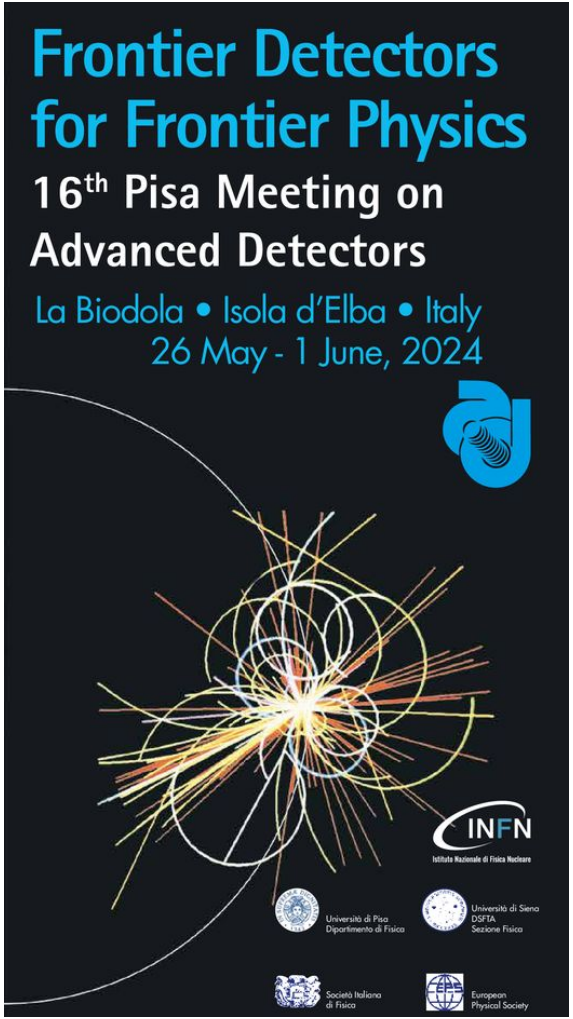
# ALCOR: a mixed-signal ASIC for the dRICH detector of the ePIC experiment at the EIC

Fabio Cossio (INFN Torino)
on behalf of the ePIC dRICH Collaboration

31 May 2024



# The Electron-Ion Collider at BNL

Major US project in nuclear physics, one of the most important scientific facilities for the future of nuclear and subnuclear physics

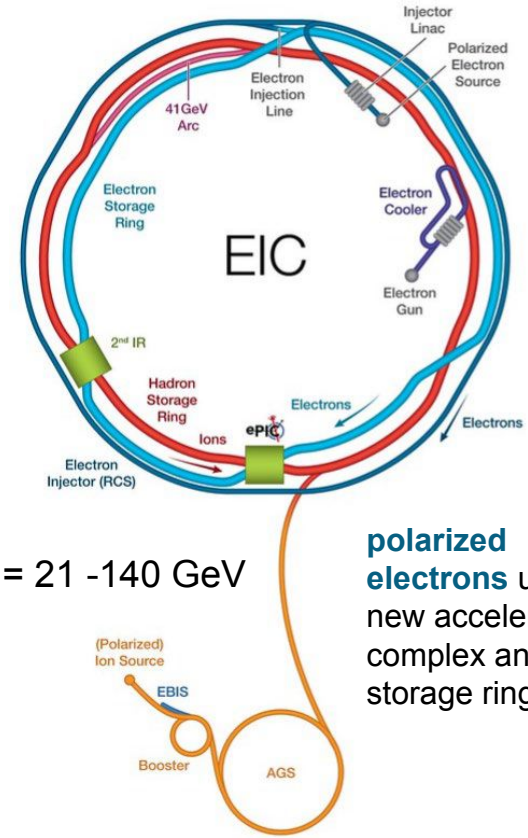
**EIC** will be the world's first collider with polarized electron, proton and light nuclear beams (≥ 70%)

**EIC** will allow to explore the secrets of QCD:

- understand origin of mass & spin of the nucleons
- provide extraordinary 3D images of the nuclear structure

Status: **approved** project progressing towards its realization at BNL, first beam operations are expected to start in the early 2030s

One experiment foreseen for now: **electron-Proton/Ion Collider (ePIC)**

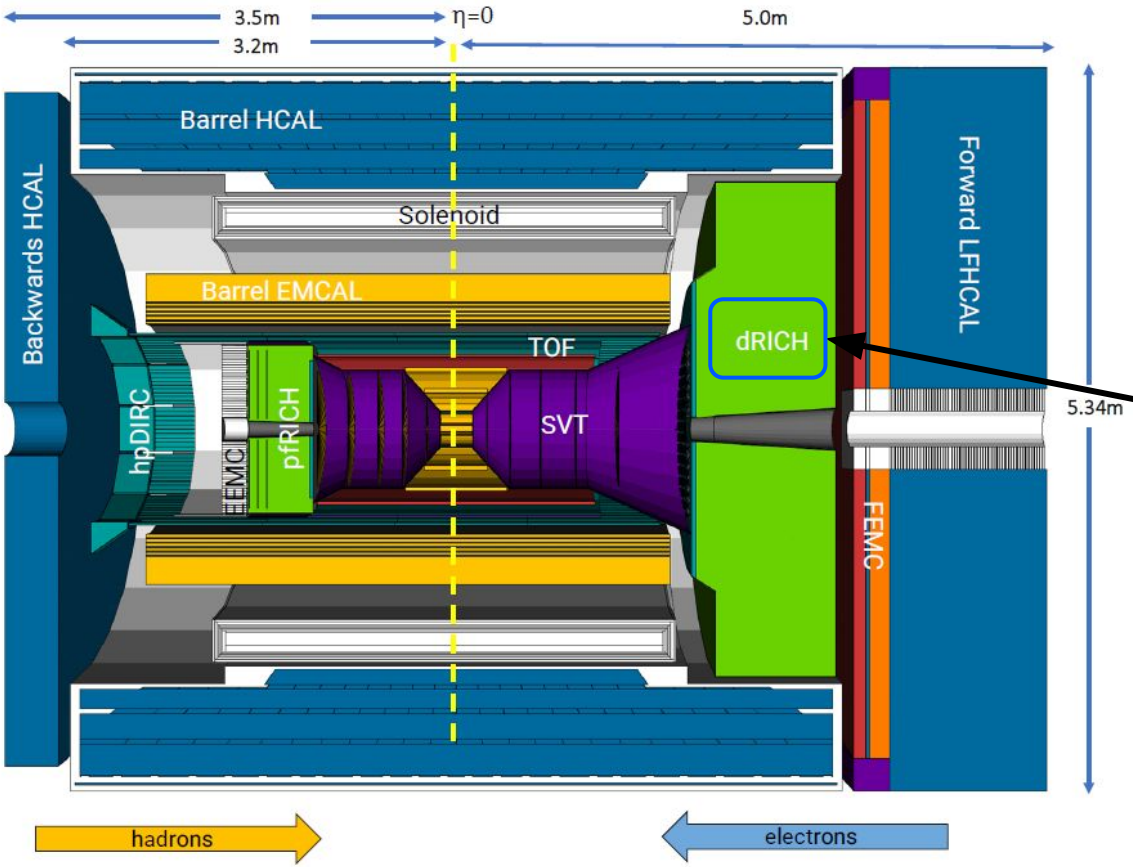



√s = 21 -140 GeV

**polarized electrons** use new accelerator complex and storage ring

**protons and nuclei** use **RHIC** infrastructure

# The ePIC barrel detector




## Tracking

- New 1.7T solenoid
- Si MAPS Tracker
- MPGDs (μRWELL / MicroMegas)

## PID

- high performance DIRC
- proximity focusing RICH
- **dual-radiator RICH**
- TOF (AC-LGAD)

## Calorimetry

- barrel: imaging EMCal
- backward: $PbWO_4$ EMCal
- forward: finely segmented
- outer barrel + backward HCal

