Progress in Dual Readout calorimeters

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on behalf of the IDEA Dual Readout group

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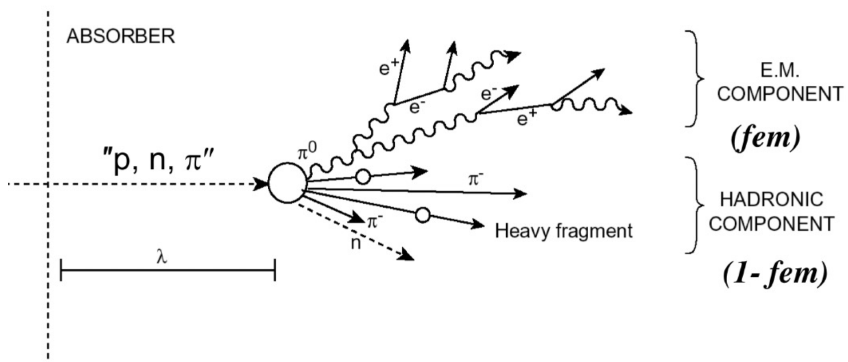
Dual Readout: the principle



- Non compensating calorimeter (h/e<1): has a different response to electromagnetic (fem) and hadronic component (1-fem)
- The fem is energy dependent: it induces a non-linear calorimetric response to hadrons and large fluctuations

- By reading two calorimetric signals (S and C) with different h/e, the fem can be measured event by event and the compensation can be achieved off-line

$$E_S = E\left(f_{\rm em} + \left(\frac{h}{e}\right)_S (1 - f_{\rm em})\right)$$

$$E_C = E\left(f_{\rm em} + \left(\frac{h}{e}\right)_C (1 - f_{\rm em})\right)$$

$$f_{\rm em} = \frac{\left(\frac{h}{e}\right)_C - \left(\frac{h}{e}\right)_S \left(\frac{E_C}{E_S}\right)}{\left(\frac{E_C}{E_S}\right)\left(1 - \left(\frac{h}{e}\right)_S\right) - \left(1 - \left(\frac{h}{e}\right)_C\right)}$$

$$E = \frac{(E_S - \chi E_C)}{1 - \chi}$$

$$\chi = \frac{1 - \left(\frac{h}{e}\right)_S}{1 - \left(\frac{h}{e}\right)_C}$$

χ does not depend from energy and particle type. It is detector dependent: it can be measured on beam tests

S. Lee et al, RevModPhys, 90, 025002 (2018)
DOI: 10.1103/RevModPhys.90.025002

The Dual Readout collaboration

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Prof. John Hauptman

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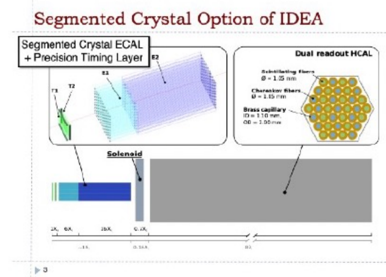
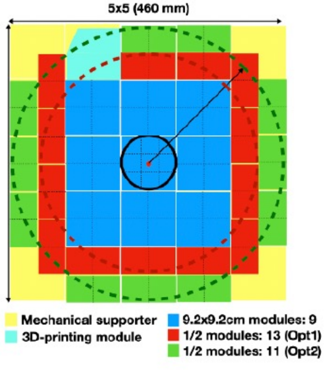
Prof. Roberto Ferrari (Pavia)
Prof. Franco Bedeschi (Pisa)
Prof. Iacopo Vivarelli

FCC
DREAM FOR FUTURE
CEPC

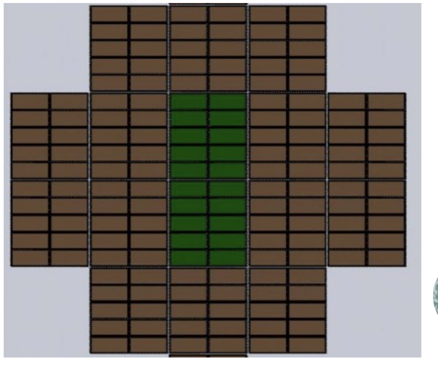
DRC with crystal



Full-size prototype detector



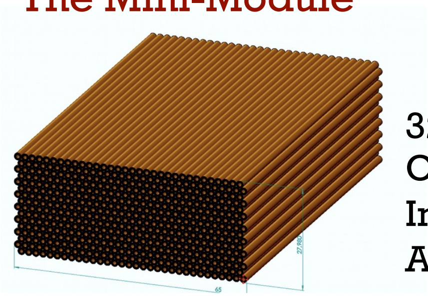
HiDRa



Prototype with hadronic containment: HiDRa

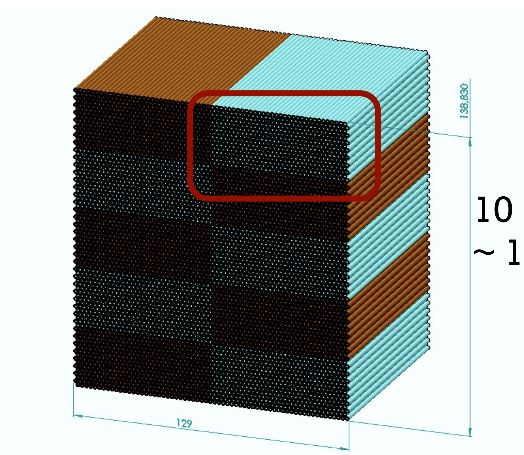
INFN-funded R&D project (2022 - 2024)

The Mini-Module

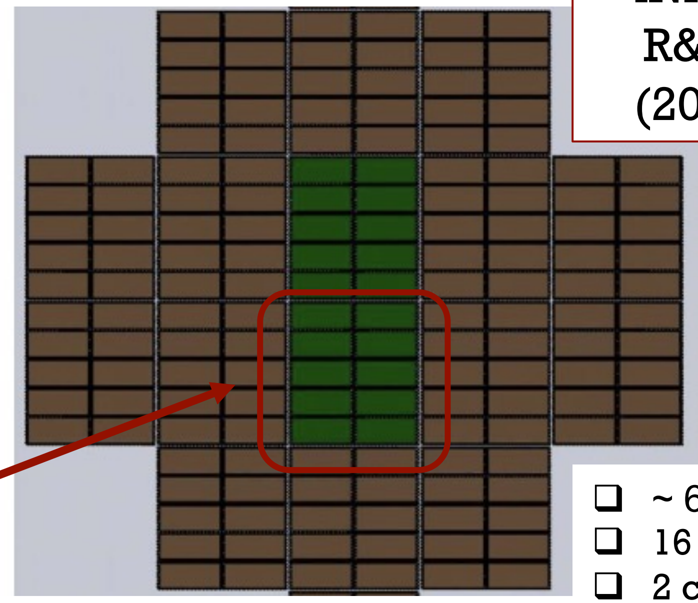


32 x 16 capillaries
Outer diameter: 2mm
Inner diameter: 1.1mm
Alternated scintillating and clear fibres

