Photon detectors and front-end electronics for RICH detectors in high particle density environments

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Technological aspects and applications of Cherenkov detectors

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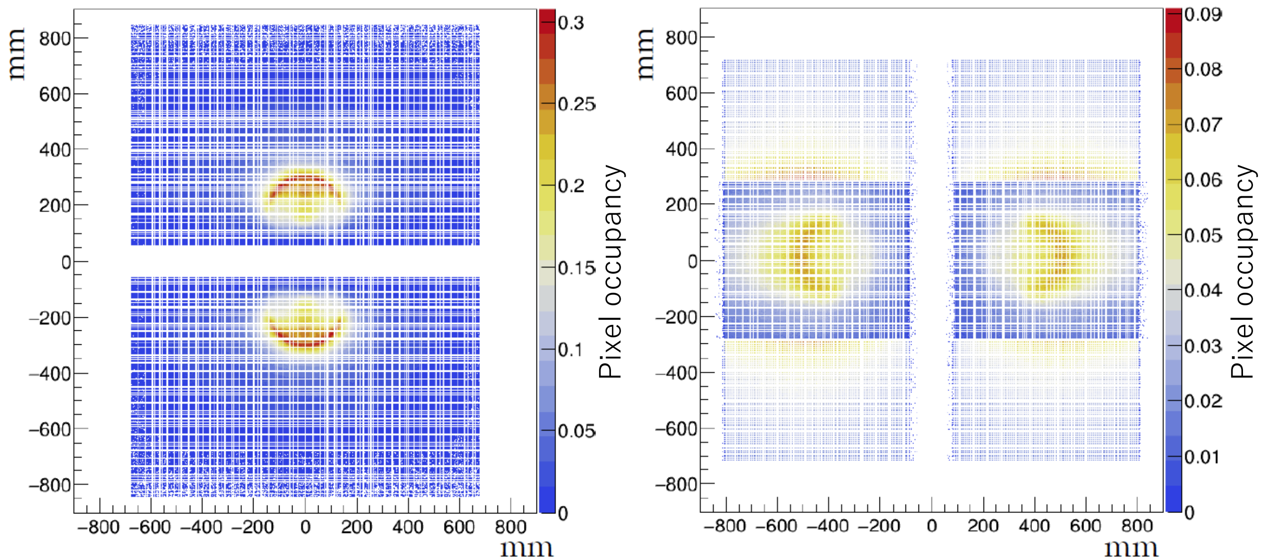
Challenge of high density and high rate

- Near-future high track density RICH and DIRC detectors will work from about 1 MHz/cm^2 up to 100 Mhz/cm^2 photon hits. This is feasible with current technology



Example of a high track density RICH: **LHCb RICH** in upcoming upgrade

Peak occupancy: 27 %
Event rate: 40 MHz
Pixel size: 0.09 cm^2

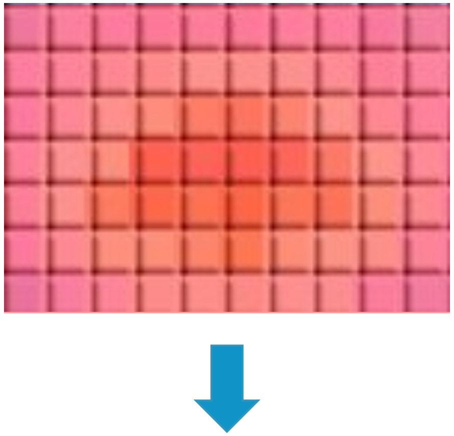
Photon rate:
40 MHz * 0.27 / 0.09 cm^2
= **120 MHz/cm^2**

Courtesy of the LHCb RICH upgrade collaboration

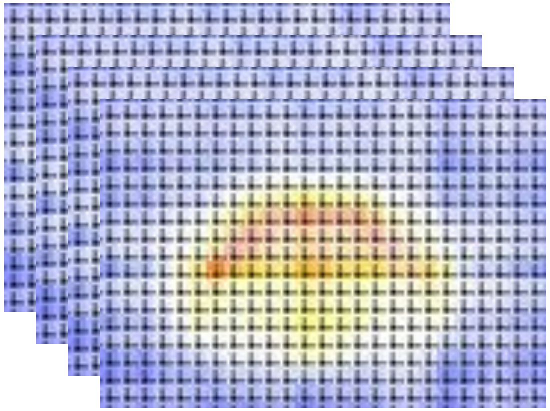
- Is the present technology ready for the next step (i.e. 1 GHz/cm^2 photon hits and beyond)?
- Main limitations for even higher track density and higher rate:
  - Detector saturation (i.e. too high occupancy, pile-up, etc.)
  - Photodetector saturation (i.e. too high anode current, gain ageing, etc.)
  - Electronics saturation (i.e. too high signal rate, dead time, increasing data rate, etc.)
  - Radiation damage on the whole detector (TID of Mrads and neutron fluence of 10^{14} n_{eq} cm^{-2})

Possible solutions

Some conceptually easy solutions:



- High track density → increase detector spatial resolution
  - This is what has been done so far in most cases
  - Larger photodetector planes and increased focal plane distance
  - Finer photodetector pixels
  - Use of DIRCs when tight spaces are available



- High track rate → increase detector timing resolution
  - Successfully pioneered in some experiments
  - Seems to be the general trend in all LHC experiments

The two approaches are not mutually exclusive. A high-segmentation and fast RICH detector is possible

This talk is focused on photodetectors and electronics, so I will only describe solutions with respect to these two components of a RICH detector

Latest photodetectors

- The most established commercial photodetectors beyond MaPMTs are SiPMs and MCPs
- Other solution do exist (HPDs, other hybrid solutions, gaseous detectors, etc.) but they are not considered in this talk
- Table of comparison of the main characteristics for usage at 1 GHz/cm^2 photon hits in radioactive environments:

	MaPMT	SiPM	MCP-based solutions
Spatial resolution	×	✓	✓ ✓
Time resolution	✓	✓	✓ ✓
Radiation hardness	✓	× ×	✓
Low dark counts	✓	×	✓
Magnetic field immunity	×	✓	✓
Low cost	×	×	×
Gain ageing	×	✓	× ×
Saturation current	×	✓	× ×
Low voltage operation	×	✓	×

SiPMs

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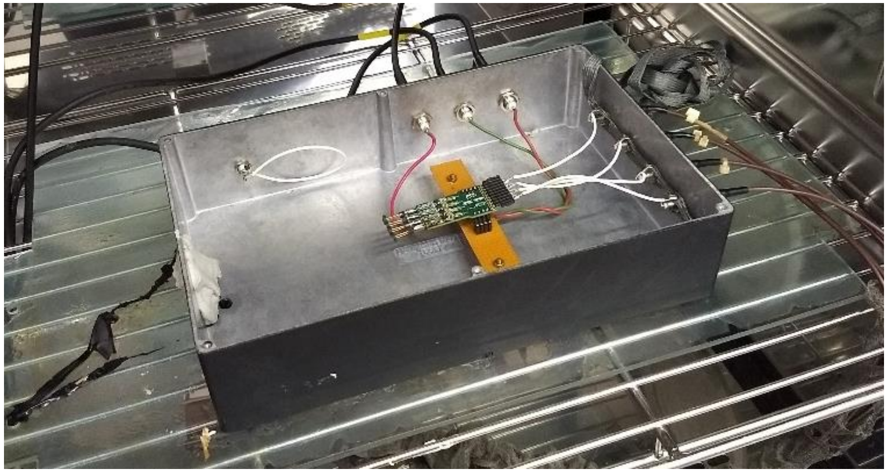
Low dark counts	✓	×	✓
Magnetic field immunity	×	✓	✓
Low cost	×	×	×
Gain ageing	×	✓	× ×
Saturation current	×	✓	× ×
Low voltage operation	×	✓	×