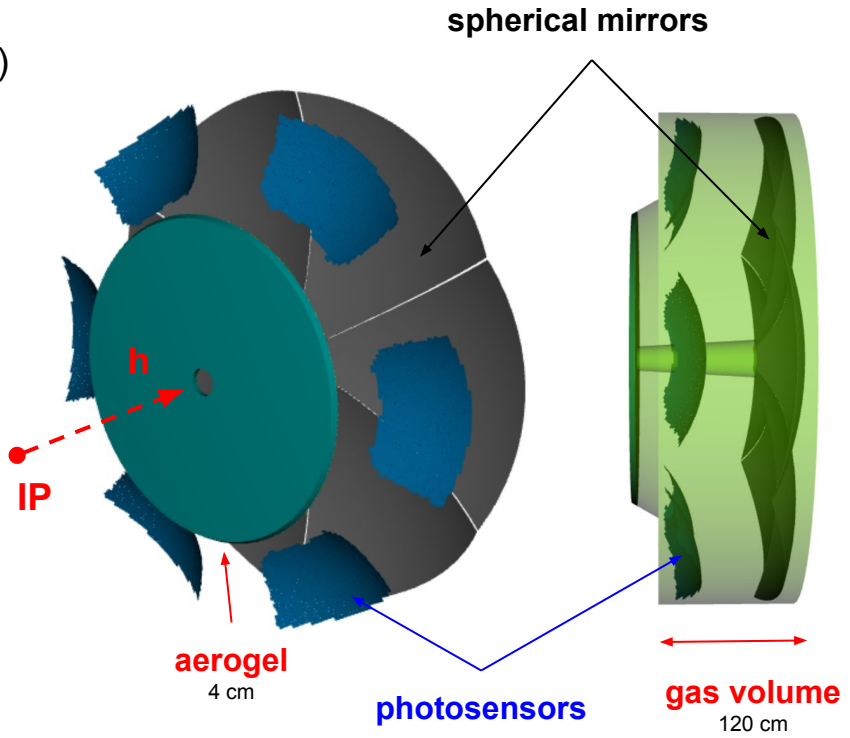
# The dual-radiator RICH (dRICH) for forward PID

Compact and cost-effective solution for broad momentum coverage (3-50 GeV/c) at forward rapidity ($1.5 < \eta < 3.5$)

- **Radiators**: aerogel (n ~ 1.02) and $C_2F_6$ (n ~ 1.0008)
- **Mirrors**: large outward-reflecting, 6 open sectors
- **Photosensors**: 3x3 $mm^2$ pixels, 0.55 $m^2$ per sector, in 1 T magnetic field and radioactive environment ($10^{10}$-$10^{11}$ $n_{eq}/cm^2$ total exposure 12 y operation)

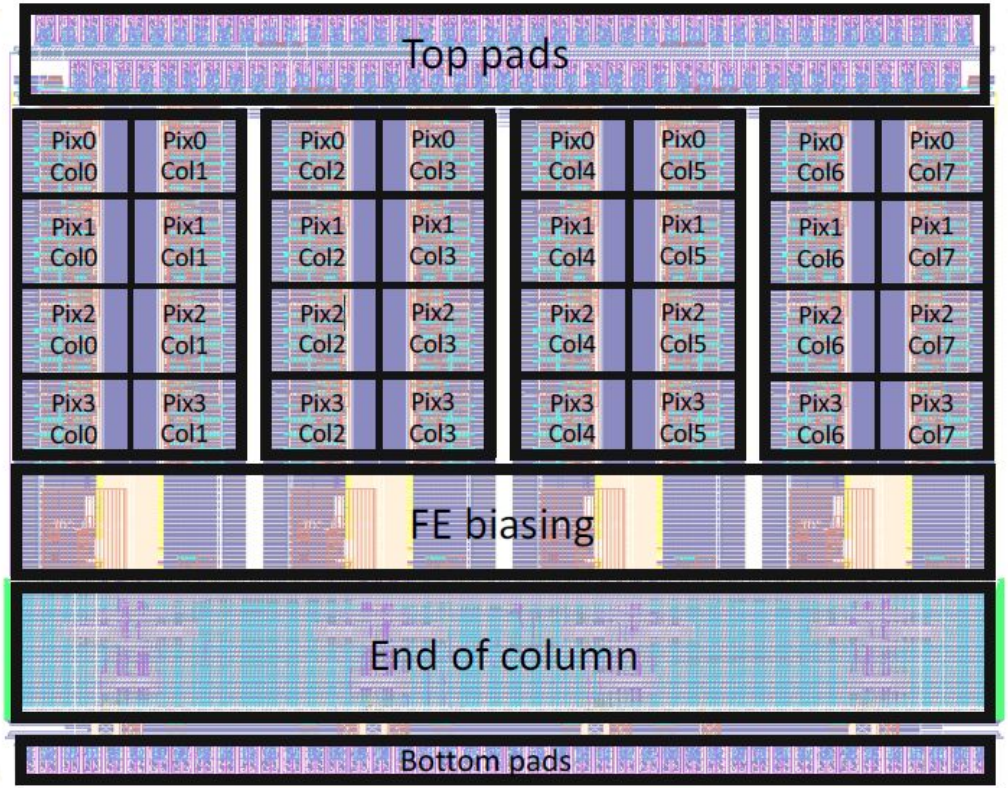
**SiPM** based readout

- ✓ Single Photon sensitivity ~ 10 phs per Cherenkov event
- ✓ Good timing performance < 100 ps
- ✓ Cheap and insensitive to magnetic fields
- ✗ **High DCR** and **high radiation sensitivity** → requires cooling, annealing, timing

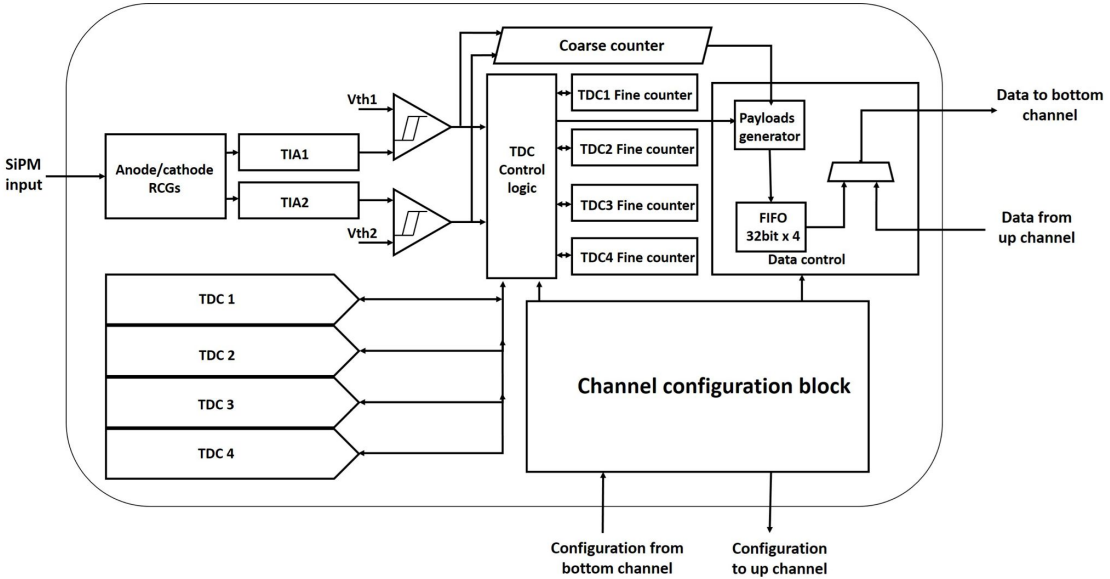


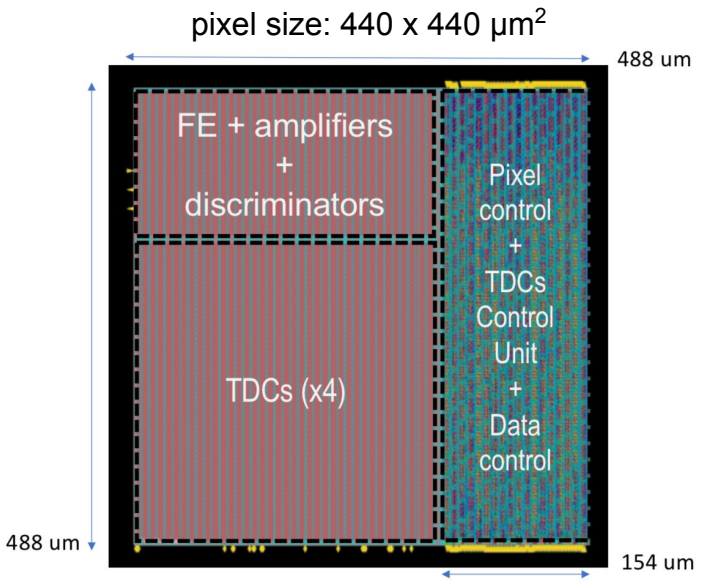
# ALCOR (**A** **L**ow Power **C**hip for **O**ptical Sensor **R**eadout)

- **32-pixel** matrix (8x4) mixed-signal ASIC (4.95 mm × 3.78 mm)
- **SiPM readout**: single-photon time tagging + Time-over-Threshold or Slew-Rate measurements
- On-chip signal amplification, conditioning and digitization: 32-bit event word
- **Fully digital output**: 4 LVDS 320 MHz DDR Tx links
- Power consumption ~10-12 mW/channel
- 0.11 µm CMOS technology



