after irradiation
- Dark count rates before irradiation: ~ **10^2 cps**
- After irradiation, the average DCR increased proportionally with the dose, by ~ 1 order of magnitude for each order of magnitude increase in dose
- More in [9]



55 nm & 110 nm CMOS SPADs:
- Single SPADs
- 55 nm SPADs were irradiated at 10^{10} n_{eq}/cm² (n10), 10^{11} n_{eq}/cm² (n11) and 10^{12} n_{eq}/cm² (n12)
- 110 nm SPADs were not yet irradiated
- results are shown for different spad architectures and diameters of 5 µm (d5), 10 µm (d10) and 25 µm (d25)
- Only one sample (55nm-NPd10) was significantly affected after irradiation of 10^{12} n_{eq}/cm²
- Large increase in afterpulses was observed for 110nm with N+/P junction and diameter of 25 µm at LN temperature



Microlenses:
- Irradiated two commercial microlens process polymers on quartz substrate
  - Lumogen – L, 120 µm thick
  - Ormostamp – OS, 500 µm thick
- No observable difference was seen even for 10^{14} n_{eq}/cm²
- More in [18]



SPAD DCR summary:
- Dark count rates for different SPADs
  - before irradiation (DCR)
  - after irradiation (DCR')
  - at room temperature (RT)
  - at liquid nitrogen temperature (LN)
- Excess voltages (V_{ex}) used are stated next to the DCR values
- More in [20]

Type	Junction	D [µm]	DCR [cps] (V_{ex} [V])	Irrad. flux (n_{eq}/cm²)	DCR' RT/LN (V_{ex} [V])
55 nm	PN	10	4 (6)	10^{12}	$3\cdot10^3$/<1 (1.25)
		10	7 (6)	10^{12}	$14\cdot10^3$/- (4)
		12	150 (6)	10^{11}	$13\cdot10^3$/- (2)
		12	6 (6)	10^{11}	$4\cdot10^3$/- (6)
	NP	8	30 (6)	10^{11}	20/- (6)
		8	40 (6)	10^{12}	400/- (6)
		9	30 (6)	10^{11}	30/- (6)
		9	30 (6)	10^{11}	60/- (6)
		10	100 (6)	10^{12}	$5\cdot10^5/3\cdot10^4$ (1.25)
		10	70 (6)	10^{11}	70/- (6)
110 nm	P+/N	10	50 (5.5)	-	-
		10	500 (6)	-	1/<1 (0.6)
		10	50 (6)	-	1/<1 (1)
		5	4 (5.5)	-	2/<1 (2.5)
		5	20 (6)	-	20/<1 (6)
	N+/P	10	$6\cdot10^3$ (6)	-	-
		10	$1\cdot10^3$ (5.5)	-	-
		5	200 (5.5)	-	100/<1 (4)
		25	$7\cdot10^3$ (1.75)	-	$4\cdot10^3/2\cdot10^6$ (4)
		10	$8\cdot10^3$ (4)	-	$6\cdot10^3$/<1 (2)
		10	$1\cdot10^4$ (1)	-	-
		10	$5\cdot10^3$ (4.5)	-	-
		10	80 (6)	-	-
180 nm	P+/N	25	100 (6)	10^{10}	$2\cdot10^5$/- (6)
				10^{11}	$1\cdot10^6$/- (6)
				10^{12}	$1\cdot10^7$/- (6)

Conclusions

Planned RICH detector upgrades ➔ high photodetector requirements
- Candidate photodetector: silicon photomultipliers
- Main challenge: neutron radiation hardness

spadRICH project: monolithic dSiPM for future RICH detectors
- CMOS SPADs in 55 nm, 110 nm and 180 nm
- Neutron irradiation up to 10^{12} n_{eq}/cm² @ JSI TRIGA
- Cryogenic characterization

Next steps
- Characterization of larger number of samples
- Improve DCR measurement for < 1 cps
- Design and test candidate detector with masking, TDC and gating

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