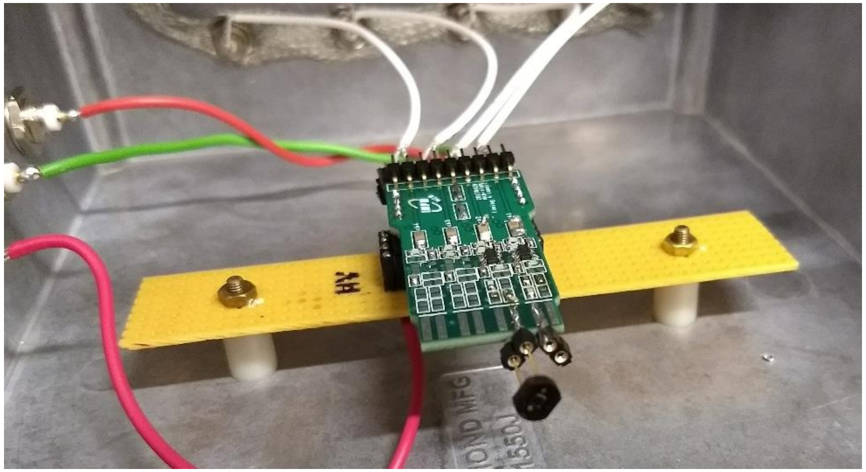
SiPM measurement setup

- Test setup for SiPM measurements:
  - Several models tested (SensL C-Series, Hamamatsu S13360-13xx, more to come…)
  - Discrete front-end electronics and oscilloscope read-out
  - Low jitter laser light source
  - Temperature control in climatic chamber

Model	SiPM size	Cell size
SensL C-Series	1x1 mm^2	20 µm
SensL C-Series	1x1 mm^2	50 µm
Hamamatsu S13360-1325CS	1.3x1.3 mm^2	25 µm
Hamamatsu S13360-1350CS	1.3x1.3 mm^2	50 µm
Hamamatsu S13360-1375CS	1.3x1.3 mm^2	75 µm



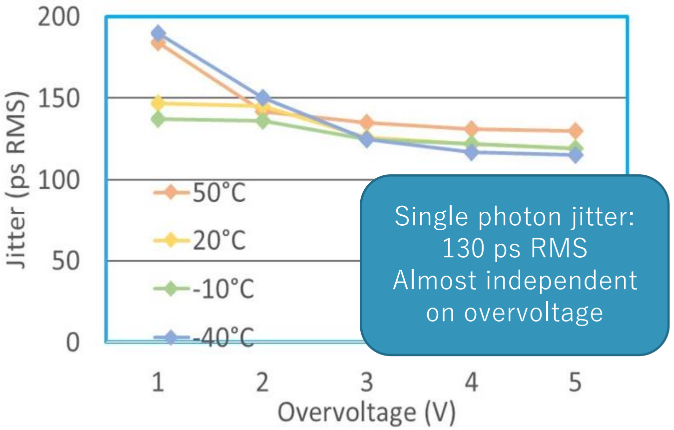
Light-tight box in climatic chamber

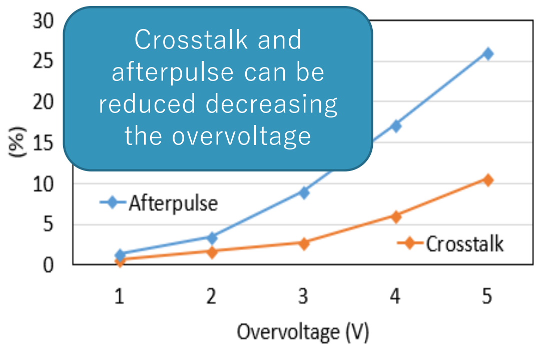


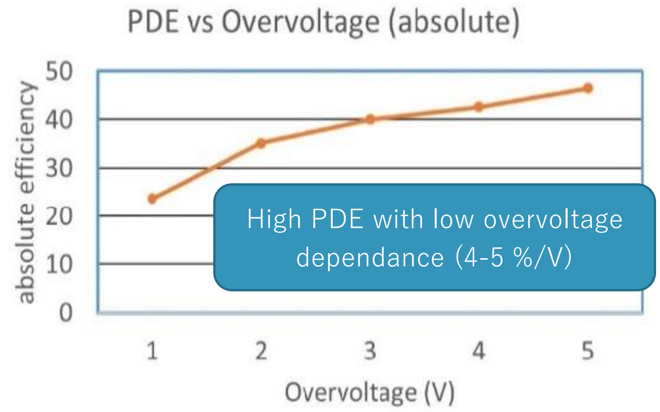
Custom discrete front-end electronics

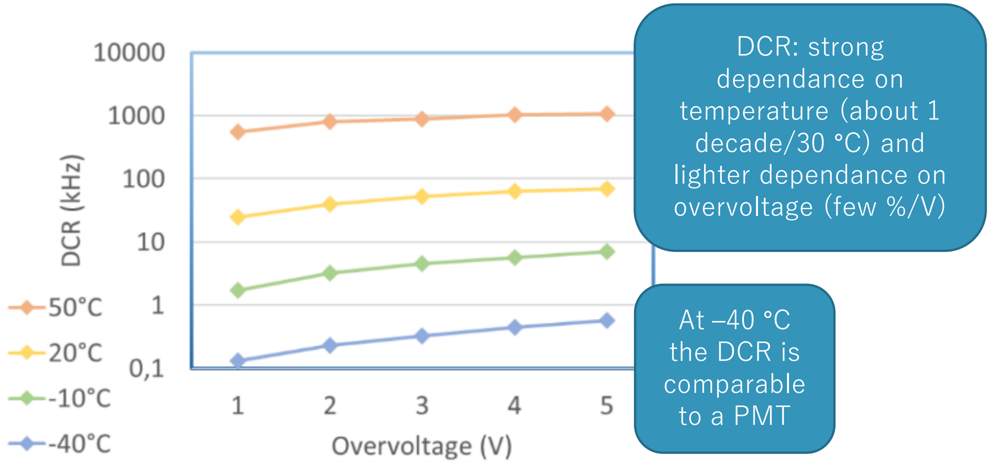
SiPM measurement results

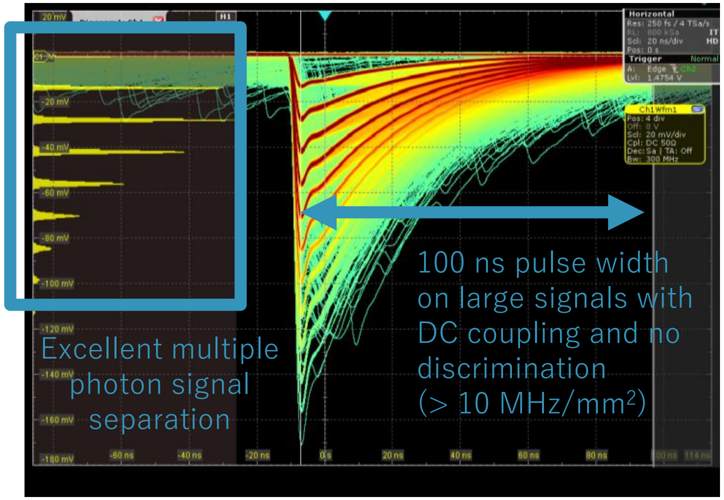
- SiPM characterization did not reveal any surprise: already several publications available
- Selection of interesting measurements made by us (on Hamamatsu S13360-1350CS, 50 μm cells):