# Pixel architecture



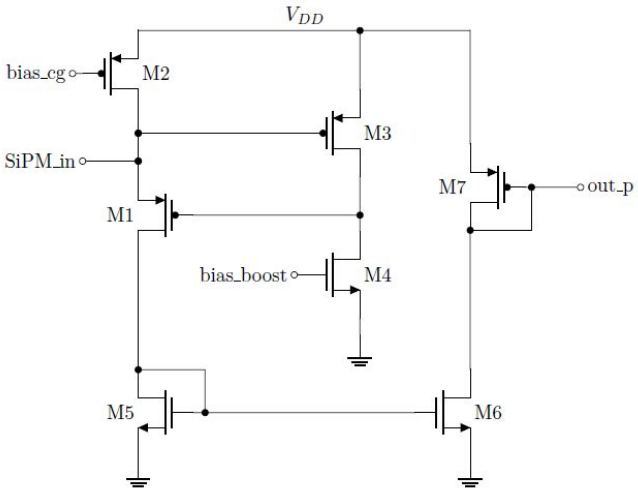



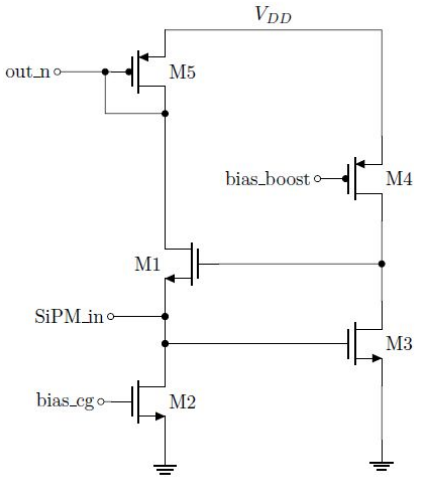

- RCG input stage current conveyor, 2 independent TIA branches with 4 gain settings
- 2 leading edge discriminators with independent (and per pixel) threshold settings (6-bit DAC)
- 4 TDCs based on analogue interpolation with 25-50 ps time-bin (at 320 MHz clock frequency)
- Pixel control logic handles TDC operation, pixel configuration and data transmission

# Pixel Front-End

### Input stage

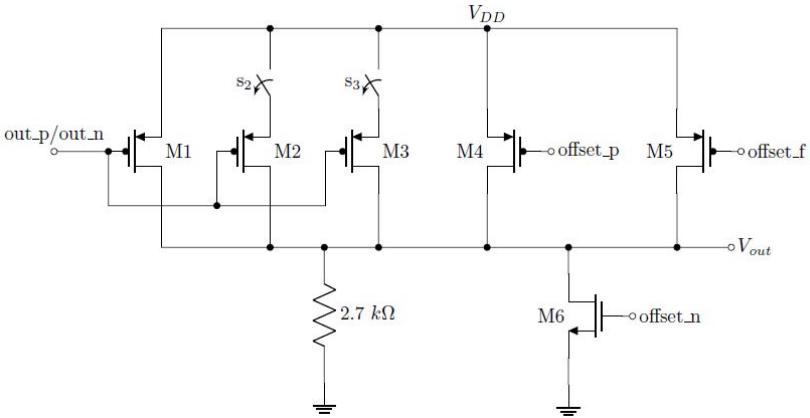
- Dual-polarity RCG current conveyor
- Programmable bias currents: CG (30-100 µA) and BOOST (1-4 mA)
- $Z_{in}$ ~ 10-20 Ω



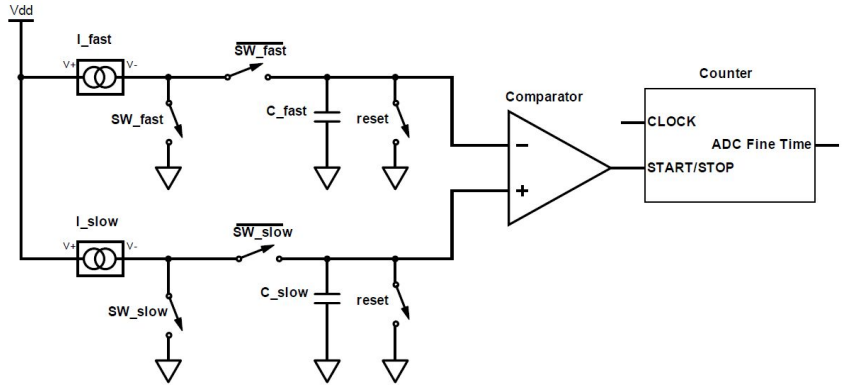

### Output stage

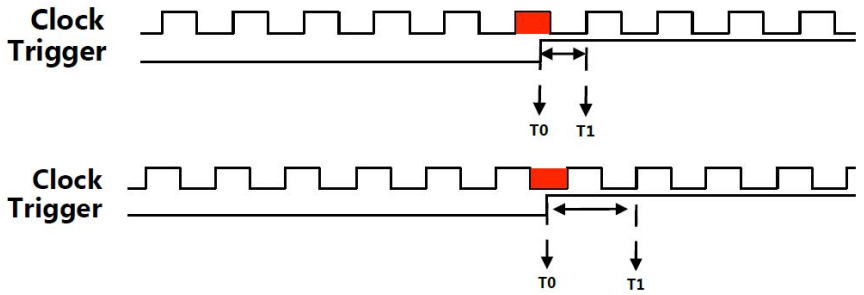
- TIA gain: 2.7 kΩ
- 4 gain settings: 1/3, 4/3, 7/3 and 10/3
- DC coupled: baseline compensation based on gain and CG bias current settings + fine offset adjustment (3-bit)



# Time to Digital Conversion

- Coarse time: 15-bit clock counter
- Fine time measurement performed by TDC based on analogue interpolation:
  - ***fast ramp***: $C_{fast}$ charged for time interval between the event trigger and the clock
  - ***slow ramp***: $C_{fast}$ charged with smaller current, counts clock cycles until $C_{slow}$ and $C_{fast}$ voltages are equal
- I.F. 64 or 128 → LSB = 25-50 ps @320 MHz
- Measured time interval: 0.5 - 1.5 clk period
- TDC conversion time: [200, 600] ns
- 4 TDCs per pixel for event derandomization

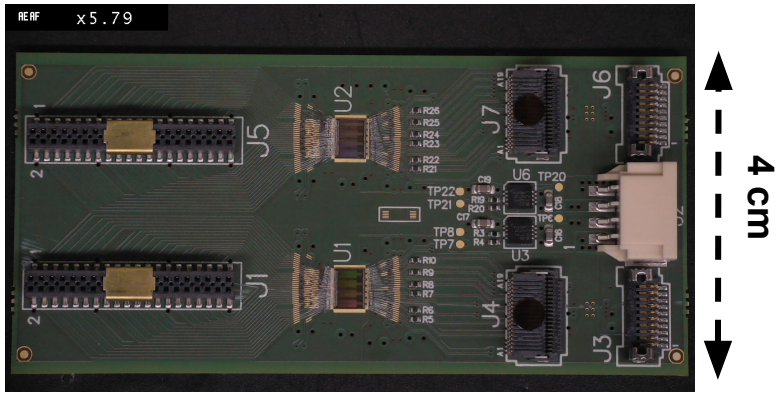


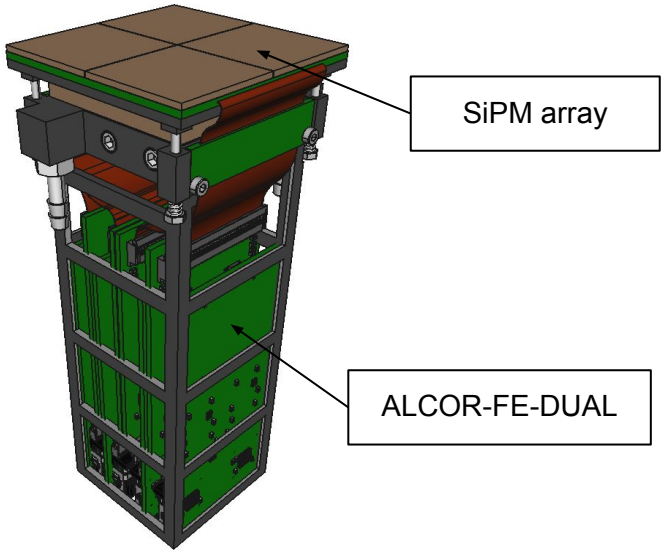
# ALCOR readout system for the dRICH prototype

