EP R&D on RICH detectors for future high energy experiments

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EP R&D day 2023-1

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R&D plans for future RICH detectors

The CERN Team has proposed a **new design** with improved Cherenkov angle resolution (0.1-0.2 mrad), based on **cooled SiPMs and Carbon-Fibre mirror optics**. The electronics will feature **ps-time resolution** within a ns-readout window.

It is **now the accepted framework** on which to build the Upgrade II.
More details are available in the LHCb Framework TDR for Upgrade II:
https://cds.cern.ch/record/2776420

A **robust R&D project** needs to be carried out, aiming at the next generation of time- and space-precision RICHes for LHCb. Moreover, we participate also in the **AidaInnova WP8.4.1** (Innovative SiPMs and future applications in PID detectors).

All these objectives are fully compliant with the recent **ECFA Roadmap** (10.17181/CERN.XDPL.W2EX , ex. DRDT 4)

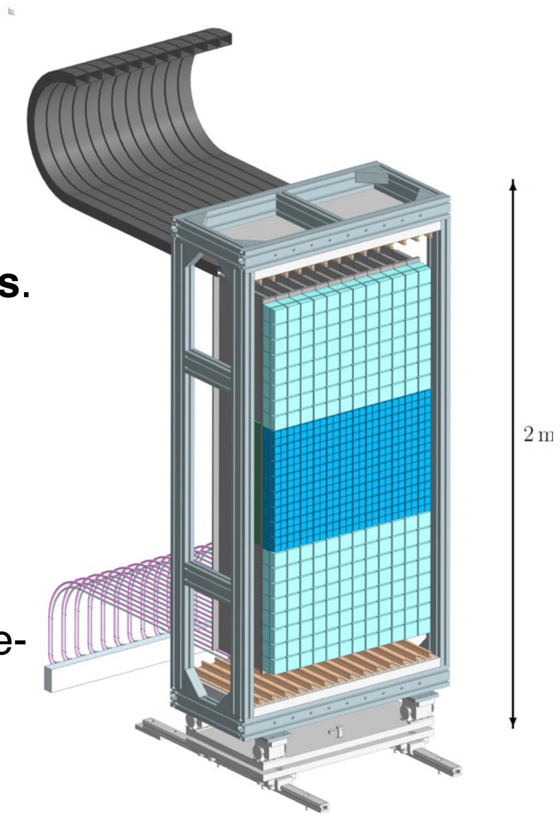


Figure 4: A CAD representation of the photodetector array.

R&D plans for future RICH detectors

Main activities together with the LHCb RICH Collab. are (in green the support from other CERN Groups):

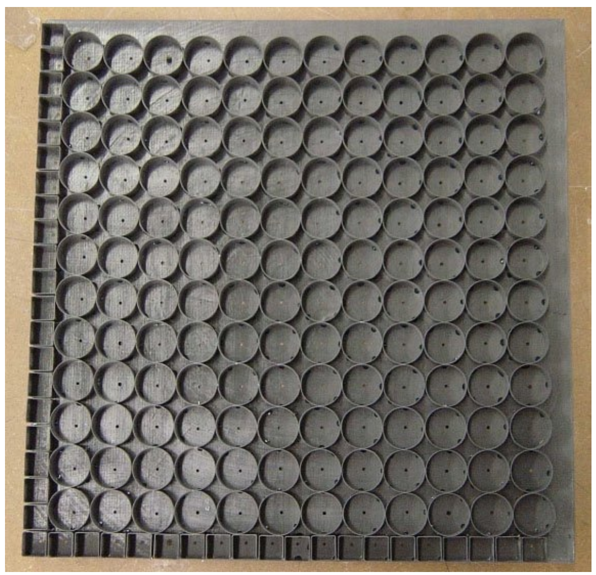
- Detector **novel designs, simulations, and software**.
- **New materials** for future Cherenkov radiators: ex., **Green Gases**; Photonic Crystals, Aerogels (EP-DT).
- **Photodetectors** with enhanced green QE (EP-DT).
- Development of a **gated optoelectronic chain**:
  Support for specific ASIC developments (**FastRICH**); (EP-ESE)
  Characterisation of systems in the laboratory or by **test-beams**. (EP-ESE, EP-DT)
- High Rates Rad. Hard **DAQ** digital architectures. (EP-ESE)
- Development of **Mechanics and Optics**:
  Composite Mirrors for both RICH1 and RICH2; Lenses and optical arrays;
  Special coatings; Precision mechanics. (EP-DT)
- Cooling/**cryogenic** systems. (TE-CRG-CI)

Light-weight composite mirrors and supports

In current RICH 1, carbon fibre-based spherical mirrors (~ 1% X_0) and support structures are already developed and produced by CMA (AZ, USA).

R&D is still needed to:

- Develop flat mirrors.
- Improve quality and radiation length.
- Reduce cost.
- Look into new developments such as Si-Carbide mirrors (up to 1.5 m and ~ 5 kg/m^2).



First flat carbon-fibre mirror prototype produced for RICH 1.