SiPM and radiation

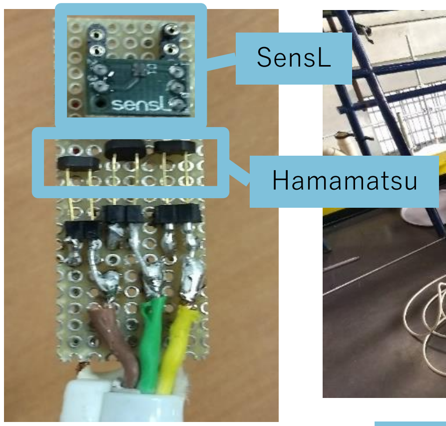
SiPMs are sensitive to displacement damage: protons, neutrons and heavy ions cause bulk damage in Silicon. Creation of traps that increase leakage (dark) current

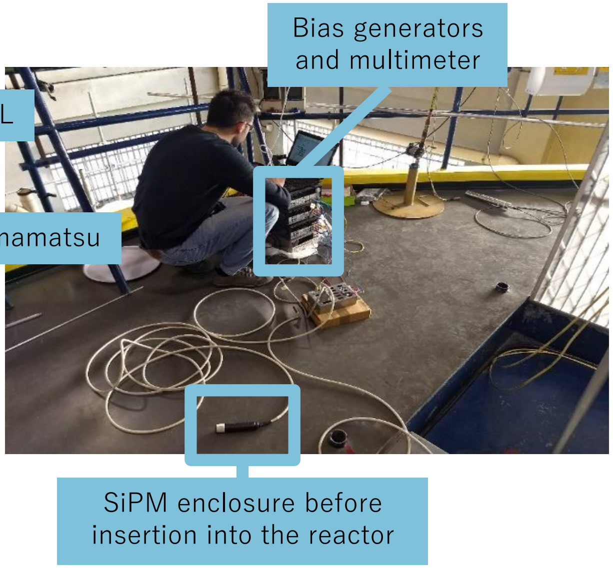
Our goals:

- How do latest SiPM models behave when irradiated up to 10^{14} cm^{-2} n_{eq}?
- Is there a way to recover radiation damage or minimize dark current by annealing or cooling?

Irradiation setup at LENA (Pavia) nuclear reactor:

Step#	Reactor power	1-Mev eq fluence
1	1.5 W	10^{11} cm^{-2}
2	15 W	10^{12} cm^{-2}
3	150 W	10^{13} cm^{-2}
4	1500 W	10^{14} cm^{-2}





Online monitoring: I-V curves

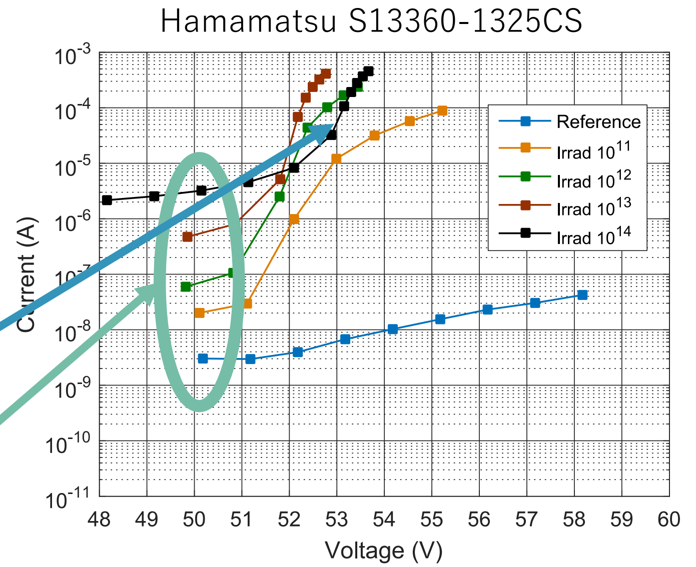
- Voltage measurement across SiPM
- Current measurement on a 10 kΩ resistance → current limited to a few 100 μA

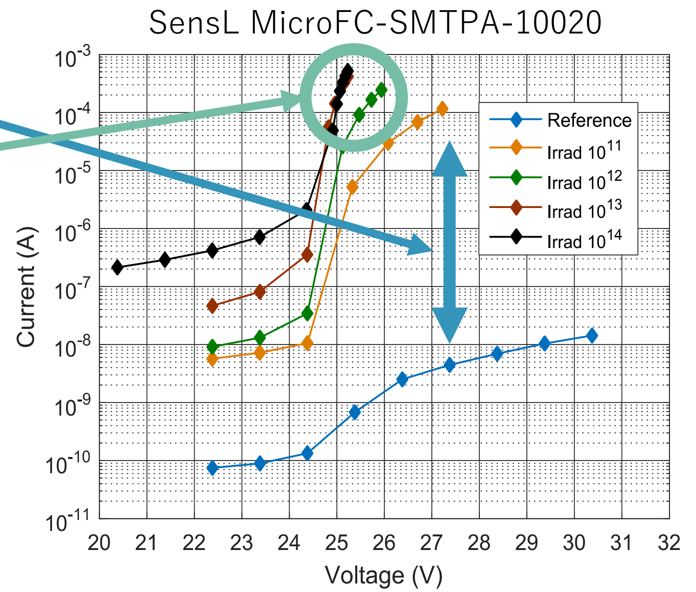
SiPM I-V curves

I-V curves acquired during irradiation at room temperature

Results:

- No breakdown voltage change up to 10^{13} n_{eq} cm^{-2}
- 1 V breakdown shift for Hamamatsu S13360-13xx (all cell sizes) at 10^{14} n_{eq} cm^{-2}
- Dark current below breakdown increase by a factor x5-x10 for each decade of fluence
- 10^4~10^5 increase in dark current above breakdown at 10^{11} n_{eq} cm^{-2}
- Dark current saturation above 10^{12} n_{eq} cm^{-2} due to SiPM cell saturation
- Operation at room temperature not possible due to high dark current, even at 10^{11} n_{eq} cm^{-2}





SiPM dark count rate

SiPM: Hamamatsu S13360-1350CS (50 μm cells)