The Module



10 Mini-modules
~ 13 x 13 x 250 cm^3

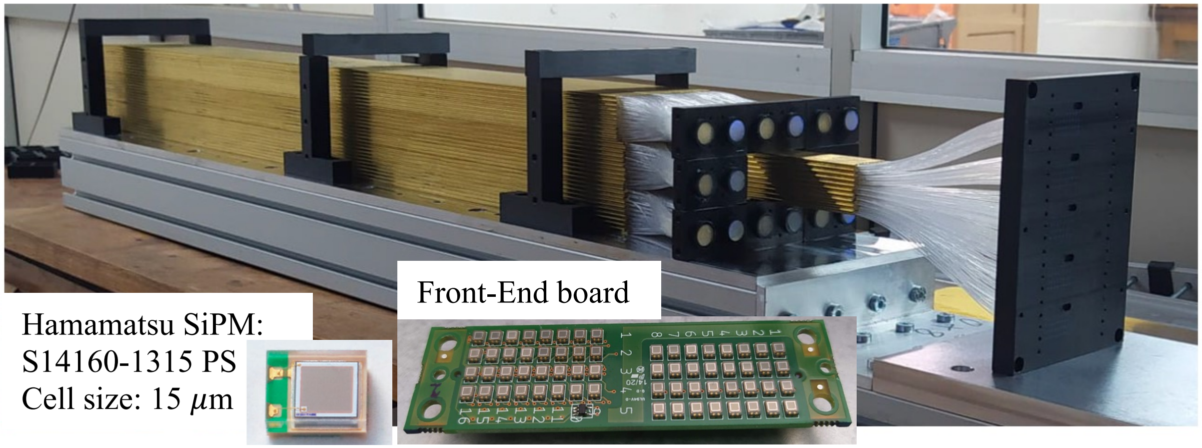


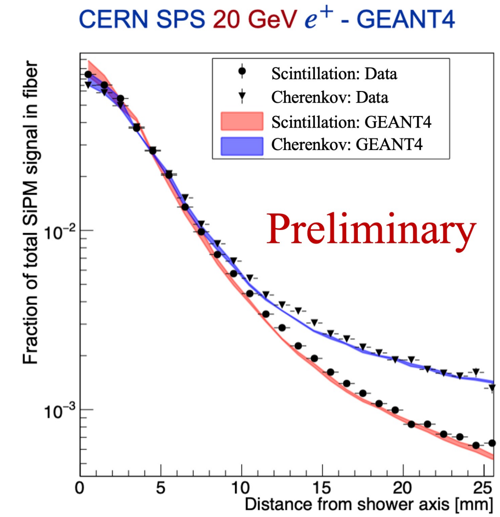
- ~ 65 x 65 x 250 cm^3
- 16 modules in total
- 2 central modules equipped with SiPMs
- 14 modules equipped with PMTs

The challenge:

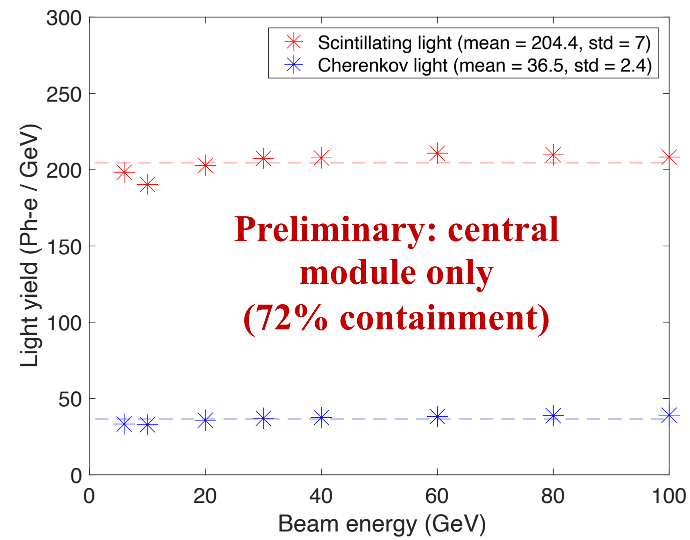
More than 10.000 SiPMs, fitting the back side of the detector, to be read out

Few results from the 2021 test beam





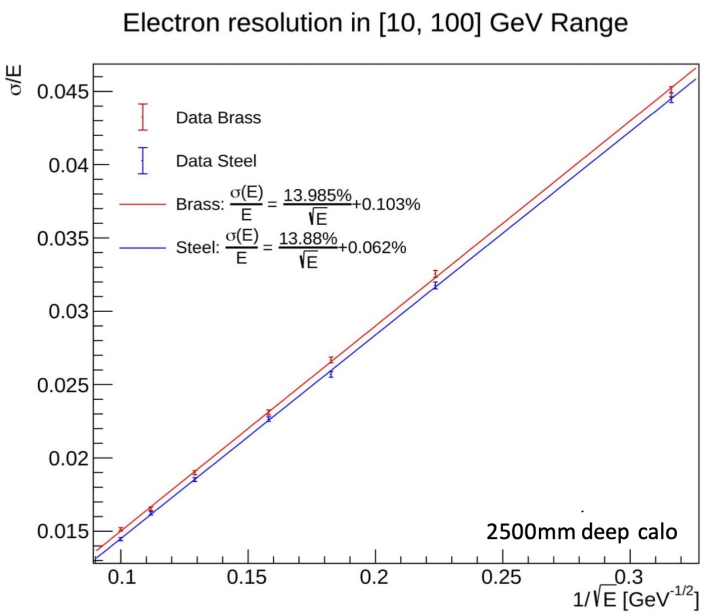
- A small prototype has been tested on beam in 2021 (@DESY and @CERN) with electrons ranging from 1 to 100 GeV
- The prototype was made of brass capillary tubes (2 mm outer diameter) each hosting a fibre of 1 mm diameter: : (10x10x100 cm^3)
- There are 9 towers containing 16x20 capillaries with alternating scintillating and clear fibres
- The central tower is equipped with SiPMs while the surrounding towers are connected to PMTs (costs saving reason)