## ALCOR-FE-DUAL

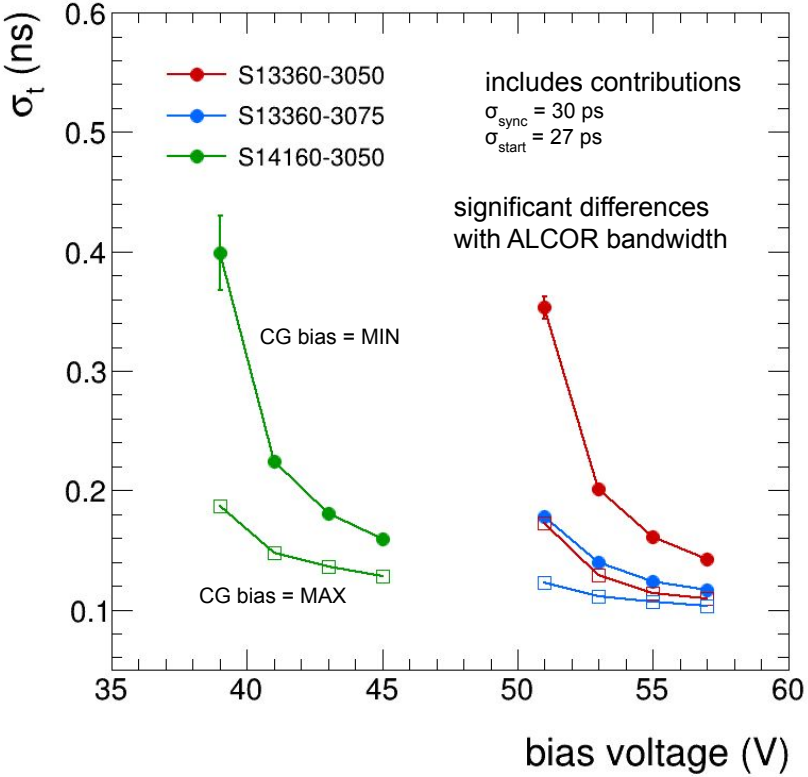
- Two **32-channel** ALCOR ASICs **wire-bonded** on the PCB
- 4 ALCOR-FE-DUAL boards for each PDU (256 channels)
- System used for 2023-2024 ePIC dRICH beam tests

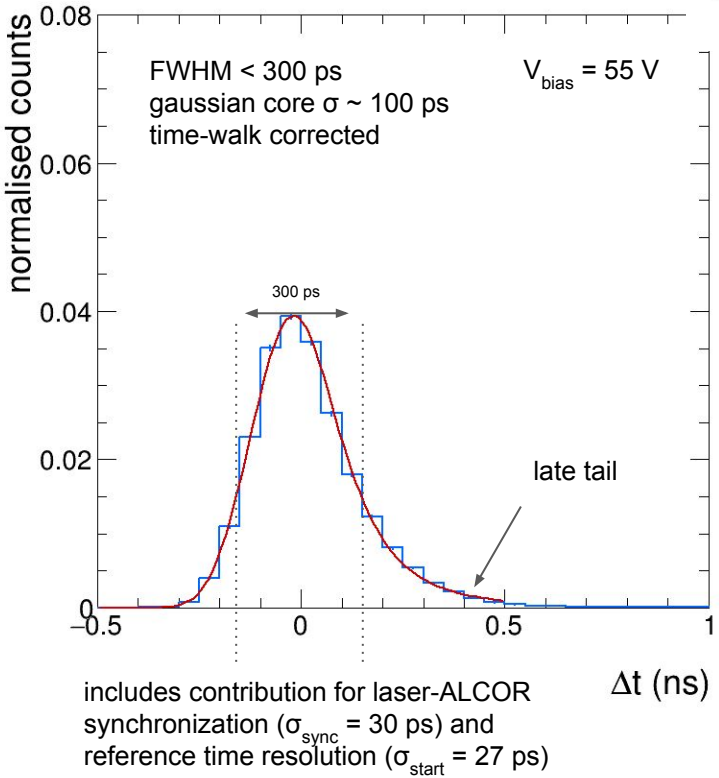



**ePIC dRICH Prototype photodetector unit (PDU)**



# Laser timing measurements

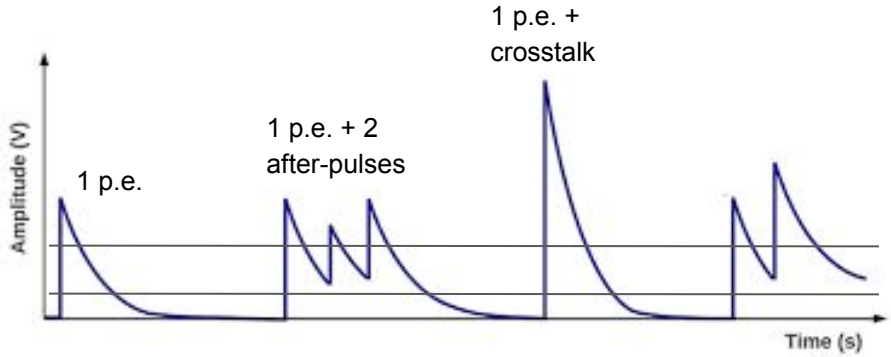


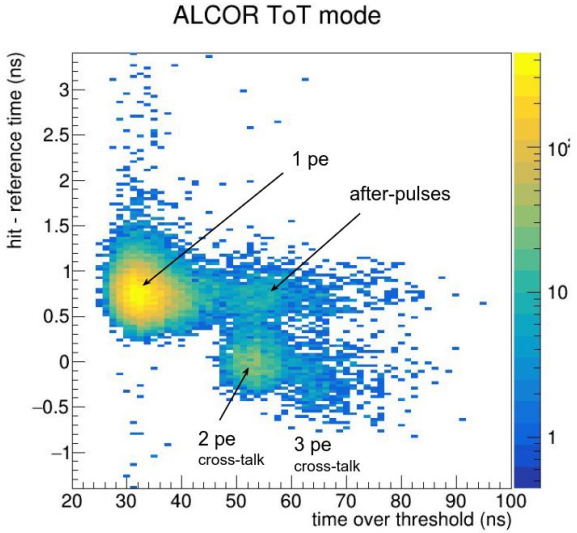




➔ Better time resolution with 75 μm SPADs, comfortably below $\sigma_t$ = 150 ps also at low Vbias

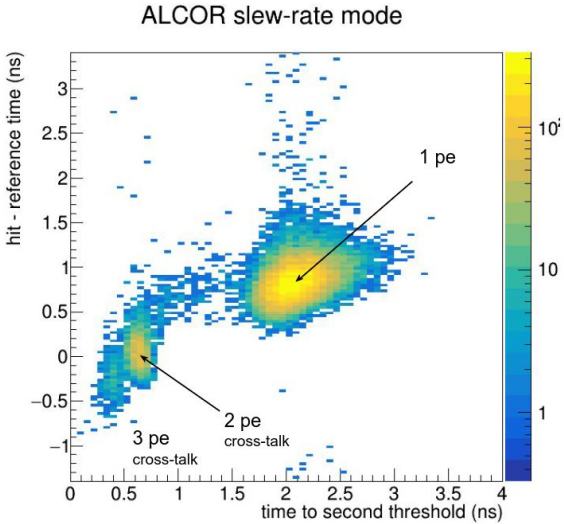
# Time walk correction

**Time walk** correction to improve overall time resolution → studies with laser setup using ***ToT*** and ***SlewRate*** measurements



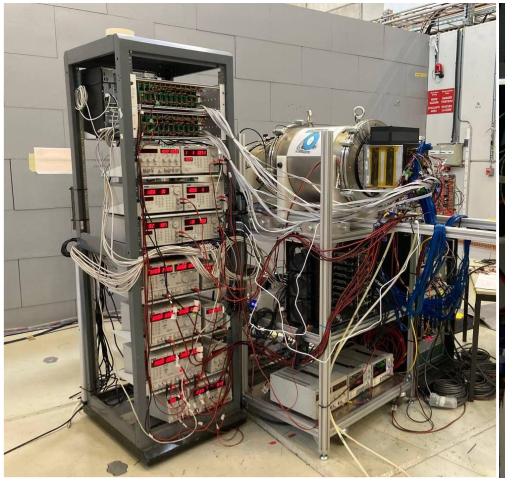

- ***ToT mode*** cannot distinguish between afterpulses (slow-rise time, large ToT) and cross-talk (fast rise-time, large ToT)
- ***SR mode*** provides better separation