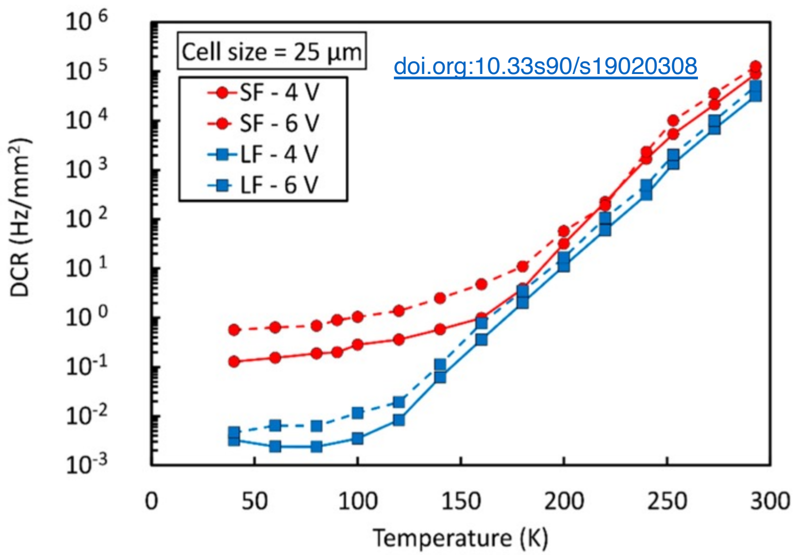
Silicon Photomultiplier (SiPM) sensors

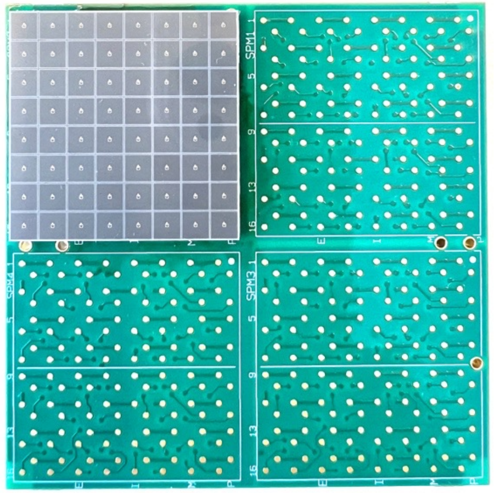
SiPMs are an attractive technology to improve the RICH pixel error (with **1mm channels**), chromatic error (**high single-photon QE** in the green wavelengths) and time response (**better than 100 ps**).

➢ **Solid-state technology** has several advantages:
- Robust sensors at low production cost,
- Small dead area and 2D arrays with pixel sizes down to 1 mm,
- Low operating voltages and insensitivity to magnetic fields and
- CMOS and 3D SiPM designs.

➢ The **high Dark Count Rate**, especially after irradiation, can be partially **mitigated by**:
- Decreasing the operating temperature (cryogenics),
- Annealing the sensor during detector down time,
- Periodic replacement of the SiPMs and
- Micro-lensing to reduce the silicon area.

Studies ongoing of SiPM arrays with high fill factor and few mm channels coupled to our prototype fast-timing readout chain.
To be continued also with cryogenic cooling in the future.



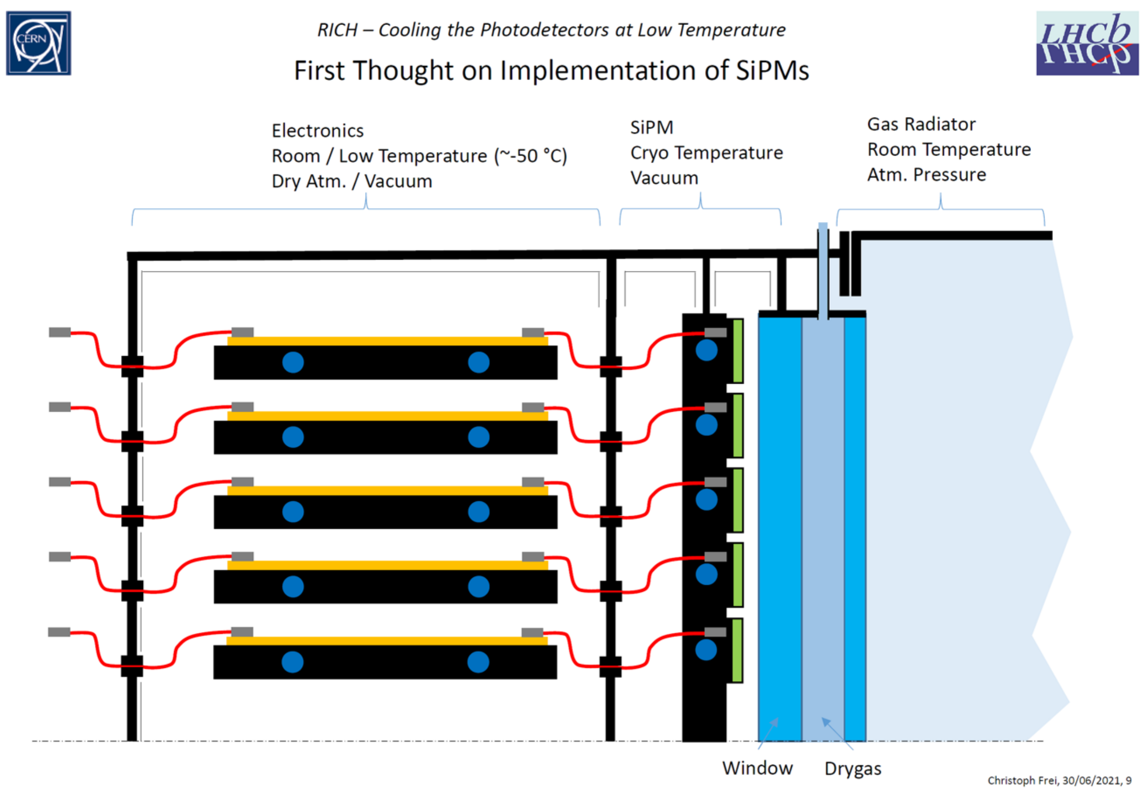


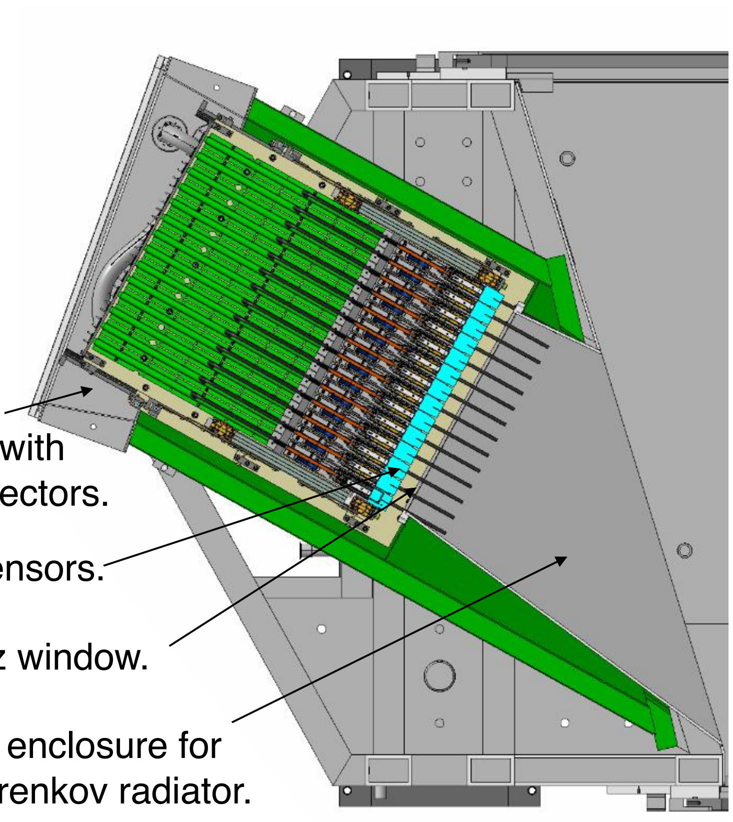
1-inch SiPM array used at the LHCb RICH beam tests.