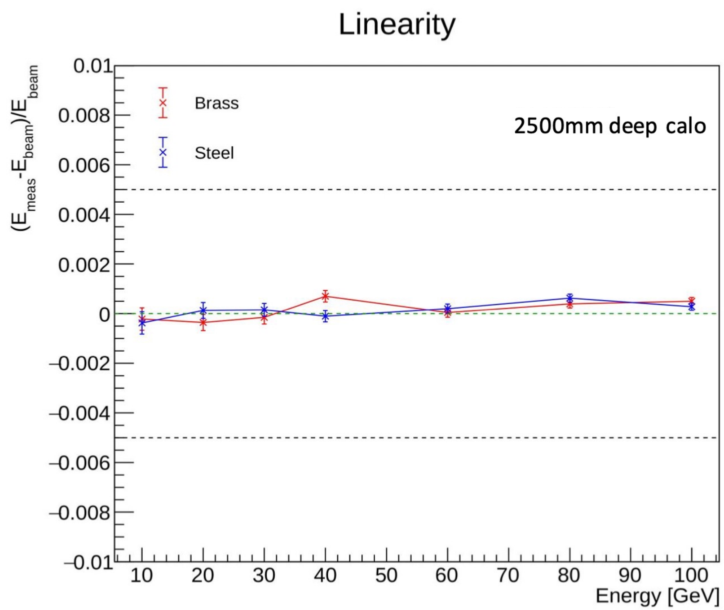


Calor2022 – DOI: 10.3390/instruments6040059

HiDRa: the expected performances

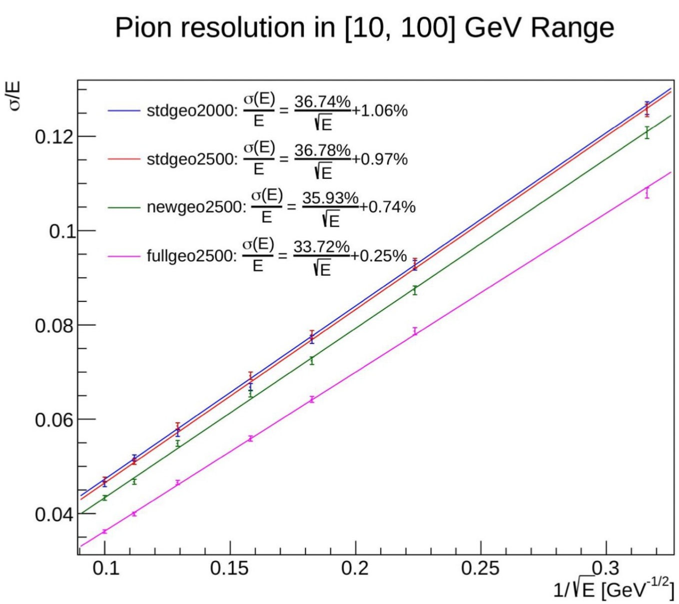
- Resolution studies performed with the HiDRa geometry based on a full simulation tuned on recent test beam results (2021)
  - Beam tilted by 2.5° in both X and Y directions
  - Capillary outer diameter = 2mm and fibre diameter =1mm
- Resolution and linearity with electrons (different absorber materials)

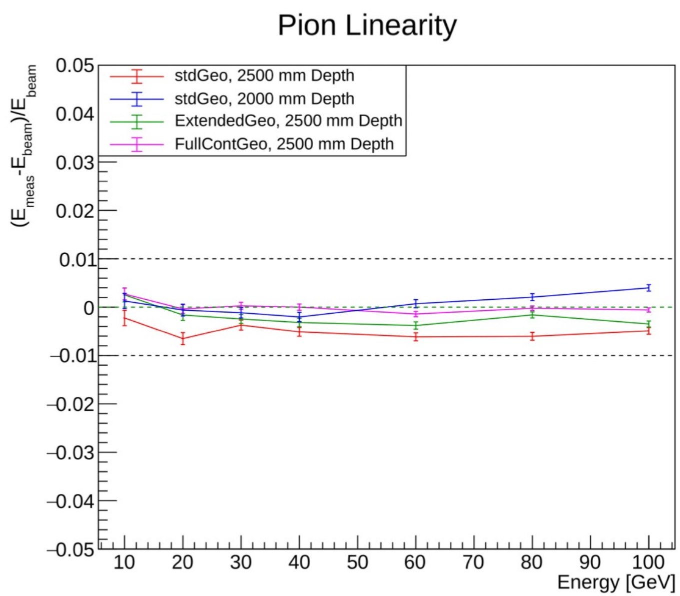


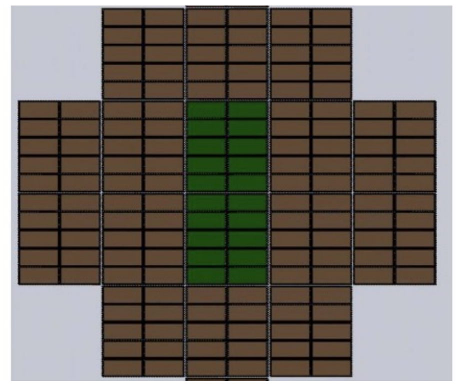


HiDRa: the expected performances

- Resolution studies performed with the HiDRa geometry based on a full simulation tuned on recent test beam results (2021)
  - Beam tilted by 2.5° in both X and Y directions
  - Capillary outer diameter = 2mm and fibre diameter =1mm
- Resolution and linearity with single pions (different geometries)



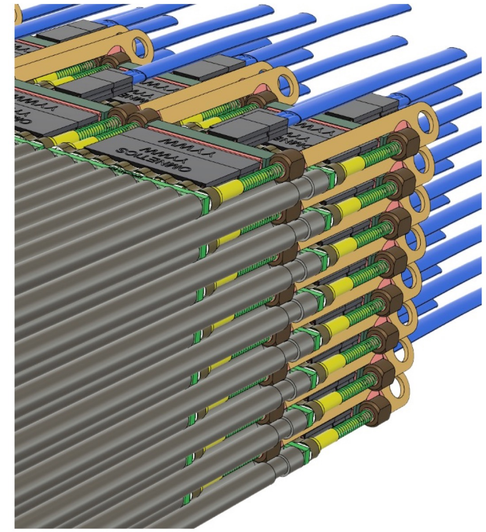




The design of a scalable solution

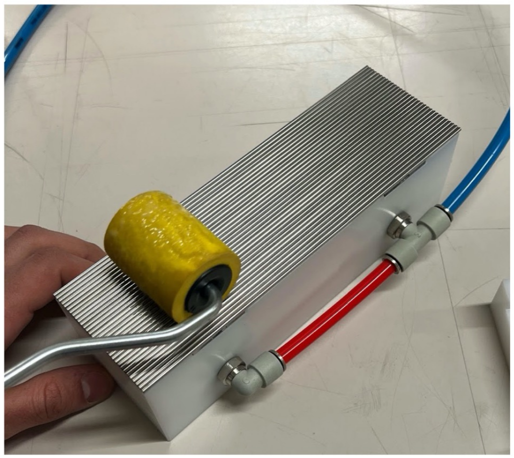
Quite challenging integration that requires:

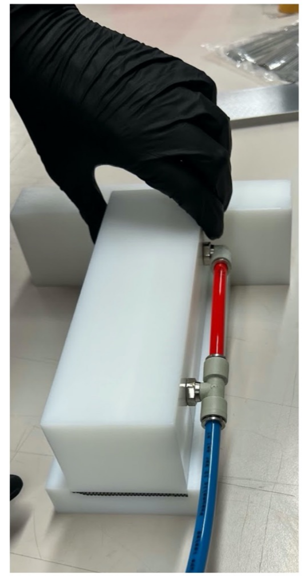
- Precise assembly procedure
- Compact components: there is almost no space in the rear part of the calorimeter
  - SiPMs
  - Mechanical support
  - Cabling and readout to serve all channels