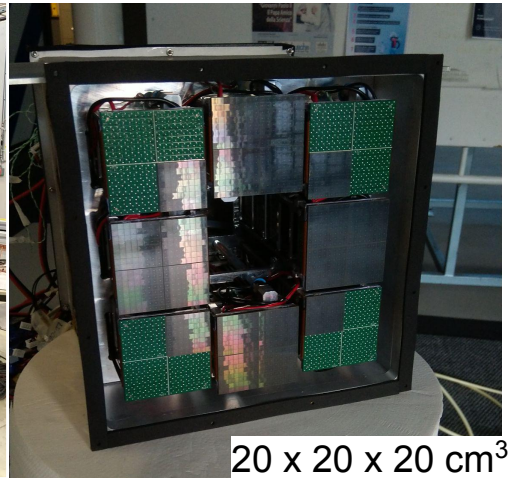


# 2023 test beam at CERN-PS

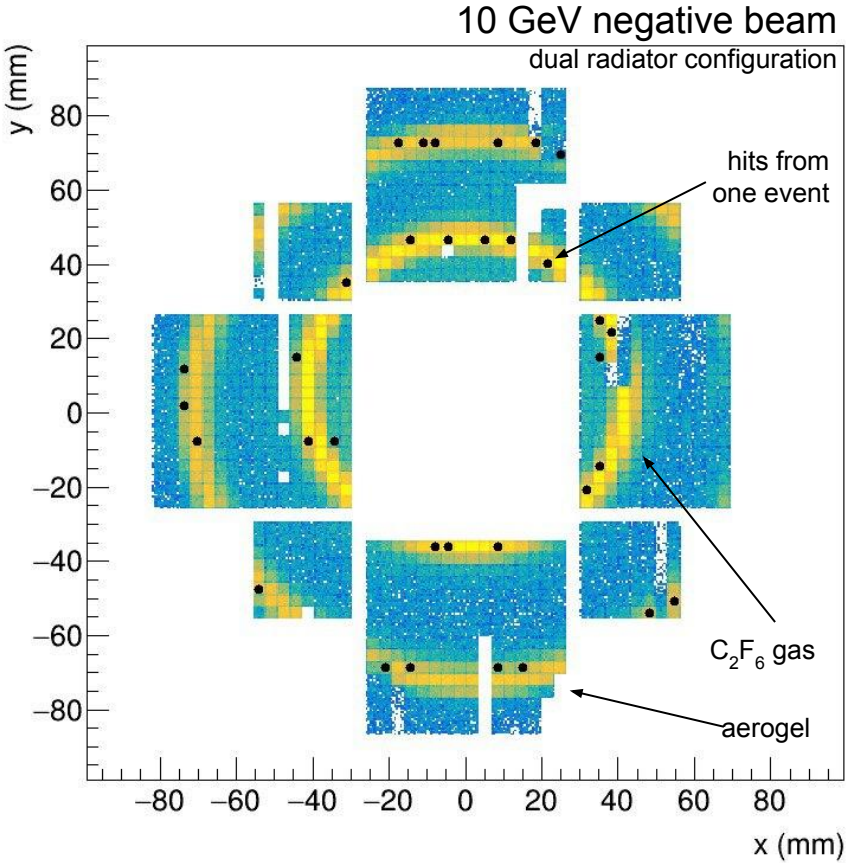
Successful beam test with prototype dRICH and PDUs (CERN-PS, October 2023)

- HPK S13360-3050 (3x3 $mm^2$, T = -30/-40°C)
- 20 FE-DUAL (40 ALCOR v2.0, 1280 channels)
- DAQ: Xilinx Kintex 7 KC705

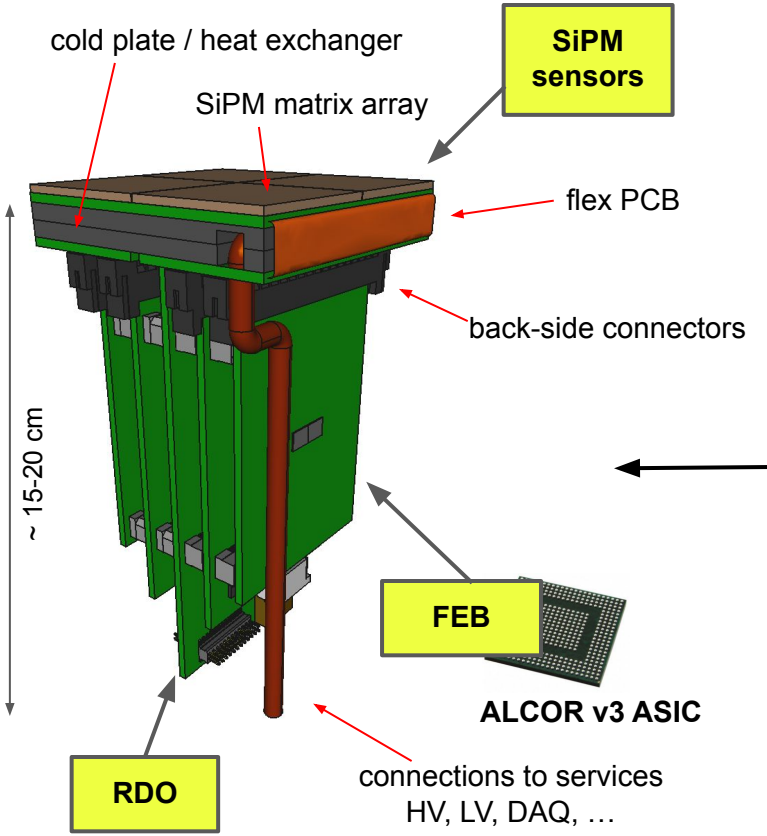




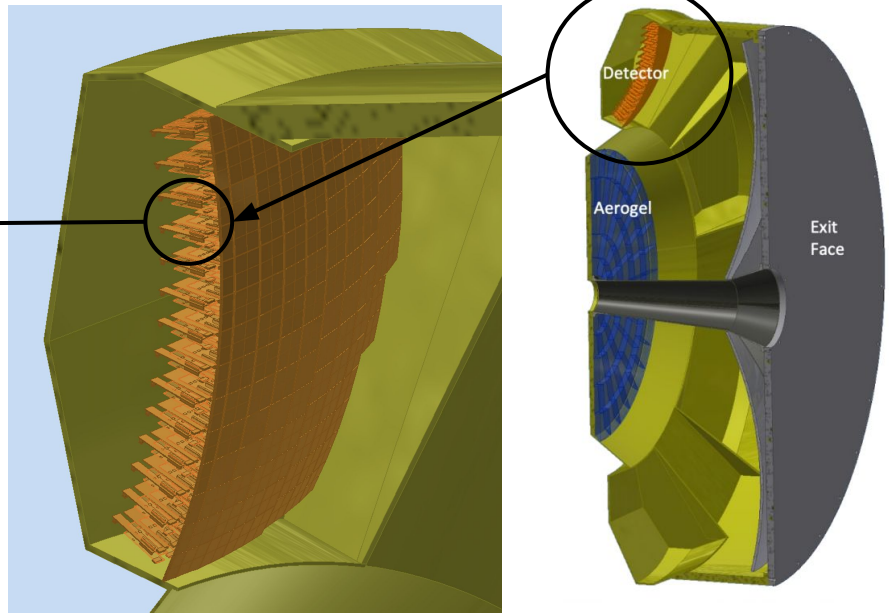
20 x 20 x 20 $cm^3$



# Conceptual design of the final layout




- Each PDU: 4x64 SiPM array device (256 channels)
- 1248 PDUs for full dRICH readout
- 4992 SiPM matrix array (8x8)
- **4992 ALCOR v3**, 64-channel each
- **319488 readout channels**



# ALCOR v3

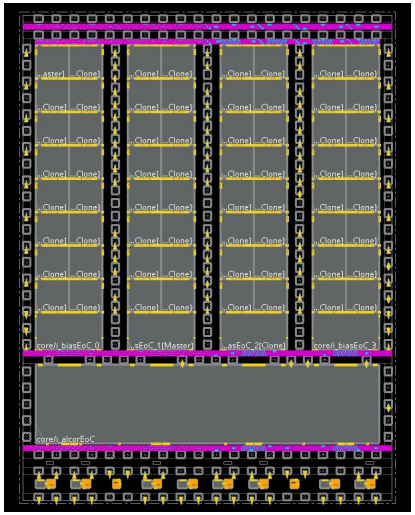
**ALCOR v2**: 32-channel wire bonded ASIC
**ALCOR v3**: 64-channel ASIC (8x8 matrix) inside BGA package (256 balls)

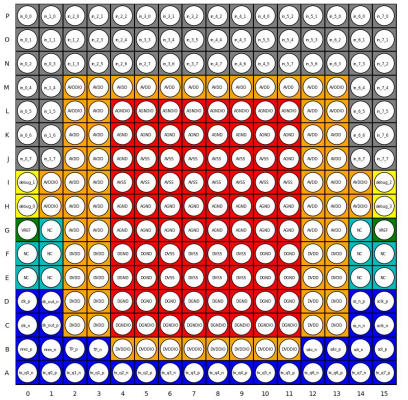
Operation of ALCOR at multiple of **EIC clock frequency** (98.52 MHz): digital logic, TDCs and serializers/drivers re-implemented and verified at **394.08 MHz**

The ePIC detector will take data using a **streaming data acquisition system** with no traditional hardware trigger

**Digital shutter**: “inhibit” pixel digital logic to reduce data throughput

- ~10.2 ns bunch crossing, ~300 ps bunch length, select 2-3 ns → 3x-5x data reduction before ALCOR digitization
- Asynchronous digital shutter implemented in ALCOR v3 pixel logic with programmable delay to compensate offsets between the channels