Low temperature / cryogenic cooling of photon detectors [1/2]

R&D into compact vessel structures has started and several meetings held with the cryogenics experts at CERN (TE-CRG-CI).

- One of the ideas could be to use two specially-coated quartz windows separated by a vacuum.
- Exploring synergies with other LHCb sub-detectors.
- **Design of a lab/testbeam demonstrator is far advanced.**



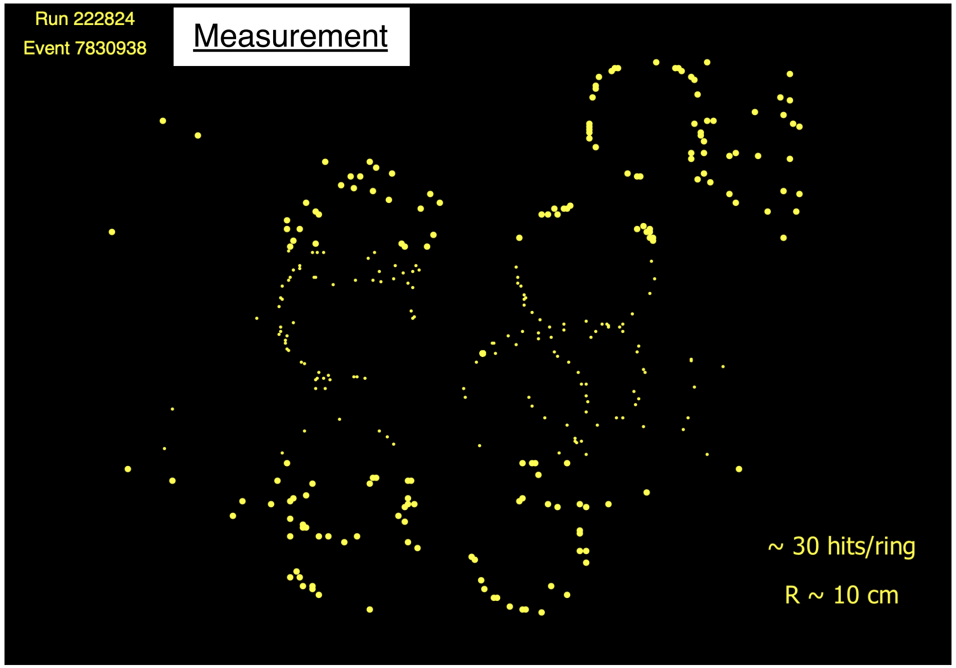


https://indico.cern.ch/event/1175130/

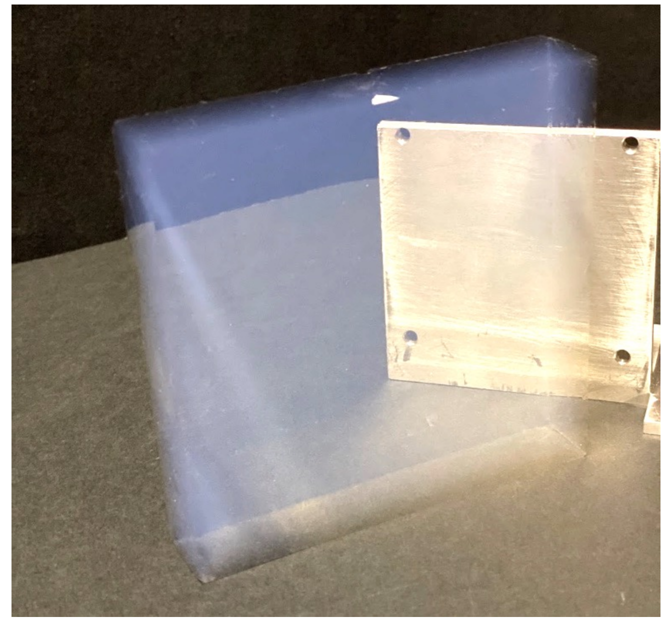
Novel radiator R&D

R&D to provide the RICH detectors with '**green gases**' and R&D of novel radiators including **aerogel**.

- Similar ref. index but lower global warming potential (GWP) where possible.
- Sensors with wavelength range shifted towards the green spectrum provide new opportunities.
- Alternative R&D into leak-less gas system.



Example: during the **LHC pilot beam tests** (in October 2021) RICH 2 was running on CO_2 (GWP=1) instead of CF_4 (GWP=4880).
Image of a collision event from the commissioning team (https://indico.cern.ch/event/1093474/).