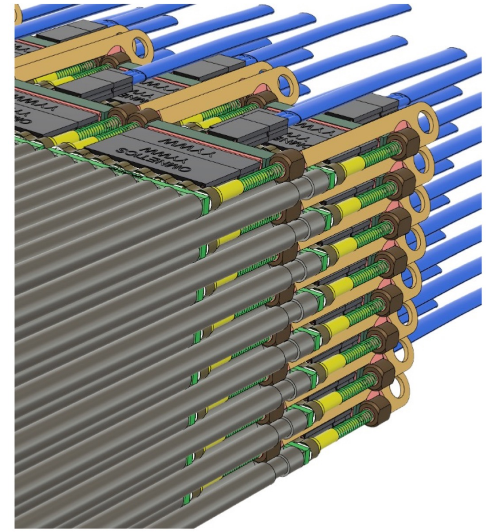


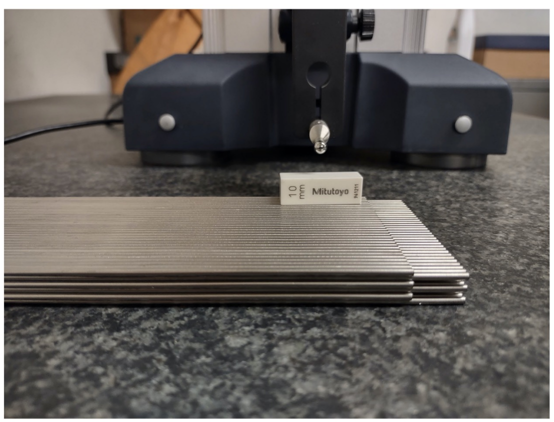
Mechanical integration

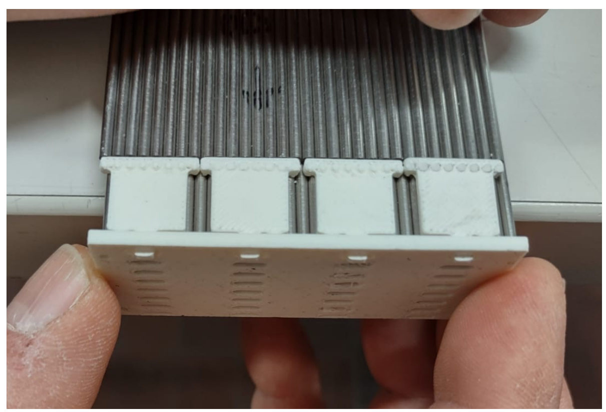
First tests with dummy components and 20cm long capillaries