Temperature: –30 °C

Bias: V_{BR} + 1.5 V

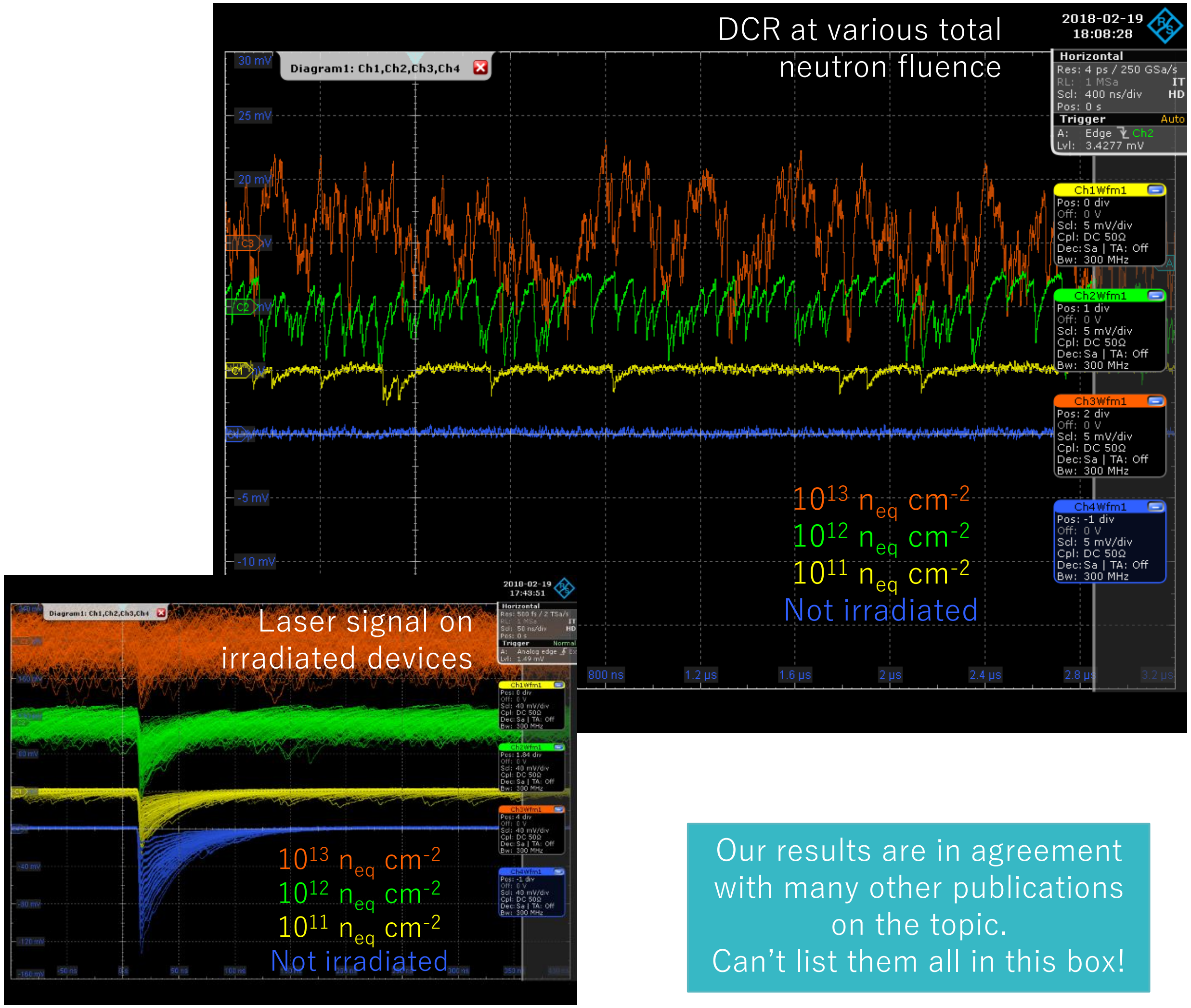
Not irradiated
< 1 kHz/cm^2

10^{11} n_{eq} cm^{-2}
200 MHz/cm^2

10^{12} n_{eq} cm^{-2}
2 GHz/cm^2

10^{13} n_{eq} cm^{-2}
? (20 GHz/cm^2)

10^{14} n_{eq} cm^{-2}
not shown…



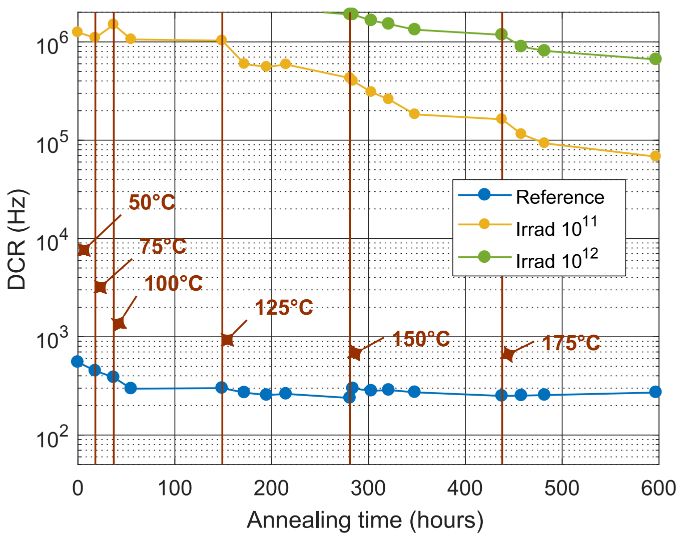
Our results are in agreement with many other publications on the topic.
Can't list them all in this box!

Operation in single photon regime quite difficult even at 10^{11} n_{eq} cm^{-2} and –30 °C

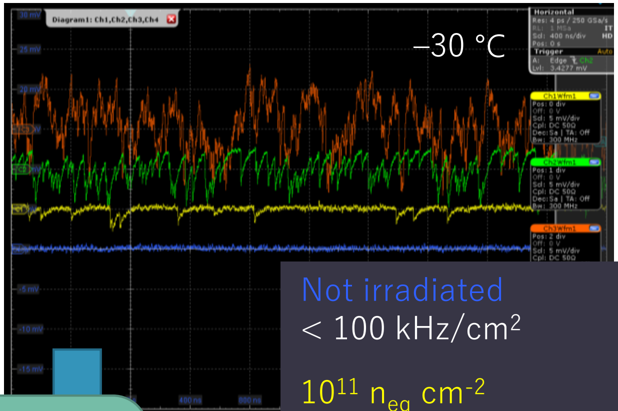
SiPM annealing and damage recovery

The radiation damage is here to stay with present generation of solid state devices

- Is there a way to recover it or mitigate it?