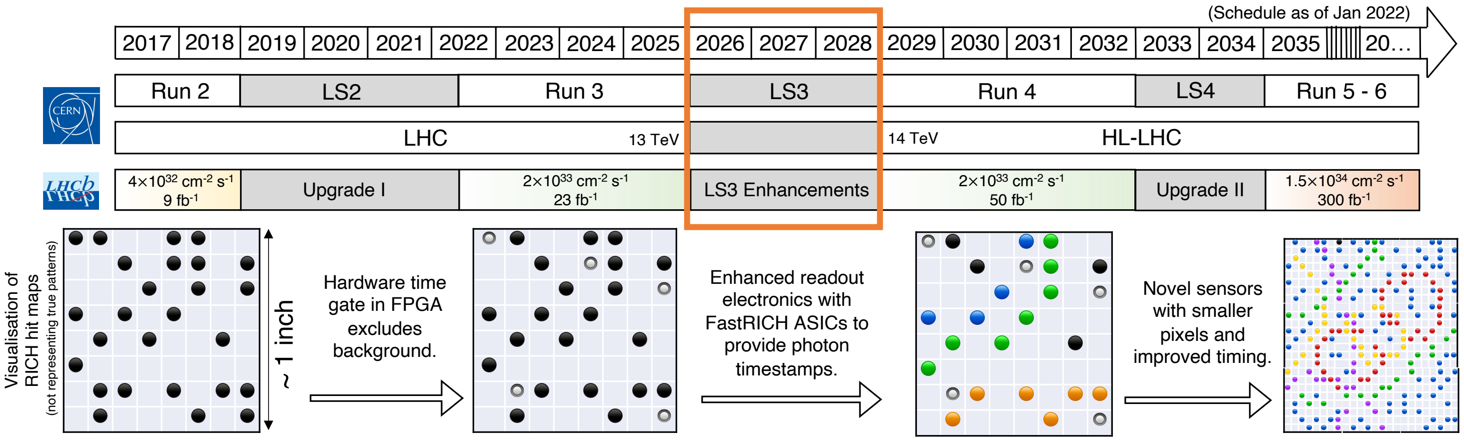


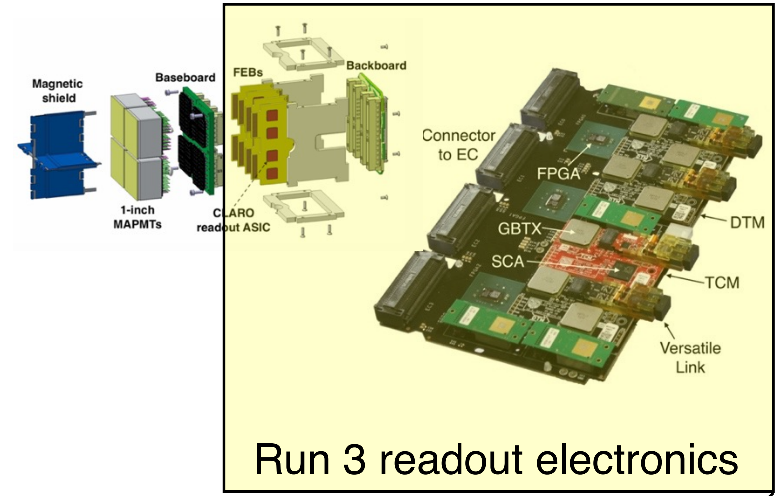
Novel silica aerogel tiles produced in Japan (https://arxiv.org/abs/1112.3121).
Hydrophobic and with improved transparency.

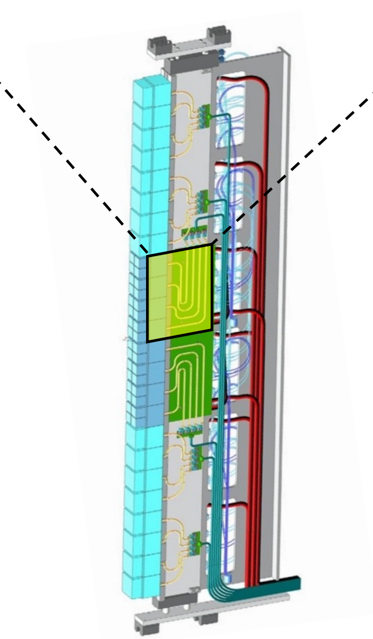
- Studied at SPS beam tests, see backup slide.

Strategy for front-end with excellent photon time resolution

Relatively long period of LS3 central to the LHCb RICH evolution.







Phased improvement of the detector,
first consolidating the readout electronics with fast-timing (**LS3, FastRICH**),
then improving the sensor technology (LS4).

- **Leave untouched in LS3** the photodetectors (MAPMTs), optics and mechanics systems, LV, HV systems, modularity and services.

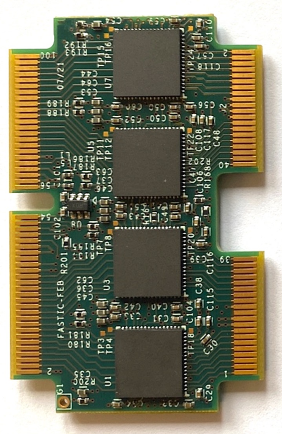
Advantages of this approach:

- Use effectively LS3 to consolidate/upgrade system and prepare for LS4;
- First ever ps-time-resolved RICH detector and a very interesting project to keep the lead of CERN in this field;
- Give a new perspective to the whole LHCb experiment, by providing a good estimation of the t_0 for each primary vertex and the time stamp of each Cherenkov photon;
- Improve maximum acceptable luminosity;
- Improve PID performance and physics throughput during Run 4 already;
- The improvements versus the costs are very favorable.

FastIC and FastRICH ASICs

The Fast Integrated Circuit (**FastIC**) is an ASIC designed in 65 nm CMOS technology by the University of Barcelona (ICCUB) and CERN-EP-ESE.

- 8-channel chip with **wide input dynamic range** (5 uA to 25 mA) for pos/neg signal polarities.
- Fast discriminator (~ 30 ps jitter).
- **Not** designed to be specifically **radiation hard**.



RICH front-end board with FastIC ASICs.

Next-generation **FastRICH** is based on the FastIC and **specific requirements of the RICH detector**.