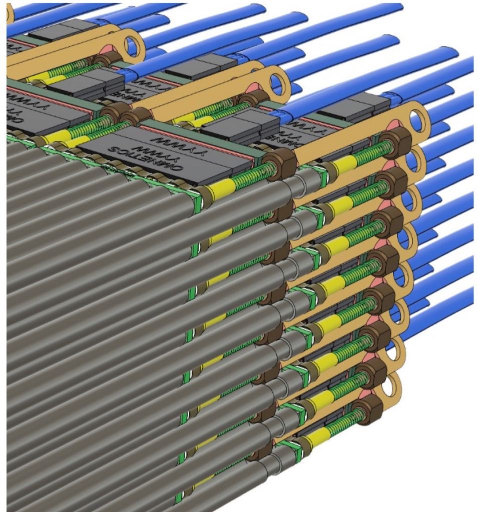


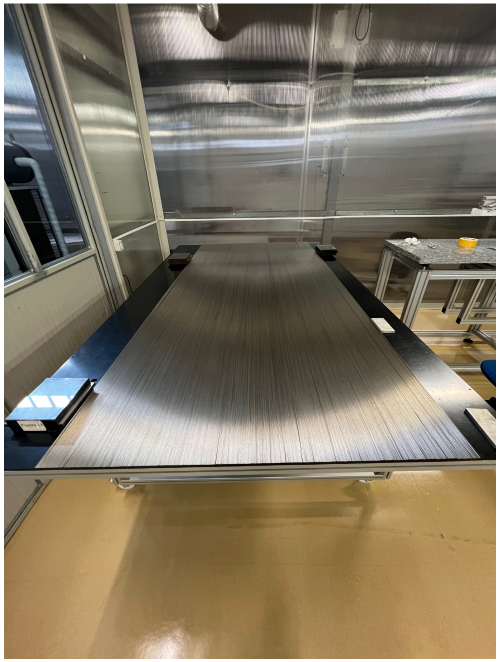


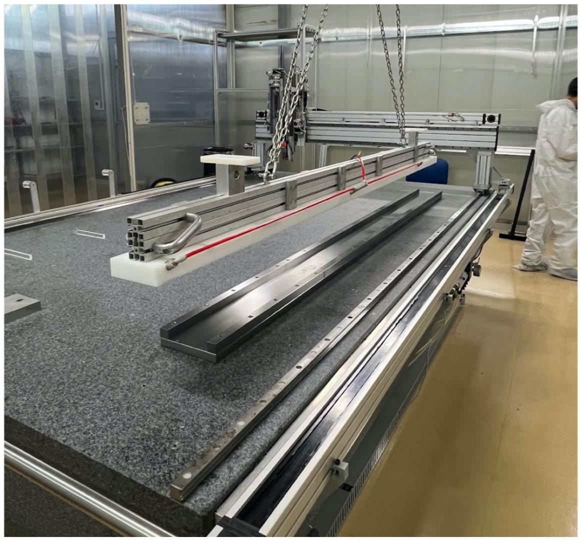


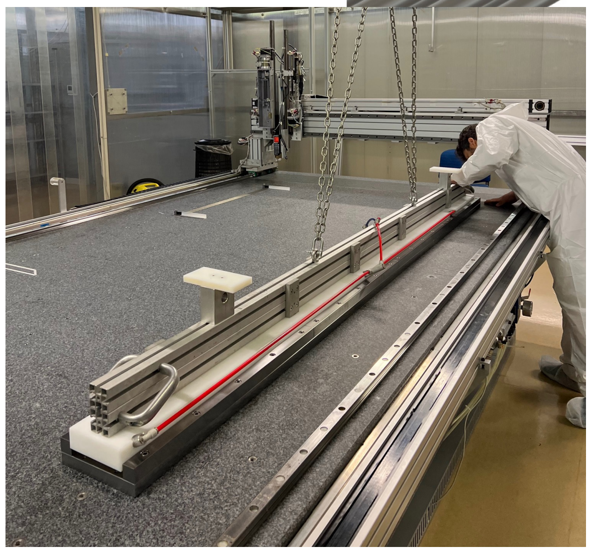
Mechanical integration

250 cm long modules: tooling and first tests

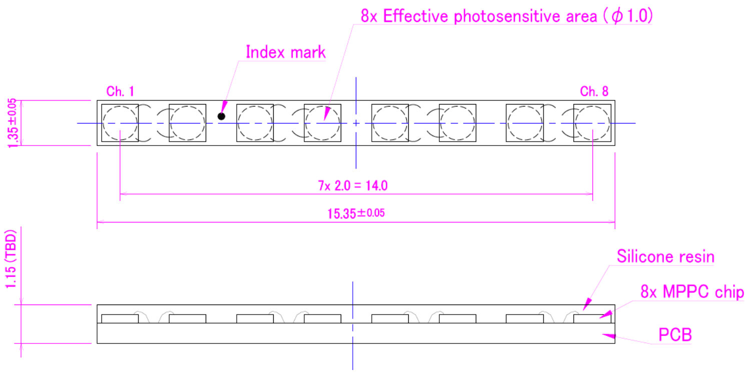






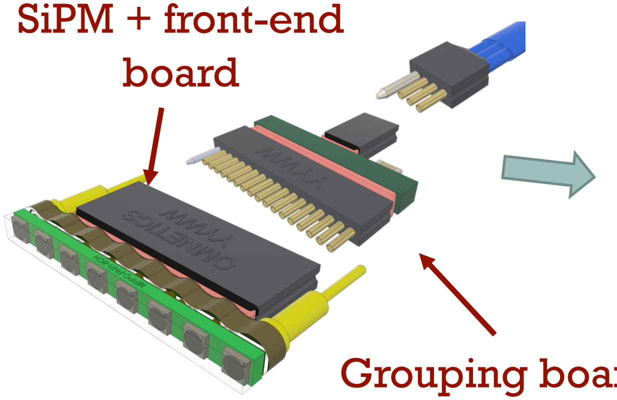


SiPM integration and redout



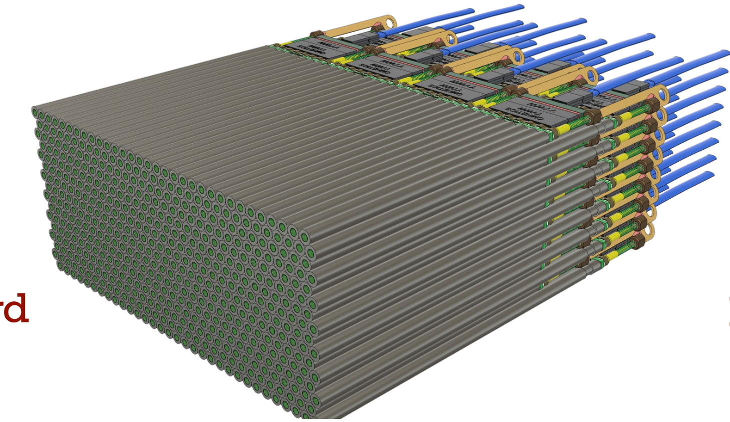
- Custom designed module with 8 SiPMs (1x1mm^2) from Hamamatsu
- SiPM interspace: 2mm
- Two options under study: 10 and 15 μm pitch

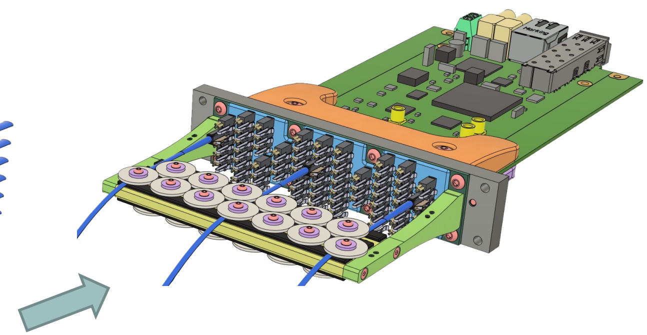
SiPM + front-end board



Grouping board

The Mini-Module





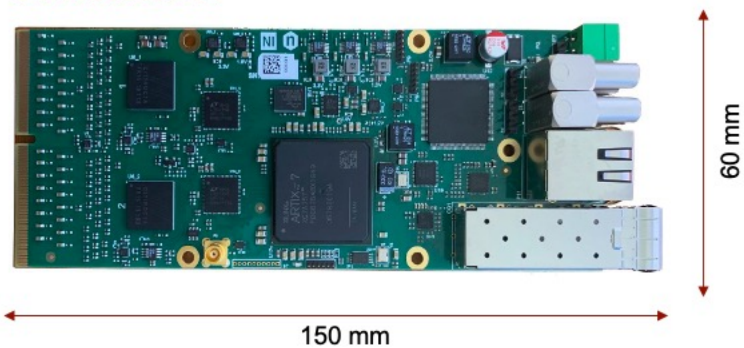
1 readout board serves 64 front-end boards with grouping

- Each bar of SiPMs will be operated at the same voltage (ΔV_{bd}<0.15V)
- The signals from 8 SiPMs is summed up in the grouping board

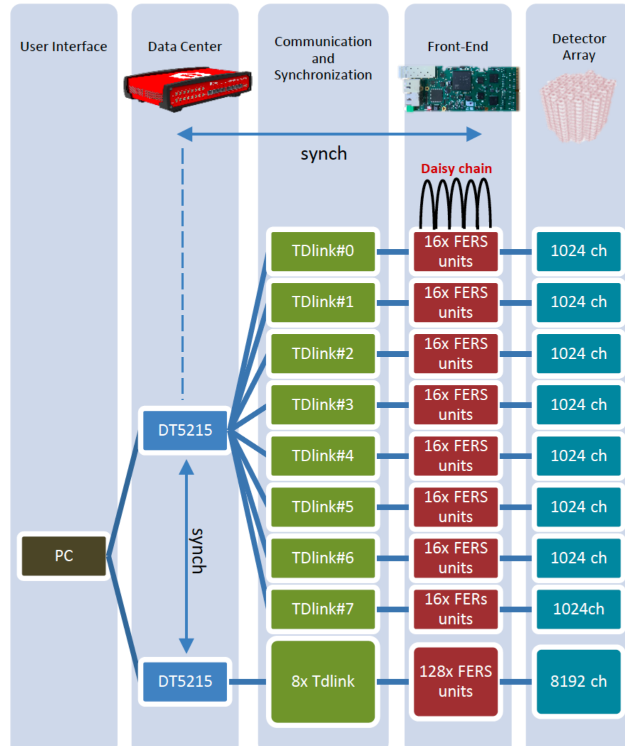
SiPM integration and redout

- The highly granular module is operated with the Caen FERS system (5200) and A5202 readout boards

FERS: A5202



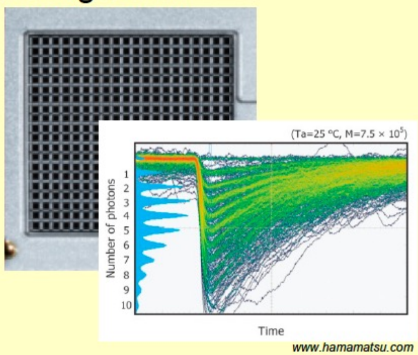
- Two Citiroc1A for reading out up to 64 SiPMs
- One (20 – 85V) HV power supply with temperature compensation
- Two 12-bit ADCs to measure the charge in all channels
- Timing measured with 64 TDCs implemented on FPGA (LSB = 500 ps)
- 2 High resolution TDCs (LSB = 50 ps)
- Optical link interface for readout (6.25 Gbit/s)