- Annealing improves dark count rates by a factor 10 after 3 weeks up to 175 °C
- Producers discourage heating for long times due to front resin window deterioration



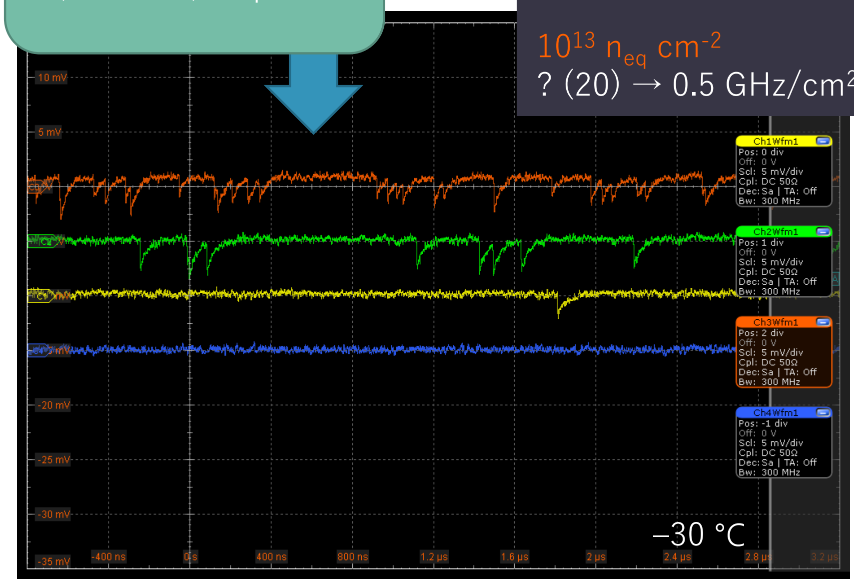
Not irradiated
< 100 kHz/cm^2

10^{11} n_{eq} cm^{-2}
200 → 20 MHz/cm^2

10^{12} n_{eq} cm^{-2}
2 → 0.2 GHz/cm^2

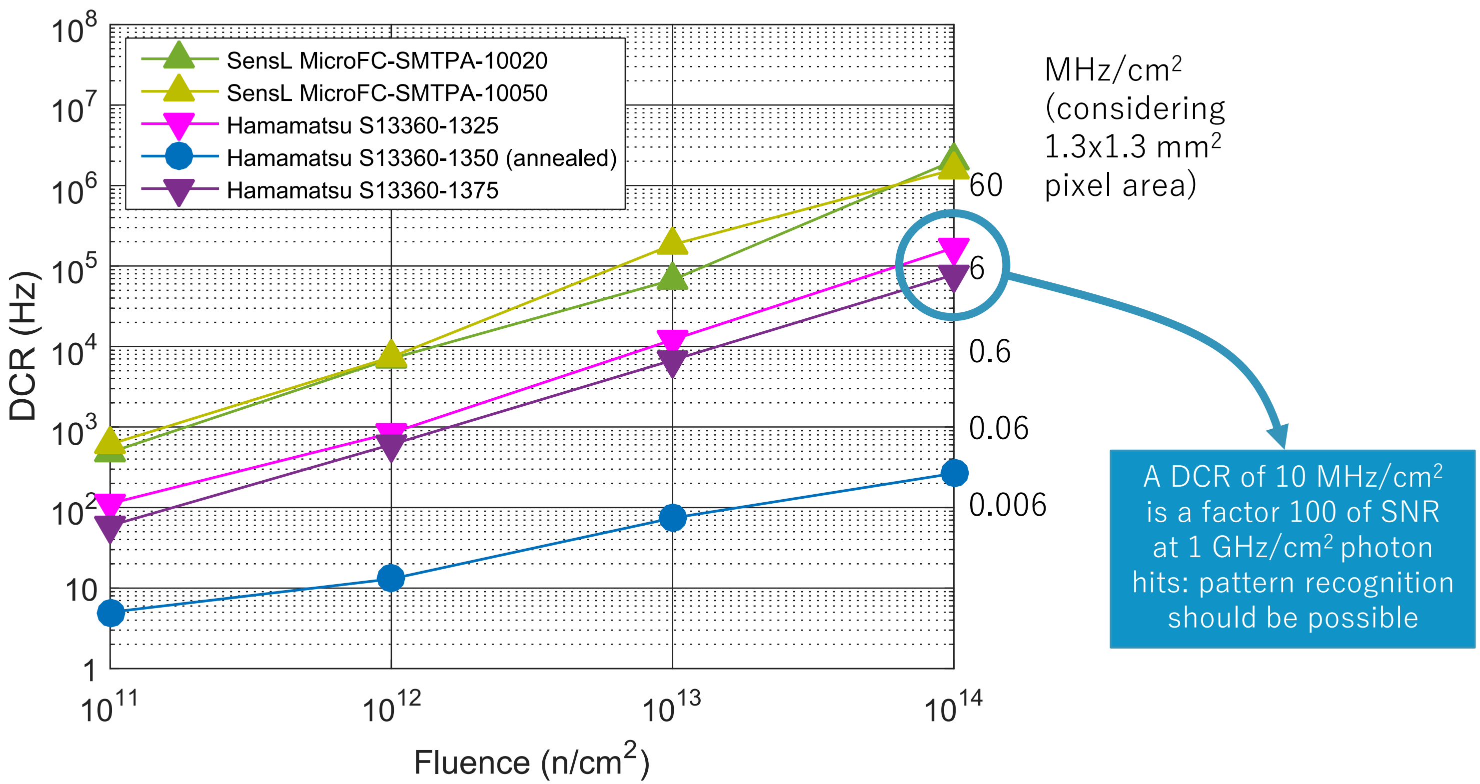
10^{13} n_{eq} cm^{-2}
? (20) → 0.5 GHz/cm^2

Annealing improves DCR but high temps (> 150 °C) required



SiPM operation in liquid nitrogen

- DCR strongly depends on temperature (about 1 decade/30 °C at temperatures close to ambient)
- We tried to operate irradiated devices in liquid nitrogen (77 K)

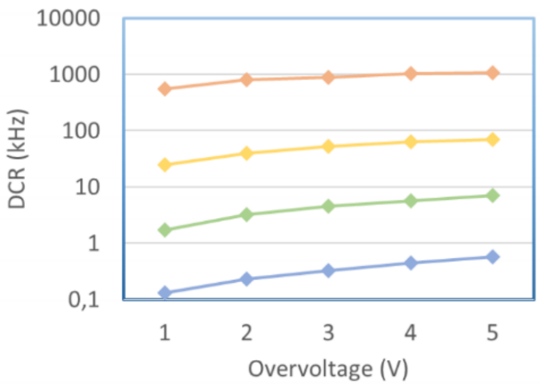


- All SiPMs, even those irradiated up to 10^{14} n_{eq}/cm^2 are usable at liquid nitrogen temperature

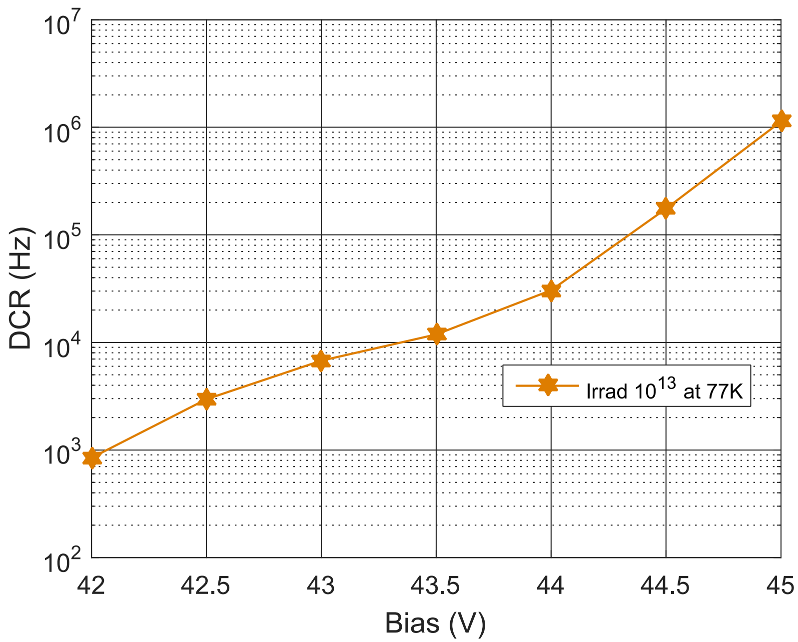
SiPM operation in liquid nitrogen (2)