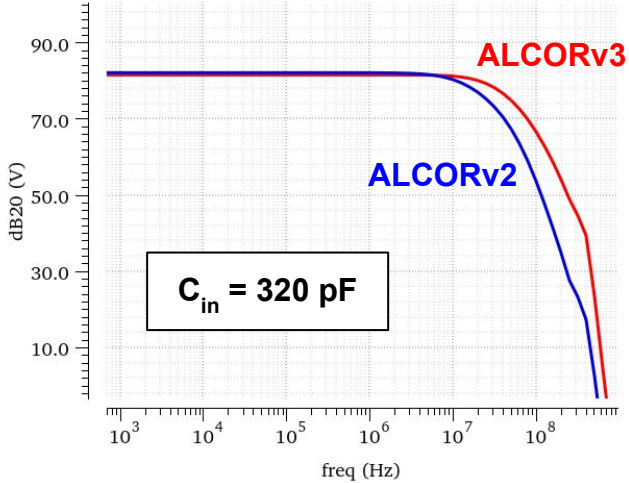
# ALCOR v3

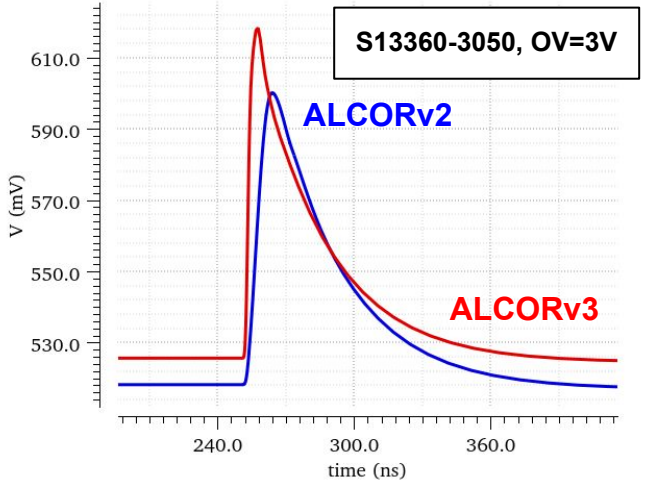
Small revisions on ALCOR FE design

- Increased amplifier bandwidth to improve time resolution
  - SR: 10 MV/s → 35 MV/s
  - rise time: 11 ns → 6 ns
  - ampl: 82 mV → 93 mV
  - rmsNoise: 1.6 mV → 2.7 mV
  - jitter: 160 ps → 80 ps

- Hysteresis discriminator to avoid re-triggering on slow tail with very low thresholds

**Tape-out scheduled during Fall 2024**



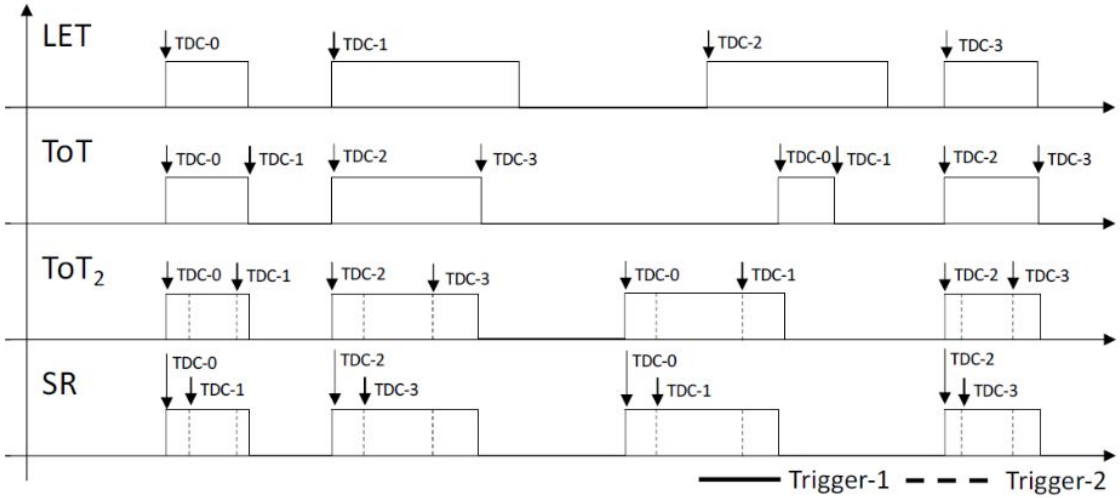



# Summary

- ALCOR is a 64-channel mixed-signal ASIC developed for the readout of the SiPM sensors for the ePIC dRICH at EIC
- Several laboratory and beam tests demonstrated the ALCOR-based readout capability to measure single photons with good time resolution, fulfilling the requirements for the ePIC dRICH
- New test beam at CERN-PS ongoing now to validate the full system and evaluate its performance (with 2048 readout channels and improved timing and tracking systems
- Design of ALCOR v3 ongoing: ASIC tape-out in Fall 2024
- Irradiation tests campaign (SEU and TID) at Centro of Proton-Therapy in Trento with ALCOR v2 foreseen in July 2024

# Backup Slides

# ALCOR pixel operating modes




4 operating modes:

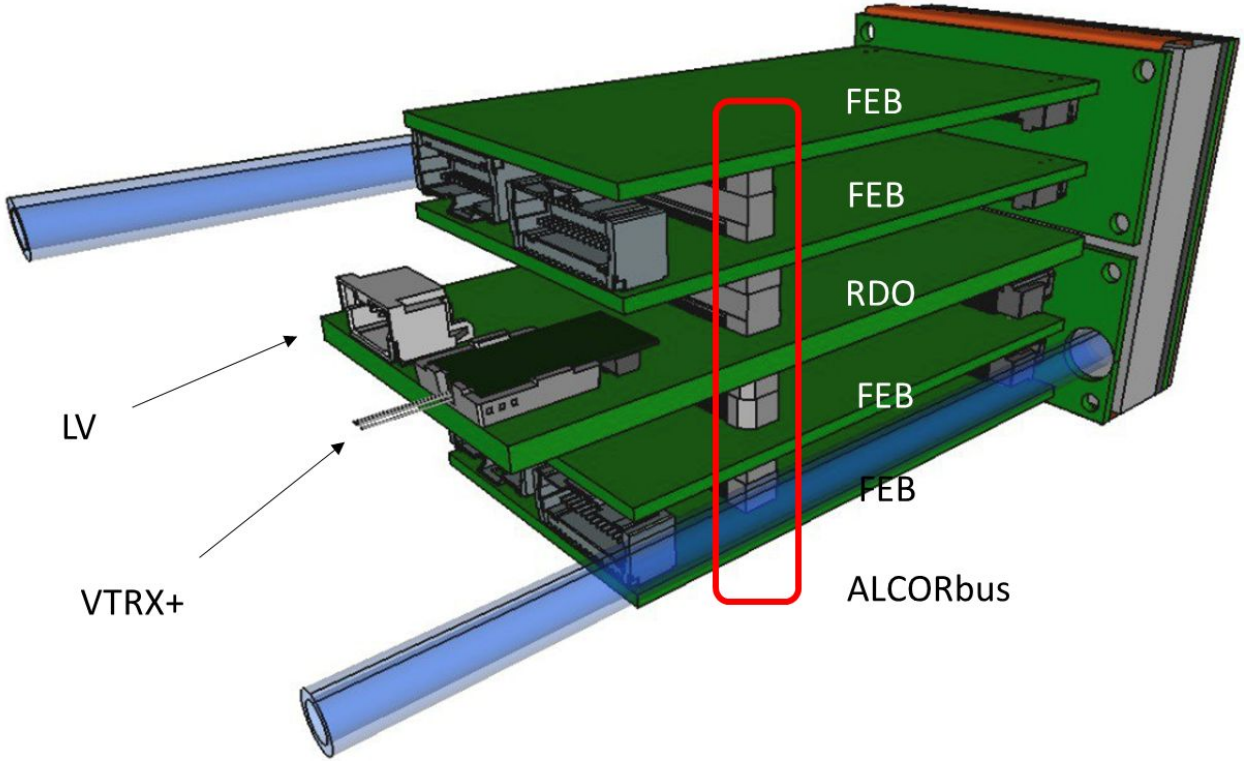
- **LET**: leading edge measurement
- **ToT**: Time-over-Threshold measurement using the first discriminator for both edges
- **ToT2**: Time-over-Threshold measurement using both discriminators
- **SR**: slew-rate measurement

Each mode can be set to:

- **FE**: normal operation mode
- **FE_TP**: send test-pulse to analogue front-end
- **TDC_TP**: send test-pulse to pixel control logic to test and calibrate TDCs (bypass front-end)

Each pixel can also be disabled

# ePIC dRICH photodetector unit (PDU)



# ePIC dRICH DAQ scheme

1248

- PDU: 1248
- RDO: 1248
- FEB: 4992

1248

I-level DAM (27)