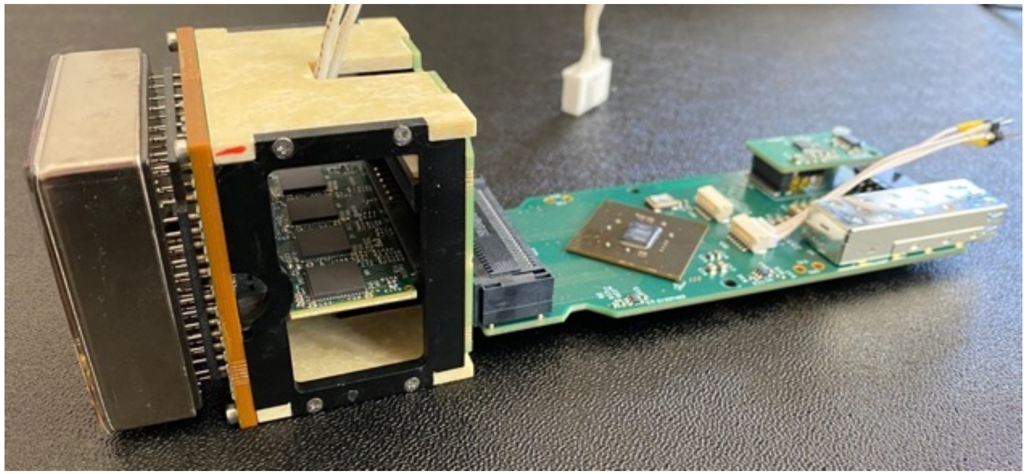
- 16-channel chip with additional **digital** signal **processing**.
- **TDC** with ~ 25 ps time bins and 40 MHz readout rate.
- **Hardware shutter time** (configurable) to limit the timestamp range to ~ 1 to 2 ns.
- **Constant-fraction discrimination** (CFD) to reduce data throughput.
- **Zero-suppressed** output over configurable number of output links to lpGBT.
- **Radiation hard** by design (~ 10^{13} n_{eq}/cm^2 and ~ 5 kGy).
- **Compatibility with lpGBT/VTRX+** and the architecture of the Run 4 and Run 5 DAQ.

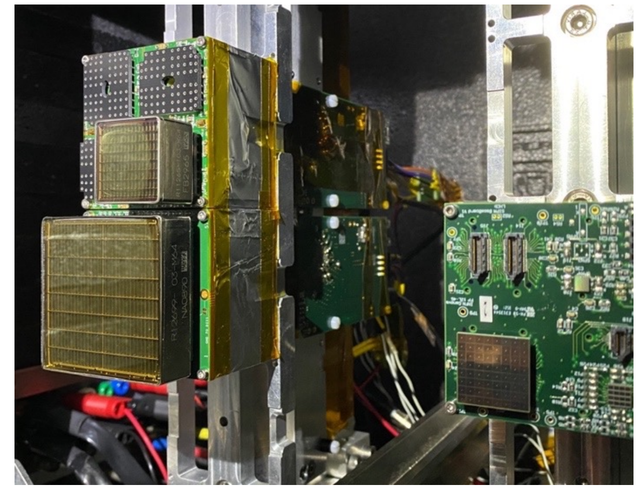
*FastRICH design ongoing (CERN-ICCUB) with analogue parts nearly completed and digital design progressing. Strong input from the RICH group in the **specifications**, the **integration** into future RICH detectors and the foreseen **validation** of the prototype ASIC.*

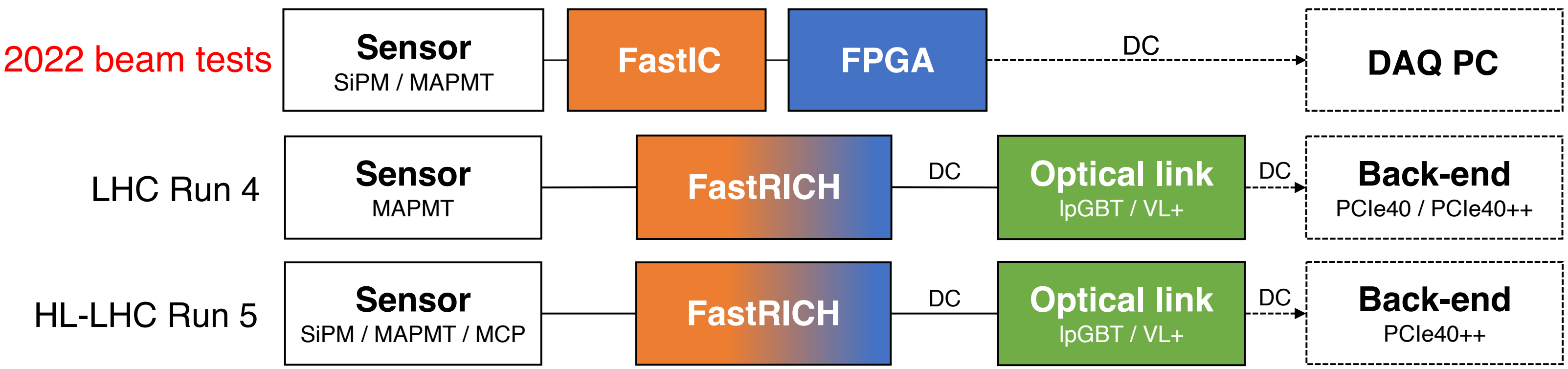
RICH prototype electronic readout chain

The **SPS test beam campaign** focuses on the development and testing of a prototype readout chain with **fast-timing information**. The **FastIC** under test will be the <u>predecessor</u> of the **FastRICH for LS3**.

- The FastIC is coupled to **SiPMs/MAPMTs** and read out by a **TDC-in-FPGA**.
- Valuable information was collected on fast-timing techniques, FastIC operation, sensor coupling, etc.







FastICs coupled to MAPMTs (1 and 2-inch devices, Run 4) and an SiPM array* (Run 5 candidate).

* Hamamatsu S13361 series using 8x8 arrays of 2.0 mm channels or 3.0 mm channels.