- At low temperatures dark count rate (i.e. leakage current) is not caused anymore by thermal generation of free carriers
- At low temperatures the dominant process is band-to-band tunneling mediated by the traps created during irradiation
- This is clear looking at the slope of DCR versus bias voltage
  - Thermal generation has linear dependance on bias voltage
  - Tunneling has exponential dependance on bias voltage

–40 to 50 °C



–196 °C

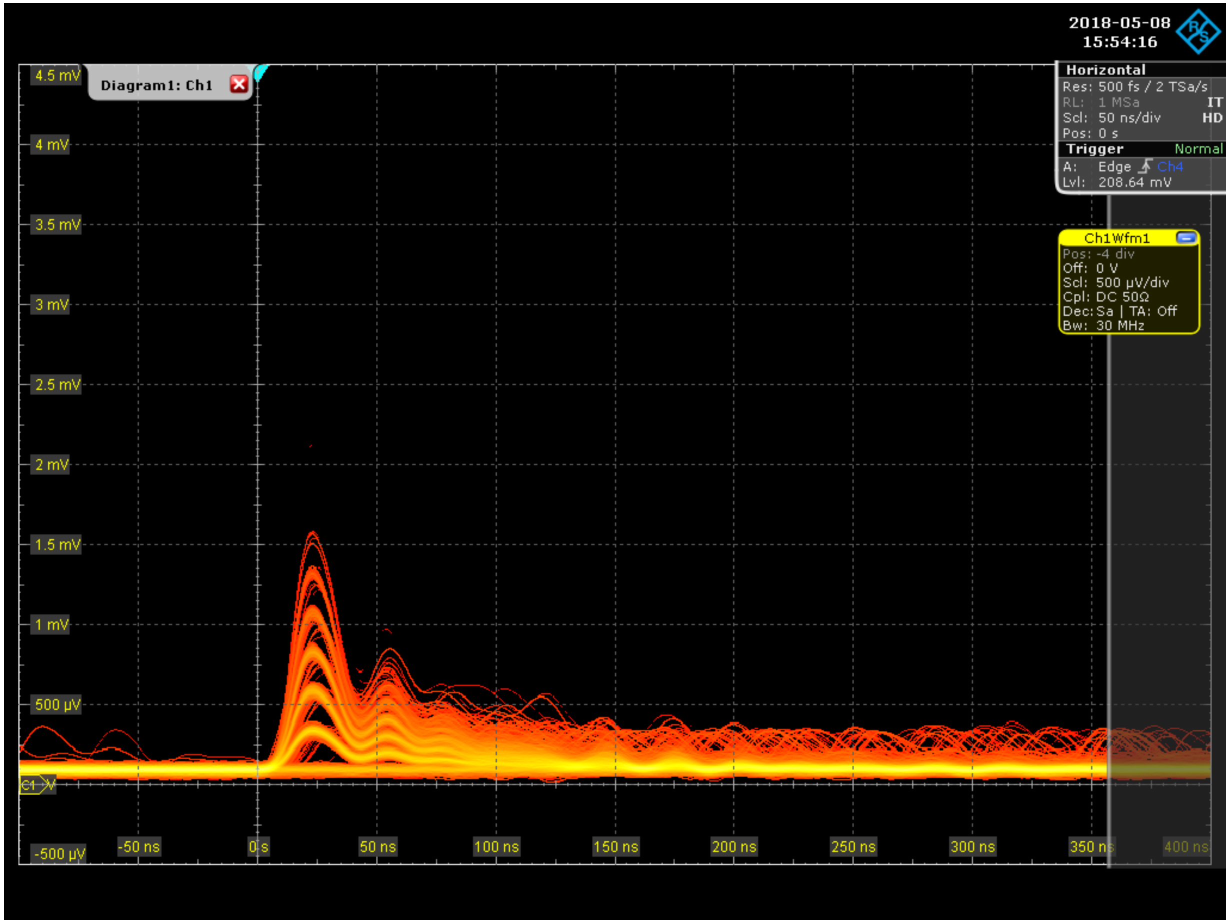


For more information on the results presented in these slides, see our paper (submitted to NIMA): **arXiv:1805.07154**

SiPM operation in liquid nitrogen (3)

Operation of SiPMs in single photon regime after irradiation at 10^{14} n_{eq}/cm^2 is possible...

... at 77 K



MCP-PMTs

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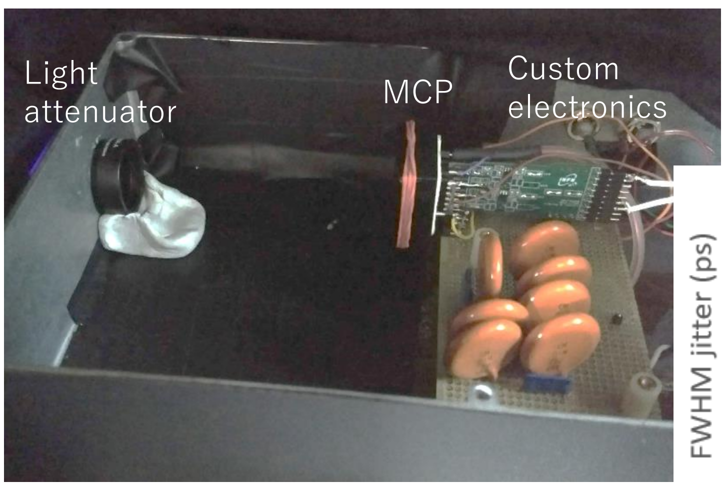
Magnetic field immunity	×	✓	✓
Low cost	×	×	×
Gain ageing	×	✓	× ×
Saturation current	×	✓	× ×
Low voltage operation	×	✓	×

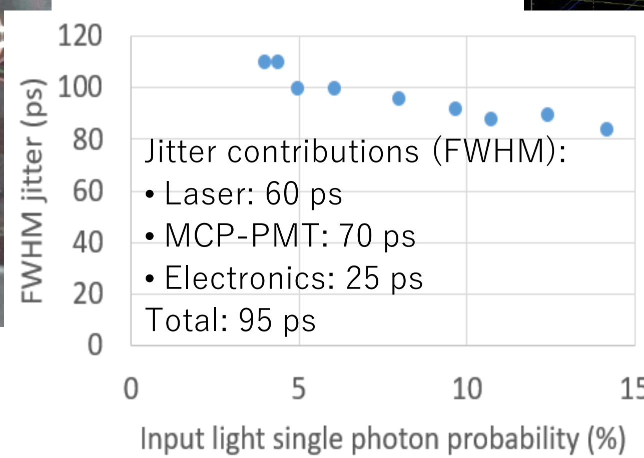
MCP-PMT measurements

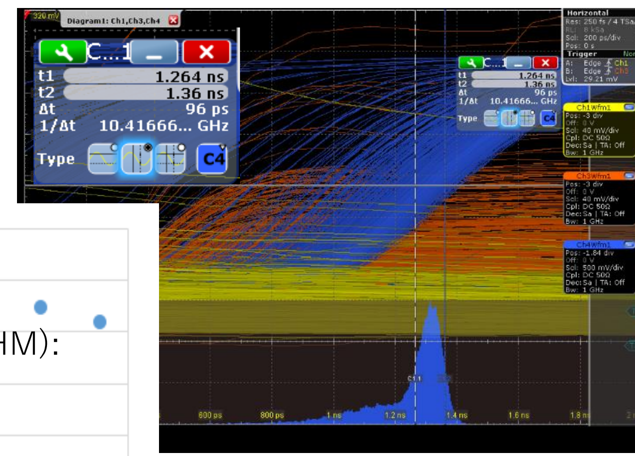
- Can MCP-PMTs be operated at 1 GHz/cm^2 photon hits?
  - High granularity to the level of 1 mm^2 per pixel or less is available (with some caveats: charge sharing, capacitive coupling, etc. which are not always desired)
  - Fast timing is proved and superior to any other device available, several groups already using MCPs for timing (see many presentations and posters here)
  - The main issues are related to ageing and saturation current (in next slide…)