- 47 links to PDU
- 1 link to II-level DAM

27

in exp. hall, rack mounted

27

II-level DAM (1)

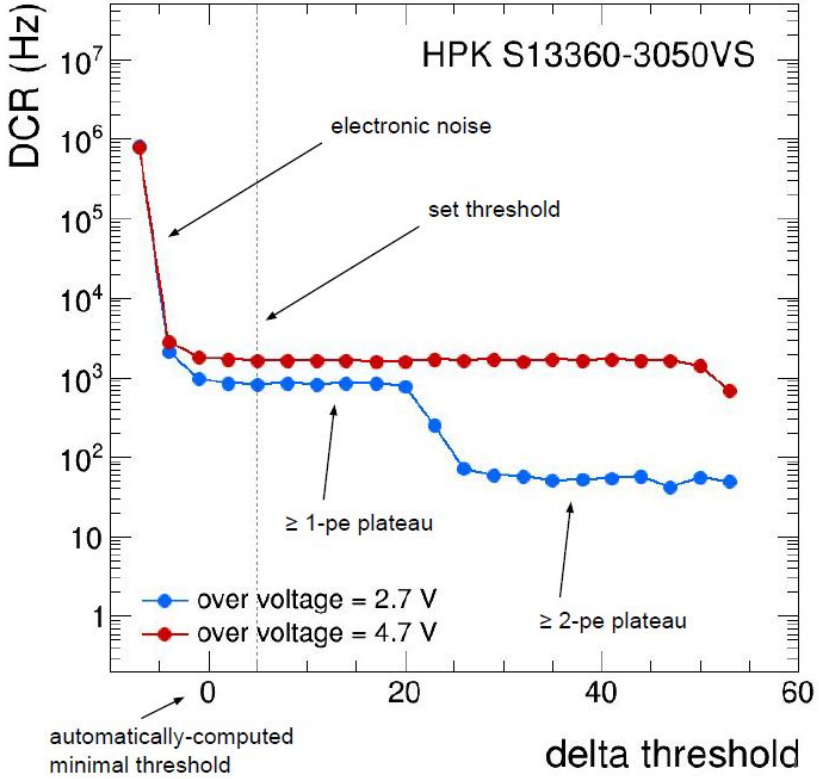
- 27 links to I-level DAM
- link from central ePIC [clock/trigger]

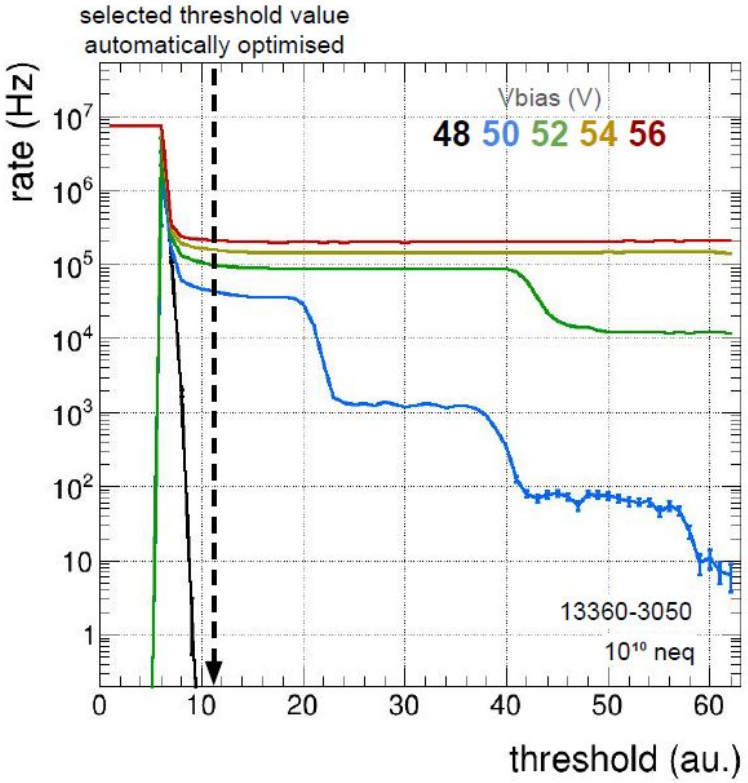
ePIC interaction tagger
able to reach our DAMS in 10 μs!

1

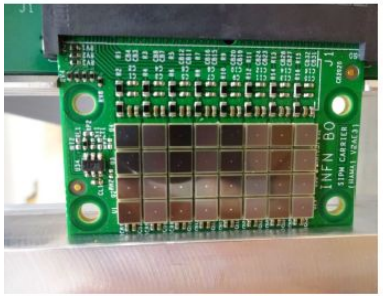
1

# ALCOR for SiPM characterization measurements



# ALCOR for SiPM characterization measurements



irradiated board
after annealing

still working!

T = -30 C

13360-3050 13360-3025

$10^{11}$ neq

$10^{10}$ neq

$10^{9}$ neq

~ $10^{8}$ neq

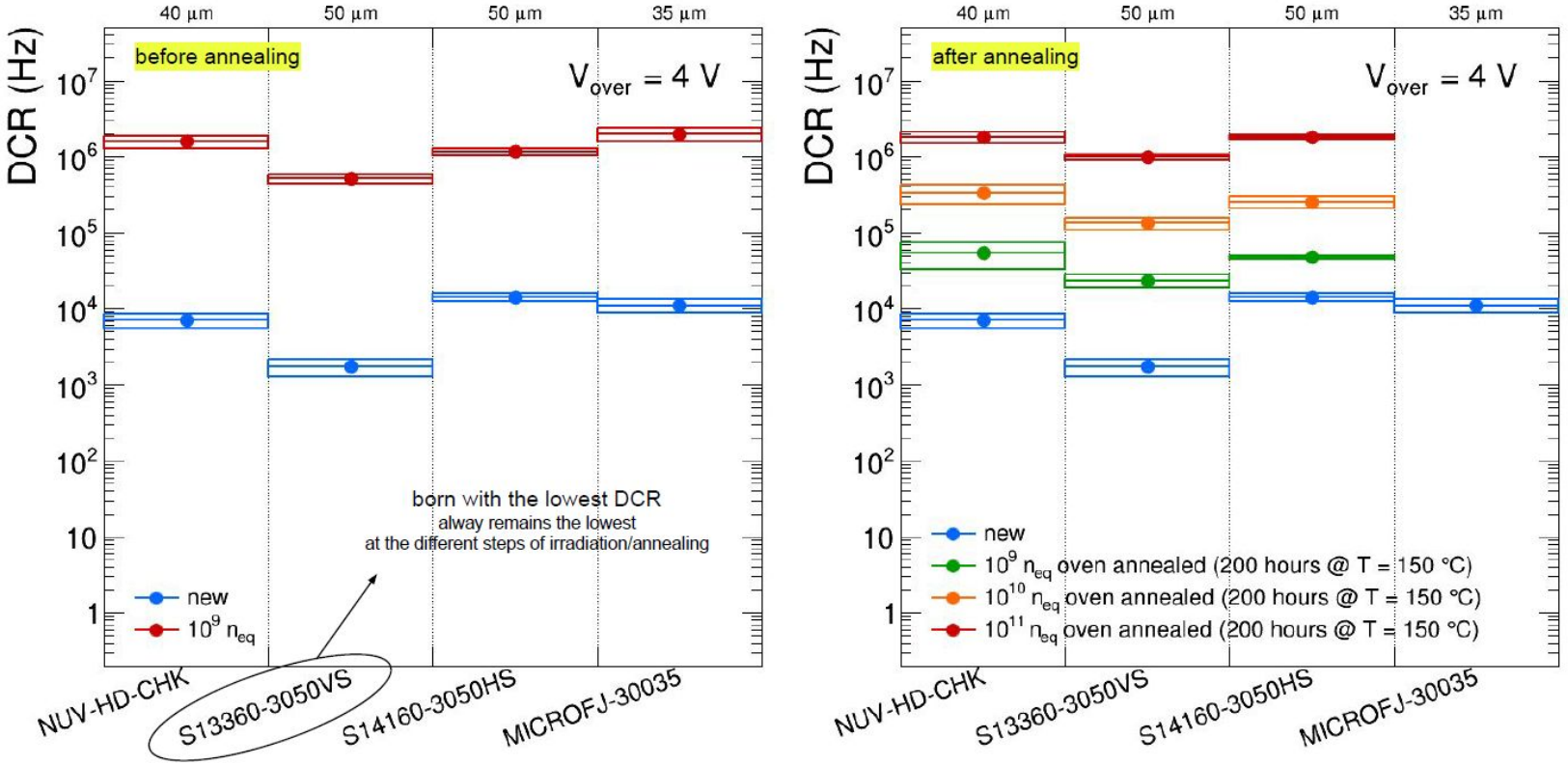
threshold (au)