Just delivered

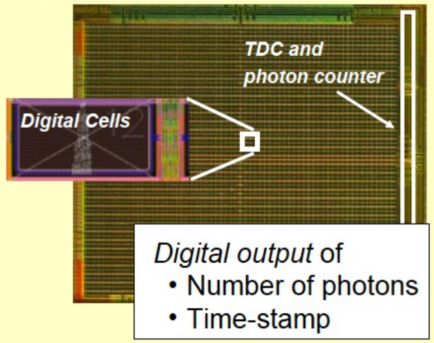
Alternatives should be considered

Analog SiPM



- Cells connected to common readout
- Analog sum of charge pulses
- Analog output signal

Digital SiPM



- Each diode is a digital switch
- Digital sum of detected photons
- Digital data output

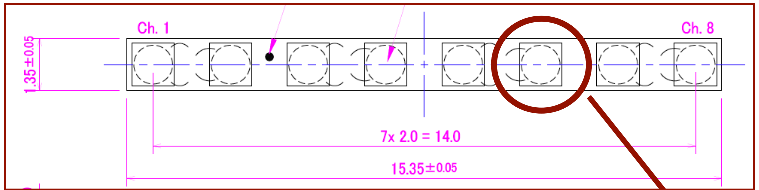
With dSiPM there is no need for analogue signal post-processing

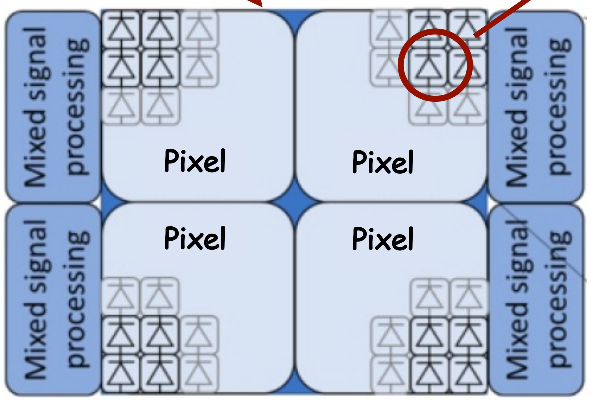
- SPAD array in CMOS technologies may offer the following benefits:
  - to embed complex functions in the same substrate (e.g. SPAD masking, counting, TDCs)
  - the design of the front-end electronics can be optimized to preserve signal integrity (especially useful for timing)
  - the monolithic structure simplifies the assembly for large area detectors
  - development costs can be kept relatively low if the design is based on standard process

Sensor requirements for DR-Calorimetry

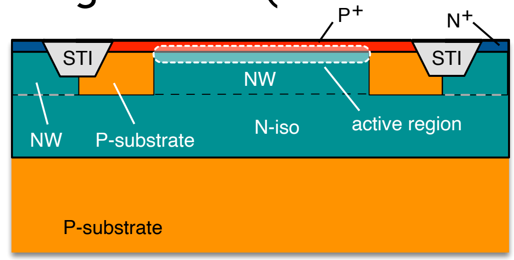
	Scintillating (Cherenkov)
Unit Area (mm^2)	1 x 1
Micro-cell pitch (μm)	10 or 15
Macro-pixel (μm^2)	500 x 500 (or less)
PDE (%)	(20 - 50)
DCR (kHz)	Not crucial
AP (%)	As low as possible (≈ 1)
Xtalk (%)	As low as possible (few %)
Trigger	External
Data: light intensity	Number of fired cells in 1 or 2 time windows (tenths ns long)
Data: time	Time of Arrival in the time window (< 100 ps) possibly TOT
Final - Package	Strip with 8 units
Connection	BGA

A possible floorplan and readout architecture





Single SPAD (150 nm CMOS technology)



- p+/n-well junction, isolated from substrate by deep n-well
- Readout electronics integrated in a monolithic structure with the sensor

- The building block consists of 8 dSiPM, 1x1mm^2, based on SPAD arrays with 15μm pitch or less
- The local electronic circuits will be kept to a minimum to guarantee high fill-factor
- The inter-dSiPM spacing is used to accommodate the processing electronics
- The 1 mm^2 dSiPM will be subdivided in quadrants (Pixel), each served by dedicated, mixed analogue and digital electronics

Summary

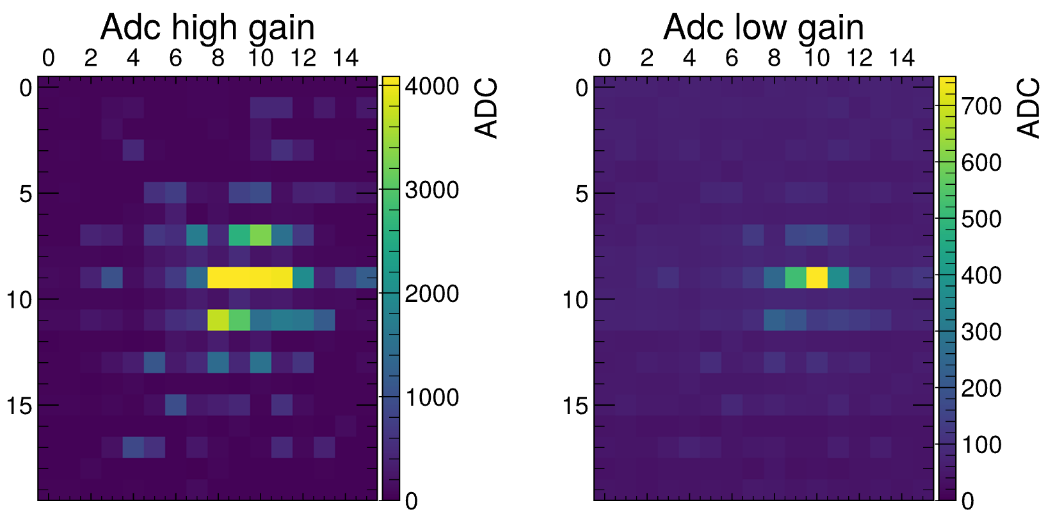
- Dual readout calorimetry is one of the techniques that guarantees the performance needed for future leptonic colliders. The use of SiPMs adds additional features to the detector response (i.e. transversal and longitudinal segmentation, the latter through timing measurements)
- Recent R&D is addressing solutions that can be considered for large production (i.e. readout, integration …) and that will be used to build and qualify on beam the hadronic scale prototype
- The dSiPM could further consolidate the reliability of a large scale system preserving the transversal segmentation (no need for grouping), improving timing information and allowing on-detector linearity correction (if needed)
  - This is pure conceptual design not yet supported by founding agencies
  - In case of interest we could be considered as a use-case