SPS test beam studies of the prototype opto-electronics chain

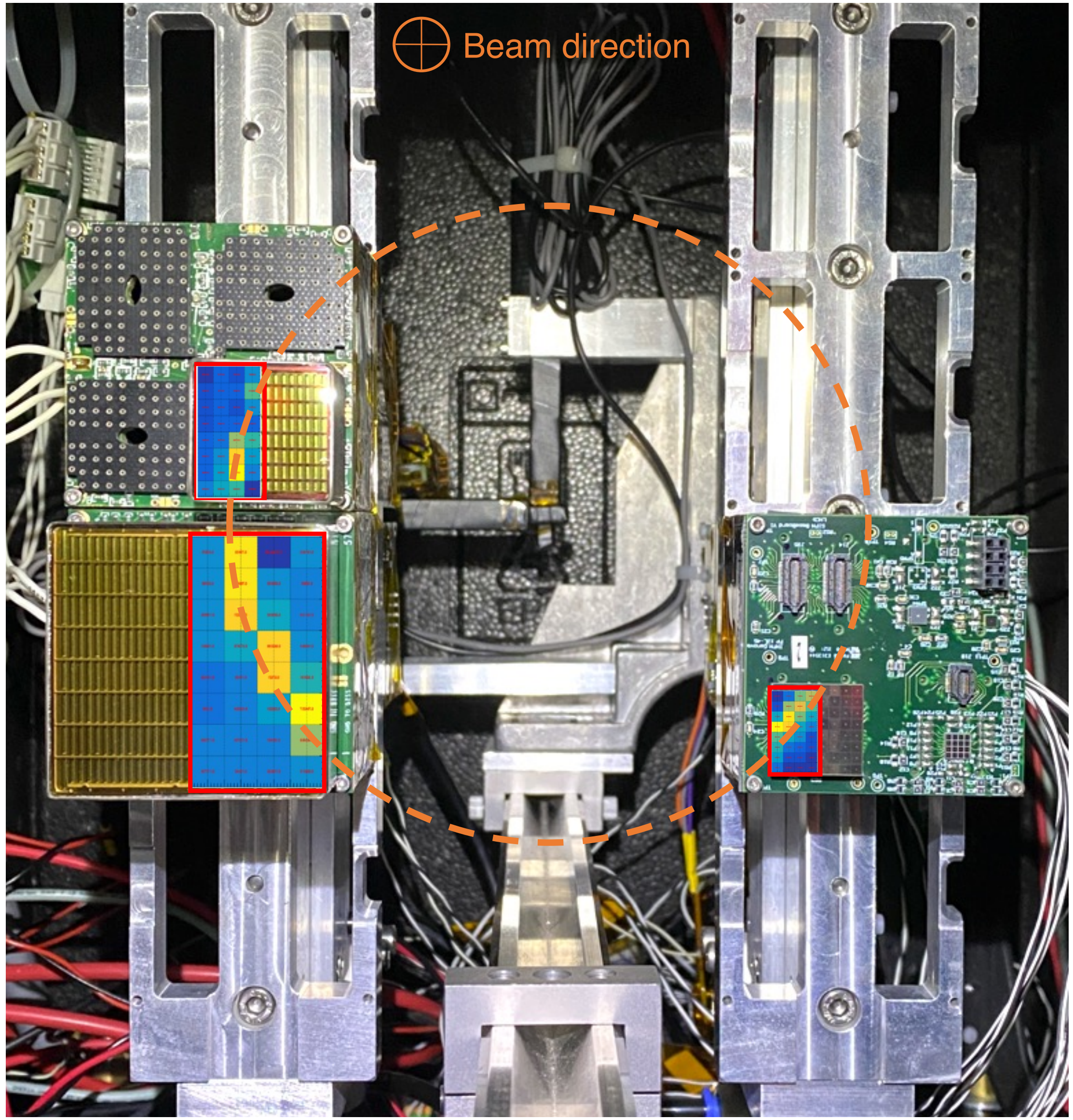
Cherenkov rings (orange-dotted line) detected during beam tests.

➢ Today, analyses ongoing.
Preliminary result for the MAPMTs is ~ 250 ps SPTR (approaching the 150 ps MAPMT spread), with scope for further improvements in the analyses, track reference timestamp, etc.

R&D is foreseen to evolve to **larger sensor areas in a cooled prototype (SiPM)**.

➢ Other photon detectors, such as LAPPDs, can also be studied with this readout chain.

Readout electronics are evolving to introduce e.g. lpGBT/VTRX+ in 2023 and to be optimally setup to **integrate and test the prototype FastRICH ASIC from 2024 onwards**.



Requested R&D funds for the MTP

Deliverables (max. 5)

date *)	item
31.12.2024	new asic for time-resolved RICH systems
1.3.2025	new aerogel radiators characterization, start of SiPM studies
1.6.2026	proto flat composite mirror
1.12.2026	New green gas proposal instead of C4F10
1.12.2028	Complete design of a cryostat for SiPMs array

Milestones (max. 5)

1.6.2024	achievement ASIC
31.12.2024	successfull test beams and analysis of new asic and aerogel tiles
1.6.2025	CO2 instead of CF4
1.12.2025	first scale model prototype composite flat mirror
1.1.2028	First demostration of cryogenic cooling of SiPMs in test beams

Resource needs

(FTE)	Goods & consumables (kCHF)	Explanations
year 1	20	mirror prototypes and coatings, Asic characteriz. and test beams
year 2	30	mirror acquisition and cryogenic set-up
year 3	40	studies on alternative C4F10 gases;
year 4	40	contr. to cryostat proto
year 5		

(FTE)	Longer Term Investm. (kCHF)	Explanantions
year 1		
year 2	30	mirror acquisition
year 3		
year 4	80	prototype Cryostat
year 5		

(FTE)	Fellows	Students	Staff* for supervision
year 1	0.5	0	1
year 2	1	0	1
year 3	1	0	1
year 4	0.5	0	1
year 5			

Conclusion

A thorough **R&D project** is ongoing, aiming towards the next generation of RICH detectors for LHCb with improved timing (order 100 ps or better) and Cherenkov angle (0.1-0.2 mrad) resolution, based on the **FastRICH ASIC coupled to cooled SiPMs** and using **carbon-fibre mirror optics**.

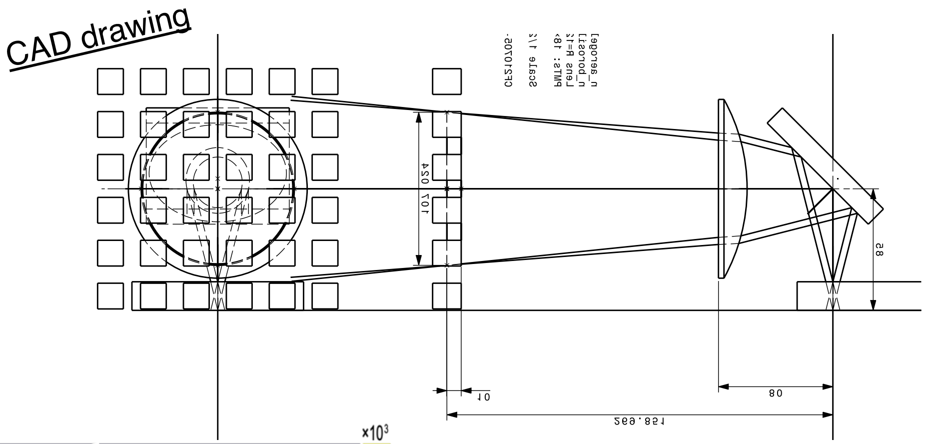
R&D has started on **cryogenic cooling of SiPMs** to lower the DCR, with at the first stage a **demonstrator** for laser lab studies and beam tests.