clear single-photon
separation up to $10^{11}$

Vbias (V)
48 50 52 54 56

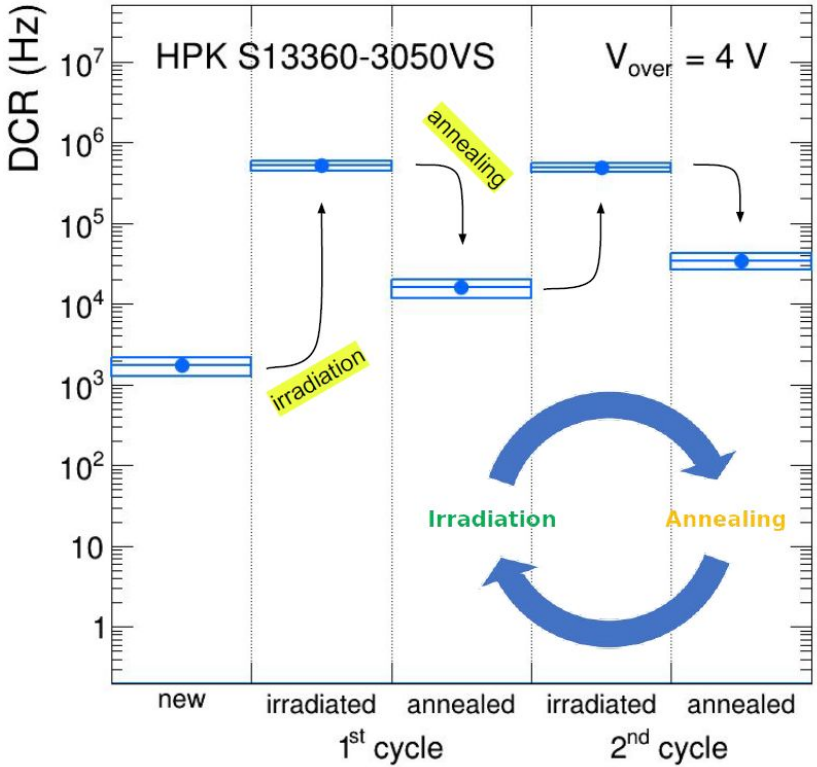
# ALCOR for SiPM characterization measurements

**DCR after irradiation and annealing**



# ALCOR for SiPM characterization measurements

**Repeated irradiation-annealing cycles**




Test reproducibility of repeated irradiation annealing cycles to simulate a realistic experimental situation

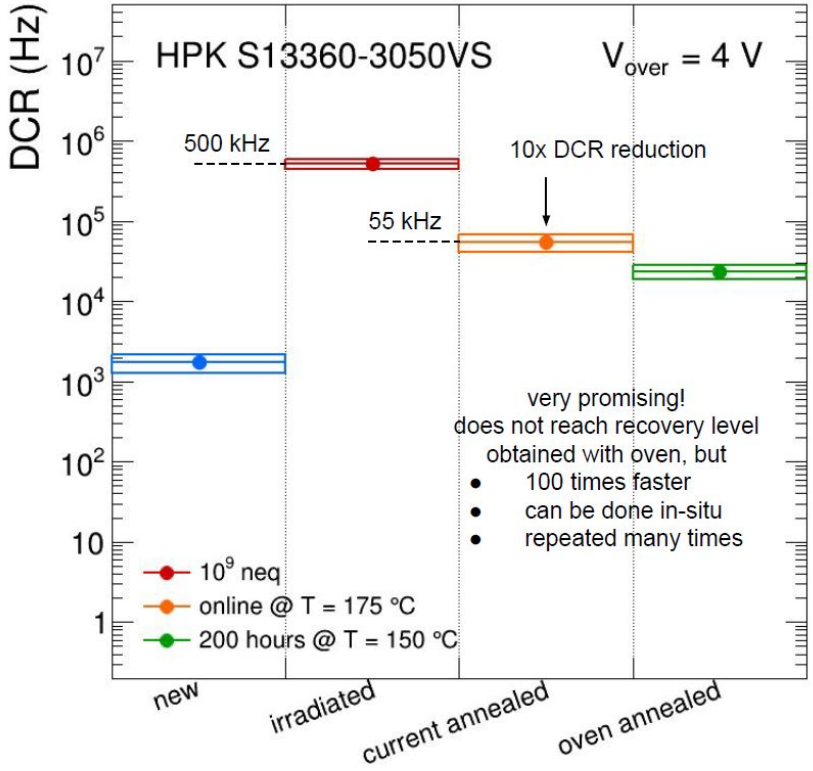
- **irradiation:** fluence/cycle of $10^9$ neq
- **annealing:** in oven for 150 hours at 150 °C

Full characterisation at each step:

- new
- after each irradiation
- after each annealing

# ALCOR for SiPM characterization measurements

**Online annealing**

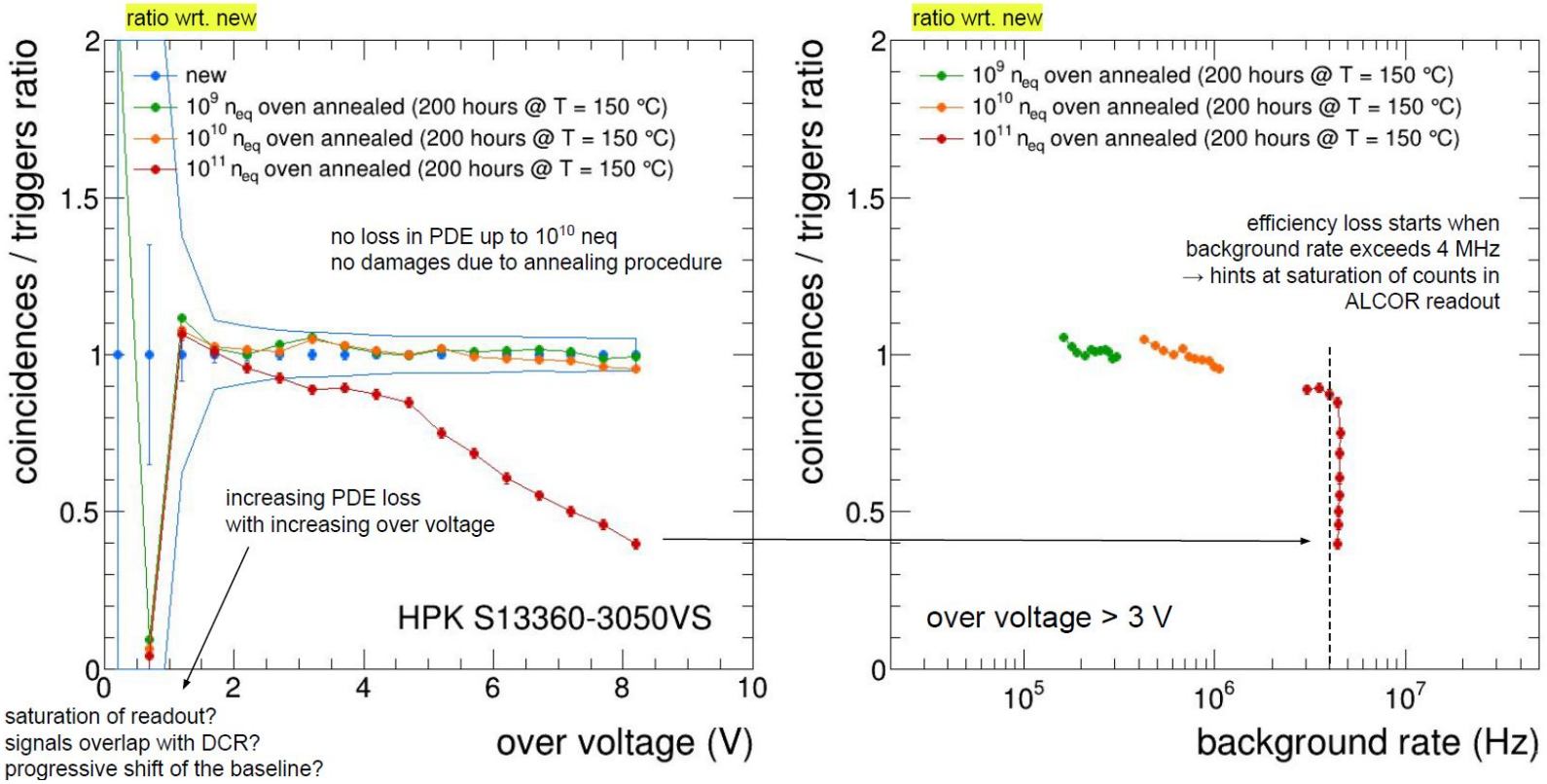



In-situ annealing:

- forward bias, ~ 1 W / sensor
- T = 175 °C, thermal camera monitor
- 30 minutes

# ALCOR for SiPM characterization measurements

**Light response after irradiation and annealing**



# The EIC schedule