To follow up the R&D, subscribe on egroups.cern.ch to idea.dualreadout@cern.ch

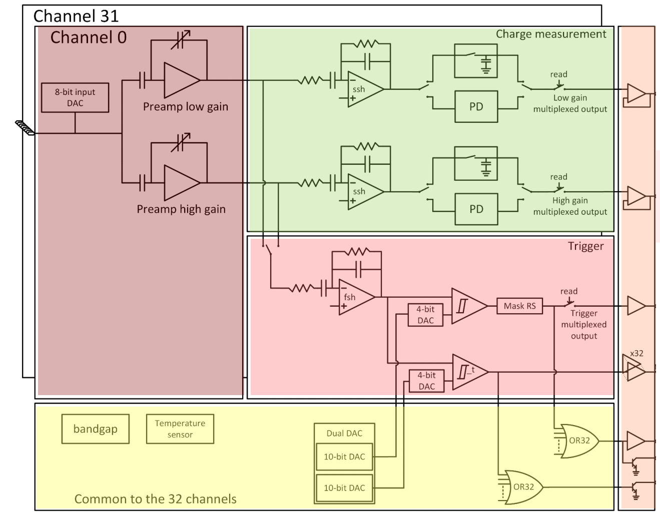
Backup

The impact of high granularity (@ DESY)

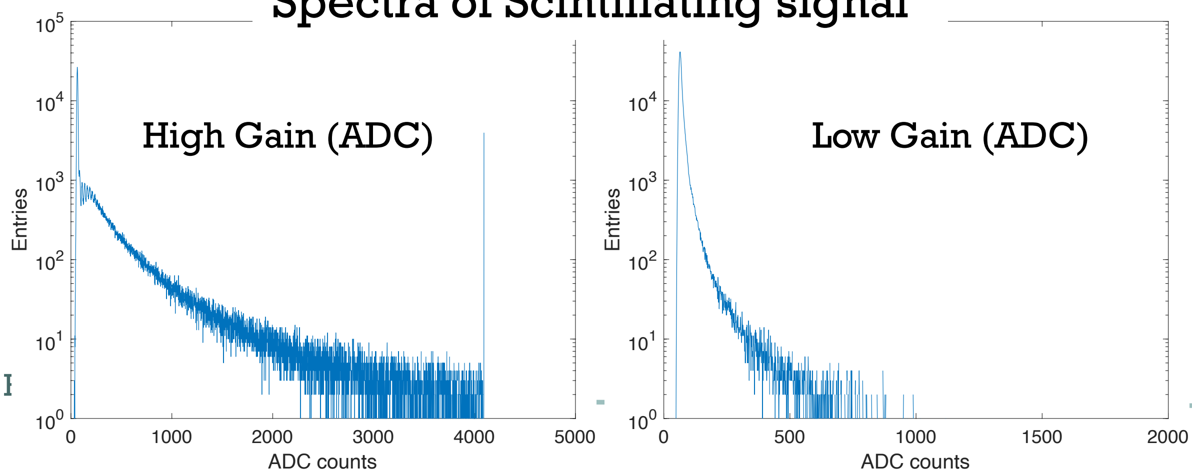
- 6 GeV event centred on the SiPM tower (Raw data)



CITIROC 1A: block diagram

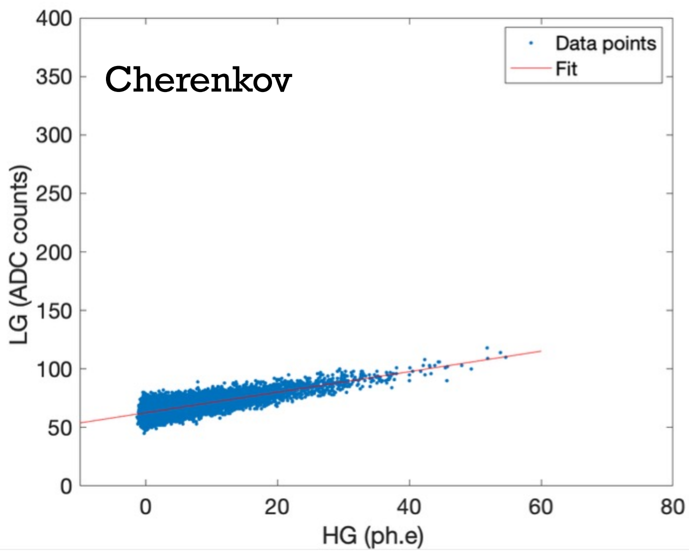


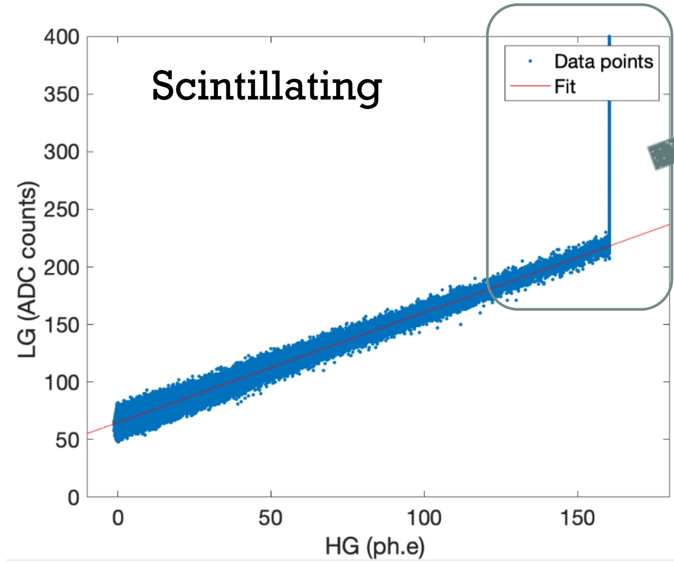
Spectra of Scintillating signal



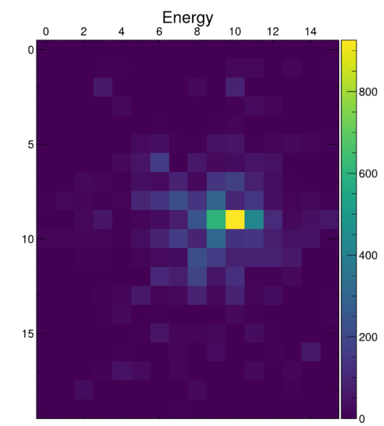
SiPM calibration (Low Gain)

- Low gain calibration (ADC/Ph-e) is based on HG - LG correlation plots

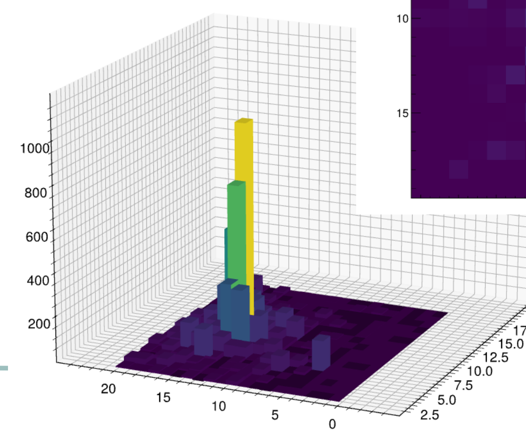




This line shows where the HG saturates and it demonstrates the possibility of using the LG