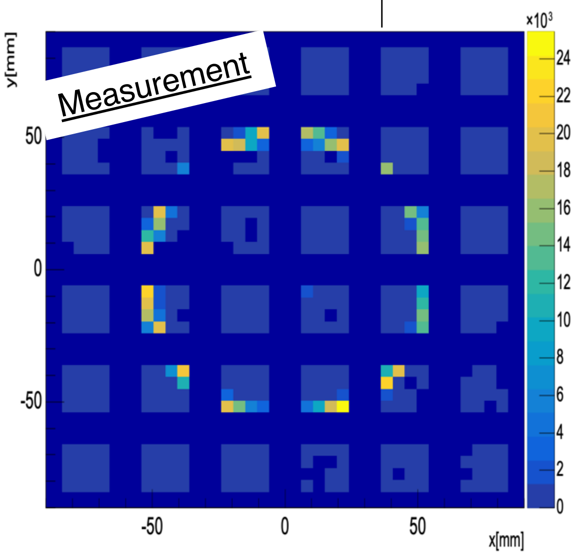
The **FastRICH ASIC is being developed** at CERN-EP-ESE and ICCUB with input for the specifications from the RICH collaboration.
It is at the core of the **LHCb LS3 enhancements** targeting the electronic readout with picosecond timing to improve PID performance in Run 4 and to make an important technological step for Upgrade II.

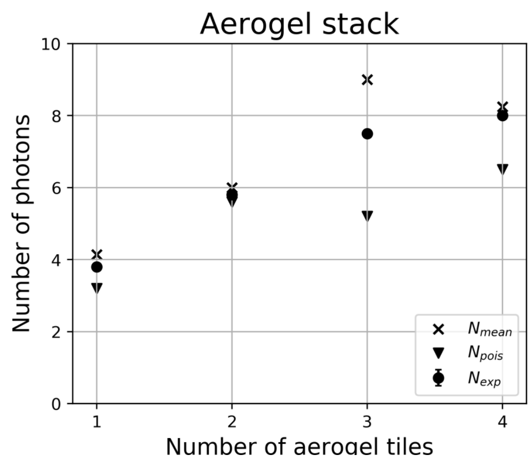
Beam tests are performed on **prototype fast-timing optoelectronic readout chains** based on the FastIC coupled to MAPMTs and SiPMs. The 2022 campaign produced encouraging results and the next phase is being prepared for **2024 onwards with the FastRICH ASIC**.