- In parallel to SiPMs we also started measurements on MCP-PMTs
  - 1 MCP-PMT model tested so far (Hamamatsu R10754-07-M16), discussion with Photek and Photonis is in place for evaluating their models



Test setup in light-tight box





Oscilloscope screenshot during jitter measurement

MCP-PMT limitations with rate

- Very interesting and stimulating results in Tuesday afternoon session. Also a really interesting paper has been recently submitted (Antamanova et al., arXiv 1807.03804)
- Maximum integrated anode charge and saturation current are well known open issues on MCP-PMTs and could be limiting factors when operating at high rates

Example with numbers:

Photon rate (detected) = **1 GHz/cm²**

Photodetector gain = **10^4 e./p.e.** = 1.6 fC/p.e.

Very low!

→ Anode current density = **1.6 μA/cm²**

Best performing MCP-PMTs have saturation current of **100 nA/cm²**

Assuming 25% duty cycle over 5 years

Very conservative!

→ Total integrated anode charge = **60 C/cm²**

Best performing MCP-PMTs have maximum integrated anode charge of **10 C/cm²**

BUT Antamanova et al. suggest that concurrent high integrated anode charge and saturation current are not achievable due to ALD process limitations (see publication above for more informations)

Interesting to see if this applies to models from all manufacturers

MCP-PMT wish-list

- MCP-PMTs currently available are not several orders of magnitude away from the specifications required to operate at 1 GHz/cm^2 photon hits
- Given the huge developments seen in recent years, MCP-PMTs could come up to par and match the requirements

- The dream-come-true MCP-PMT:
  - Tens of ps jitter and 500 ps pulse width
  - 1 mm^2 pixels
  - Less than 10% crosstalk
  - Gain of 10^5
  - Saturation current of at least 10 μA/cm^2
  - Integrated anode charge of at least 100 C/cm^2

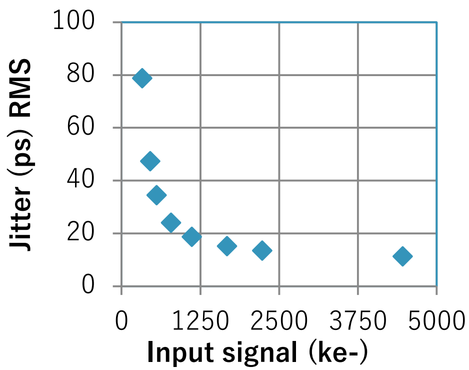
  - … given all these specs, it should cost less than 1 M€ per device ☺

New front-end electronics solutions

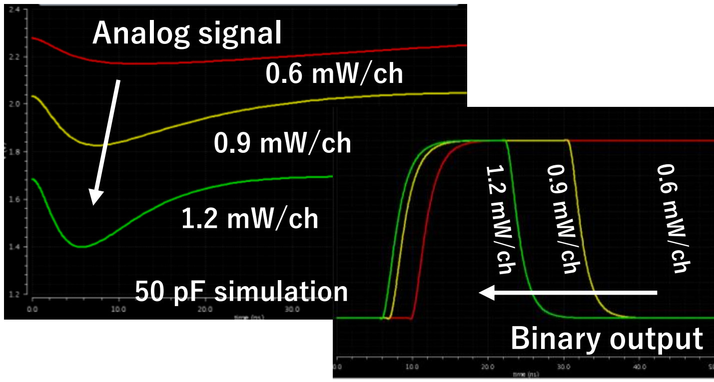
- High track density and high rates have big implications also on front-end electronics
  - High spatial resolution → high channel density
    - Low power consumption
    - High trace and connector density

    → manageable easily with proper design, more channel per chip, etc.
  - High rate → tighter timing constraints and performance needed
    - Improve timing precision
    - Reduce recovery times
    - Implement architectures for timing measurements

    → require more effort
- Many high performance front-end electronics solutions exist
- The starting point for our group is the CLARO chip*, which was developed for the readout of pixellated photodetectors and will be used in LHCb RICH upgrade with MaPMTs



- Timing performance of CLARO-CMOS is excellent (about 20 ps at 1 Me-)
- Operation with higher input capacity of SiPMs (35 pF/mm²) is possible
- Low power consumption in the 1-1.5 mW/channel range



*CLARO-CMOS: 10.1088/1748-0221/7/11/P11026 (Bicocca)
CLAROv3: 10.1088/1748-0221/12/08/P08019 (Bicocca, Ferrara, Krakow, Sevilla)
...more info in M. Fiorini talk on Friday

New front-end electronics solutions (2)

General remarks

- Trade-off between low power consumption and speed/timing will be stronger than ever (possibly conflicting)
- Increased radiation background means that more digital electronics will have to be integrated in front-end chip w.r.t. current solution implemented in the CLARO (binary output with external digital readout, e.g. FPGA)
- Cryogenic-cooled photodetectors (SiPMs) imply strict power consumption requirements on front-end electronics
- Low input signals and timing performance (MCP-PMTs) require front-end electronics as close as possible to the photodetector to minimise stray capacitance and noise

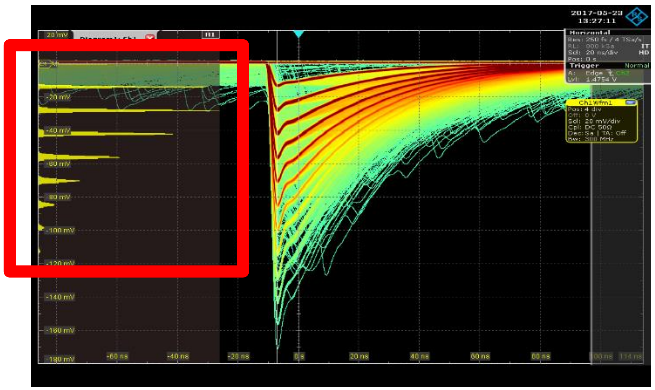
Our strategies for a front-end chip for high particle density RICH detector:

- Keep simple front-end design in order to reduce power consumption
- Find new architecture solutions that could simplify digital circuitry and minimize chip complexity
- Possibility of discriminating 1 vs 2 photons to cope with high pixel occupancy