- After the calibration we can see the deposited energy in each fiber

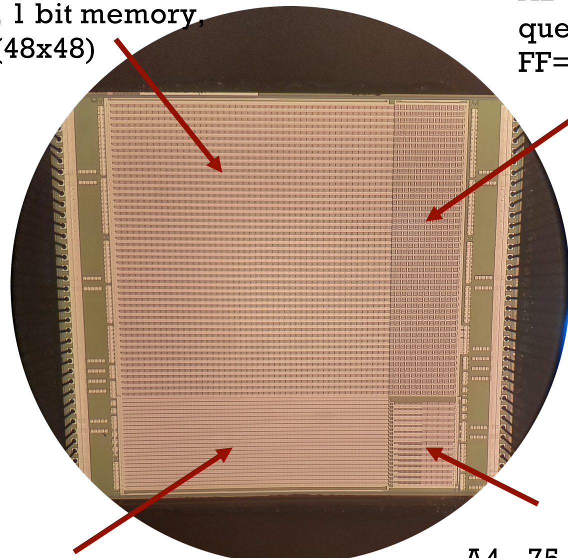


Some studies in 150 nm CMOS technology

- SPAD arrays with different active area and quenching architecture

A1 - 75 um pitch, passive quenching, 1 bit memory, FF=65% (48x48)

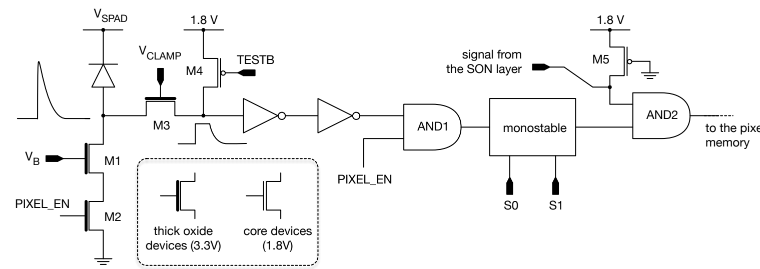
A2 - 75 um pitch, passive quenching, 10 bit counter, FF=48% (48x12)



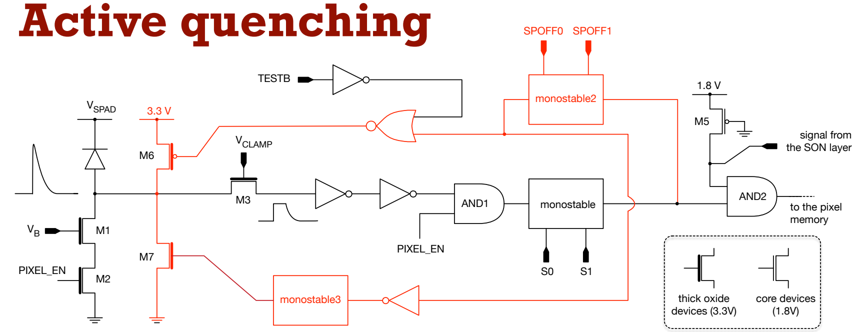
A3 - 50 um pitch, passive quenching, 1 bit memory, FF=42% (24x72)

A4 - 75 um pitch, active quenching, 1 bit memory, FF=52% (6x7)

Passive quenching

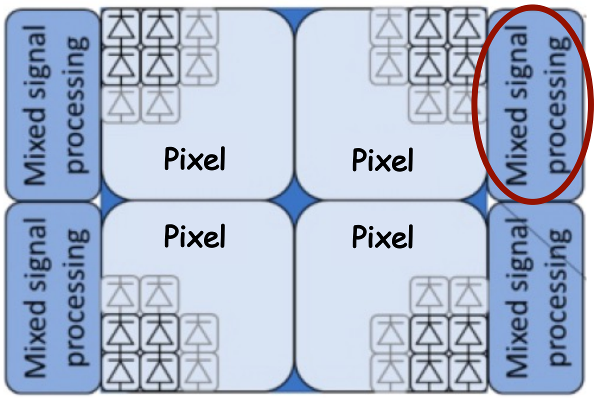


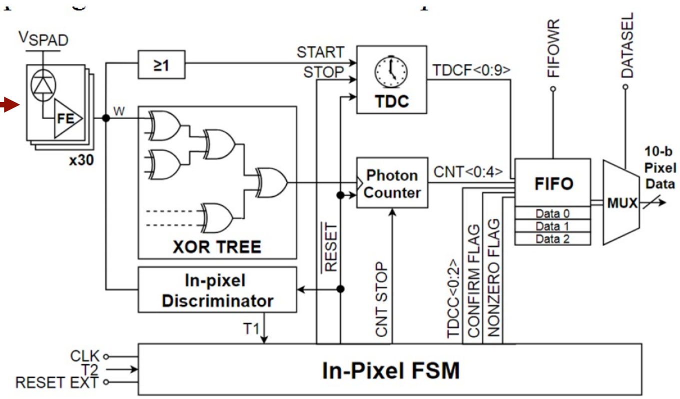
Active quenching

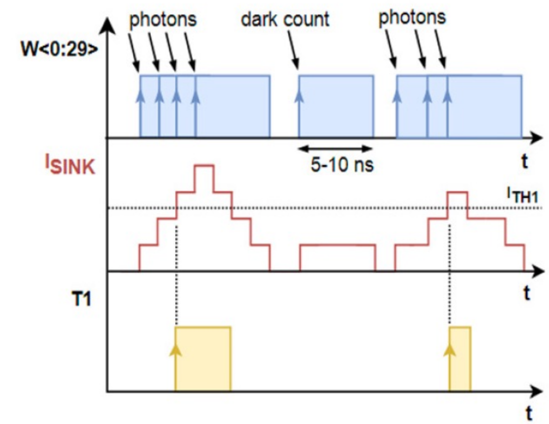


L. Ratti et al, Front. Phys., 14 January 2021
https://doi.org/10.3389/fphy.2020.607319

A possible floorplan and readout architecture







- The signal from SPADs in one pixel increments the photon counter (intensity measurement)
- The same signals are combined (e.g. current summation) to generate an event validation (in-pixel discrimination)
- A TDC per pixel may measure the arrival time of the earlier occurring photon (50ps) and, eventually, the TOT
- The whole system is governed by reconfigurable digital logic, making the dSiPM adaptable to a variety of measurements (amplitude, width etc).
- Data will be read out through serializers at the end of the 8-dSiPM row.

E. Manuzzato *et al*, *ESSCIRC*, 2019, pp. 75-78
doi: 10.1109/ESSCIRC.2019.8902571.