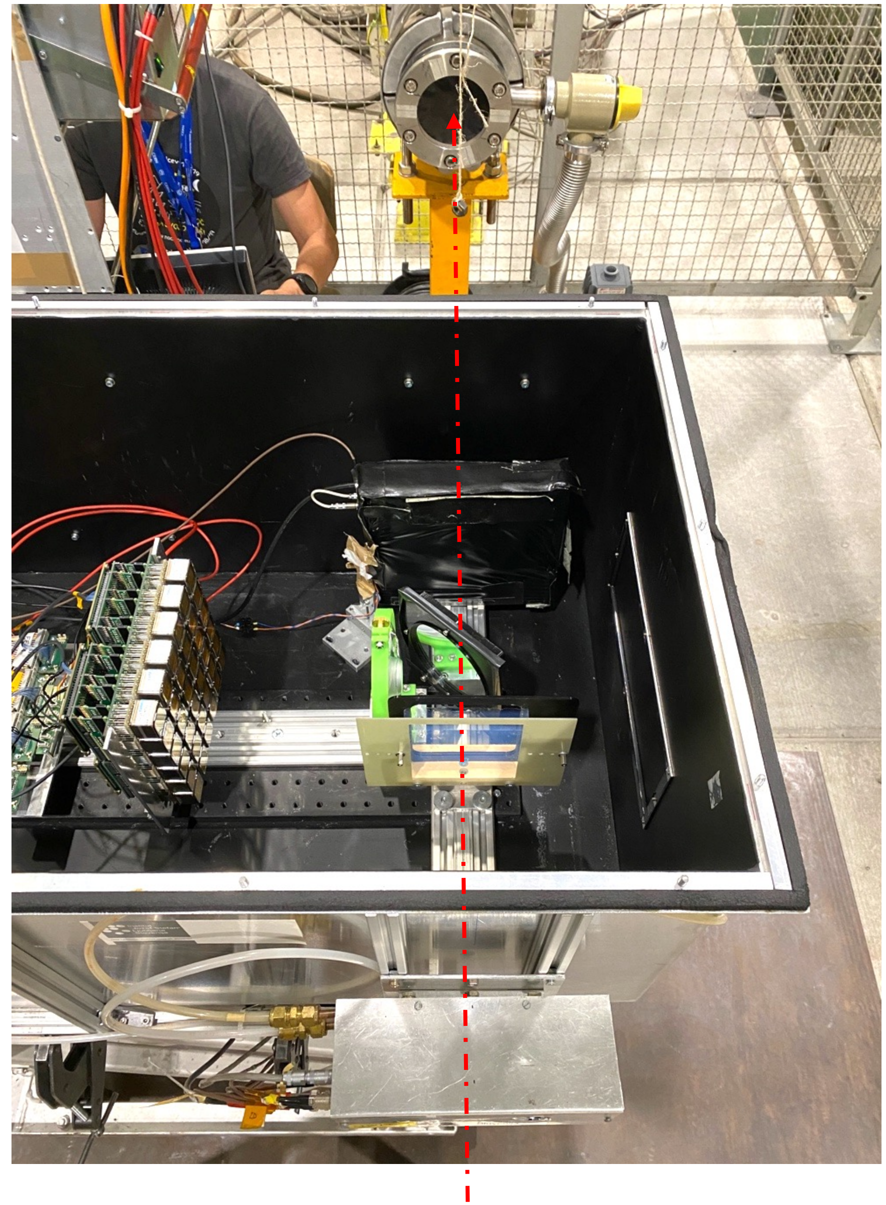
Backup

Novel radiator R&D







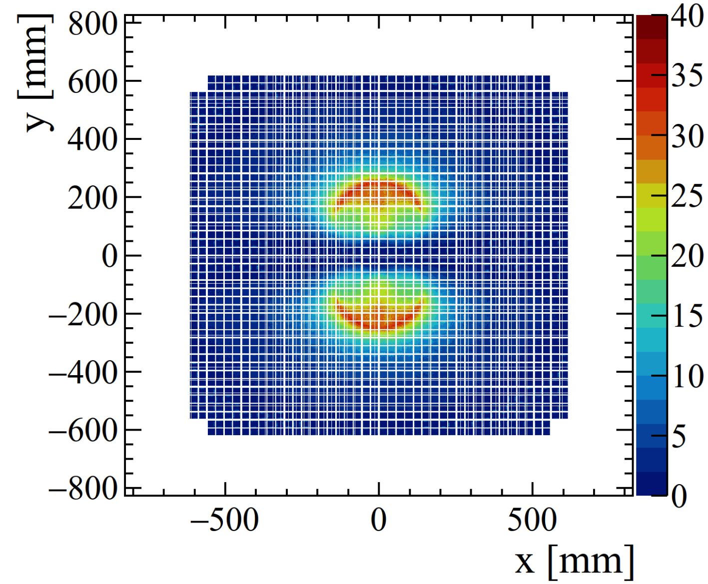


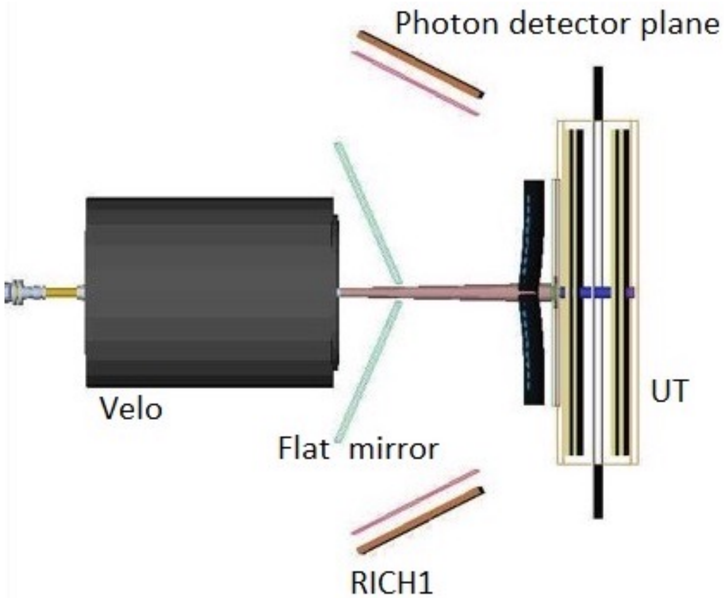
Results show high transparency (nearly linear for thicknesses up to 8 cm) and, taking into account various corrections, a yield of $\mathcal{O}(50)$ photons / cm of aerogel.

RICH resolutions

The RICH detectors can benefit from a range of improvements to reduce the photon occupancy and improve the Cherenkov angle resolution in the high-multiplicity (x 7.5) environment during HL-LHC Run 5.

- Improved **granularity** to 1.0 x 1.0 mm^2 channels avoids the peak photon occupancy from exceeding 100 %.
- SiPM with **enhanced sensitivity in the green** wavelengths reduces the chromatic error.
  Additional studies ongoing on MCP-based detectors and next generation MaPMTs.
- **Redesign of the optics** with lightweight flat mirrors placed inside the acceptance reduces emission point error.





Configuration		Overall [mrad]	Chromatic [mrad]	Emission pt. [mrad]	Pixel [mrad]	Yield
RICH1	MaPMT	0.80	0.52	0.36	0.50	63
	SiPM	0.40	0.11	0.36	0.15	47
	SiPM & geometry	0.22	0.11	0.12	0.15	34
RICH2	MaPMT	0.50	0.34	0.32	0.22	34
	SiPM & geometry	0.13	0.1	0.05	0.07	20-30

Table 4.2: Examples of peak occupancies in RICH1 obtained using the LHCb simulation framework, assuming a pixel size of $2.8 \times 2.8\,\text{mm}^2$ for the MaPMT and $1 \times 1\,\text{mm}^2$ for the SiPM.

(Source: FTDR)

Sensor considerations

Generally, RICH detectors require **highly efficient single-photon sensors**.
There is no ‘perfect’ sensor that satisfies all the future RICH requirements.

- **R&D is ongoing** into several candidates.
- **Silicon photomultipliers (SiPMs)** are a highly attractive ‘off the shelve’ technology but suffer from a high DCR especially after irradiation.
- Micro-channel plate (MCP)-based detectors have excellent time resolution but relatively poor anode current capability and gain ageing.

	SiPM / Solid-state	MAPMT	HPD	MCP family
Time res. [ps]	60	150	~ 100	~30
Channel size [mm]	≥ 1	≥ 2.8	Custom (R&D)	Custom (R&D)
Peak quantum efficiency	> 45 % at 460 nm	> 35 % at 350 nm	30 % at 400 nm	20-30 % at 350 nm
Dark-count rate [Hz/mm^2]	$\mathcal{O}(10^5 - 10^7)$ at room T	1	1	1
Radiation tolerance	Lattice defects	UV glass window	Si ASIC	UV glass window
Gain ageing (50%) [C/cm^2]	SPAD	~ 10^3	Si ASIC	$\mathcal{O}(10)$ ALD
Bias voltage [V]	10-100	$\mathcal{O}(10^3)$	$\mathcal{O}(10^4)$	$\mathcal{O}(10^3)$
Robustness in B-field	Not affected	RICH 1 shielding (< 5 mT)	Orientation dependent	Micro-channel (< 2 T)