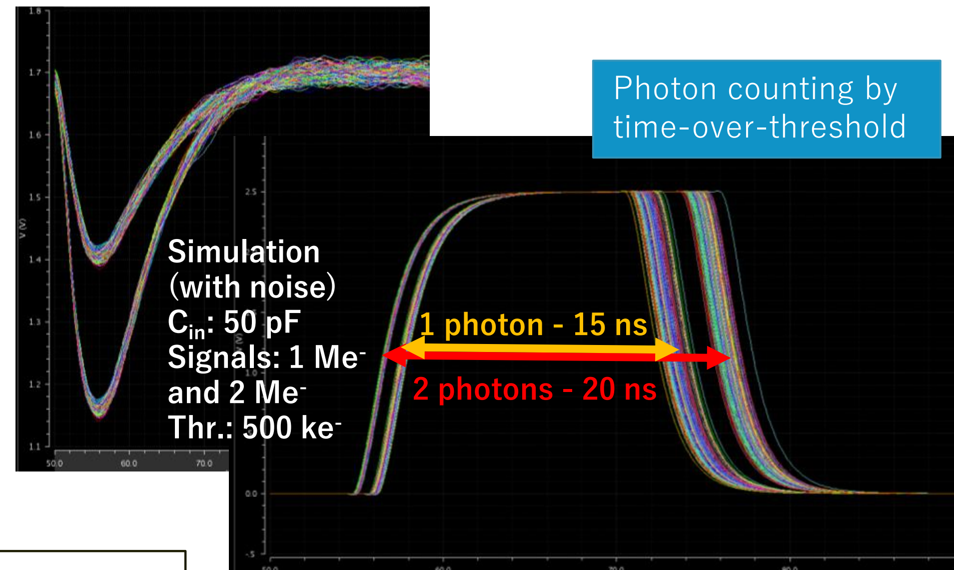
New front-end electronics solutions (3)

Front-end electronics development is strictly related to photodetector characteristics (in future more than ever). Present architecture could be expanded to exploit photodetectors features

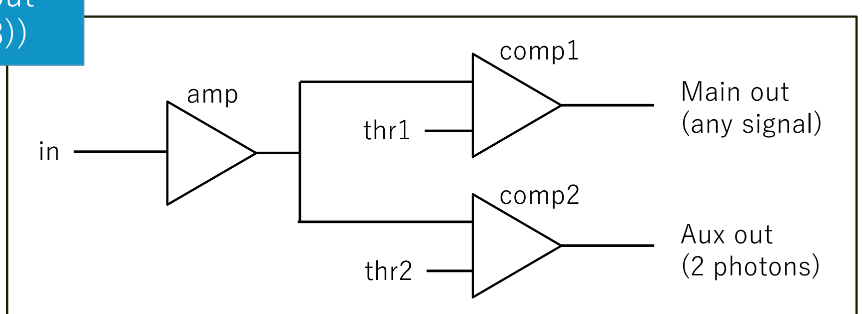
- Example 1: photodetector with excellent photon counting capability (i.e. SiPM)



Photon counting by time-over-threshold



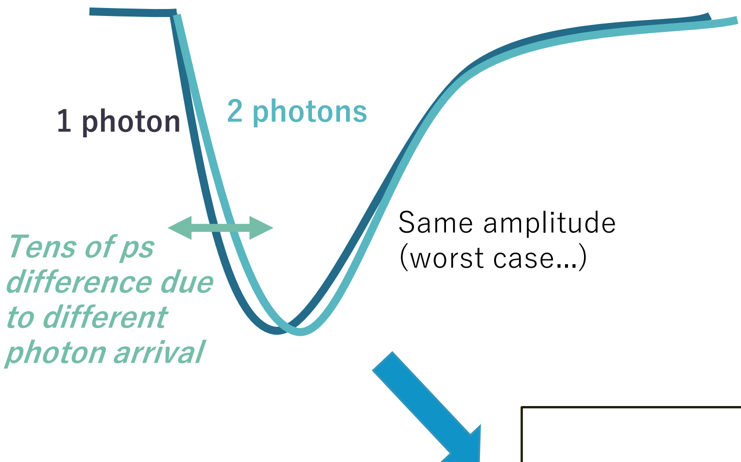
1.6 bit readout
($1.6 = \log_2(3)$)



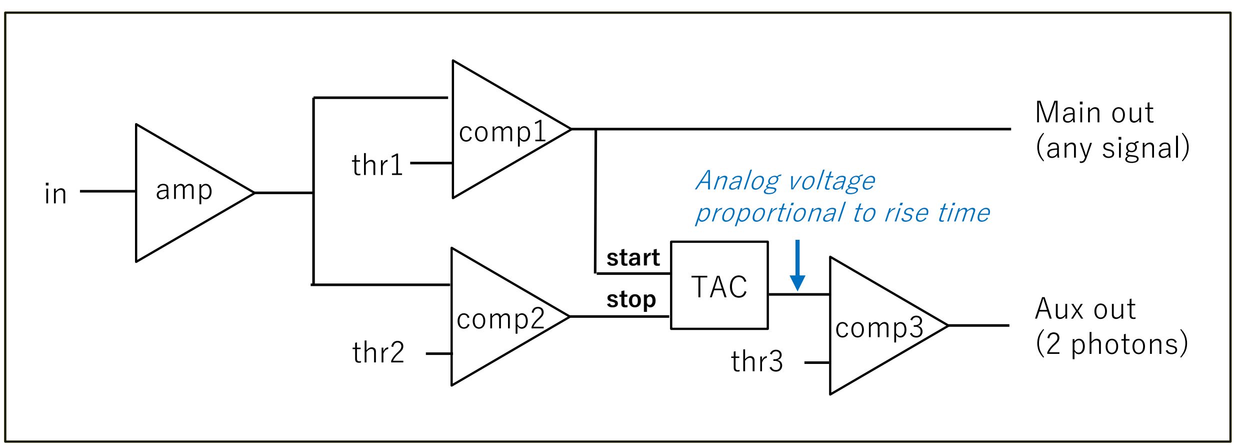
New front-end electronics solutions (4)

Front-end electronics development is strictly related to photodetector characteristics (in future more than ever). Present architecture could be expanded to exploit photodetectors features

- Example 2: photodetector with excellent timing performance (i.e. MCP)



- «amp» + «comp1» as in the standard readout with discriminator
- A second comparator and a «TAC» (time to amplitude) to generate a voltage proportional to the time difference between the threshold crossing times, i.e. proportional to rise time
- TAC output discriminated by another comparator (comp3) to generate a digital signal «aux out» if the rise time is longer than a given value, i.e. if two photons are detected



Final comments

There isn't a clear winner for the race to the perfect photodetector for RICH detectors with photon hits up to 1 GHz/cm^2 and beyond

- **SiPMs**
  - Could be technologically ready
  - If the photodetector plane could be cooled at liquid nitrogen temperature (annealing is not sufficient), which is a huge effort
- **MCP-PMTs**
  - Would offer interesting features with better timing and charge sharing (but also add complexity)
  - Are behind SiPMs on the technological side due to saturation and ageing characteristics

- **Front-end electronics** have to wait the choice of photodetector
  - In the meanwhile new architectures can be simulated
  - Start study of more scaled CMOS technology nodes

Wider considerations about a high track track density RICH detector could be found in Sajan's poster «Prospects for future upgrade of the LHCb RICH system", in which framework some of the ideas presented here have been raised

Thank you

Спасибо