Fermilab

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Synergistic Activities: TOF Requirements on FCFDv1

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U.S. DEPARTMENT of ENERGY
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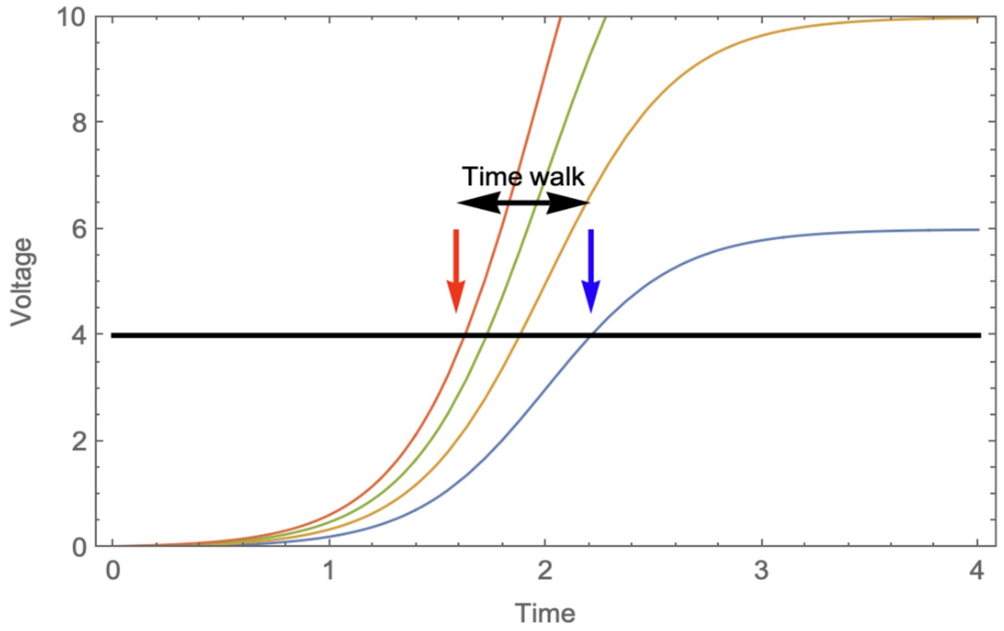
Introduction

- A robust fast-timing measurement technique for LGADs
  - Easy to use and stable: no corrections, or calibrations and threshold adjustments
- CFD approach achieves better performance, especially for low S/N systems, such as LGADs (NIM A 940 (2019), pp 119-124)
  - CFD offers significant reduction in noise, as demonstrated in TOFHIR ASIC for CMS barrel timing detector
    - Improvement in the time resolution by x3.5 in TOFHIR
  - CFD-based readout is much simpler in operation and maintenance
    - No need to maintain the calibration and monitoring system, computing workflows, database maintenance, payloads, etc…

FCFD Readout for Timing Detectors

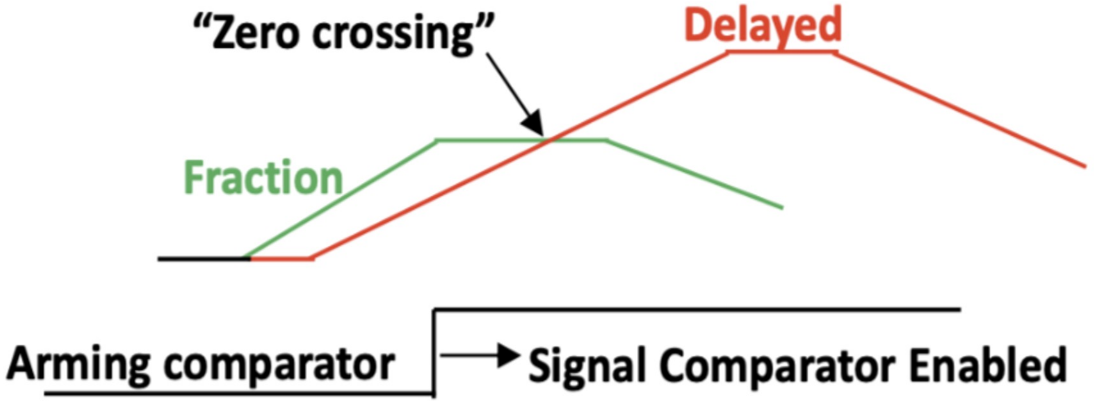
- Time-walk effect is well known & must be corrected for best performance
- Conventionally addressed with online or offline corrections via some type of LUT
- A hardware-enabled correction via CFD built into the readout ASIC design offers much simpler solution



FCFD Readout for Timing Detectors

- Primary application is (AC-)LGAD sensors for MIP signals
- But can be used for many types of precision timing detectors

- Main features of the CFD are:
  - Integrator & Follower to create the “fraction” signal
  - Comparator for “arming” and timestamping



A. Apresyan et. al, **NIM A 1056, 2023, p168655**
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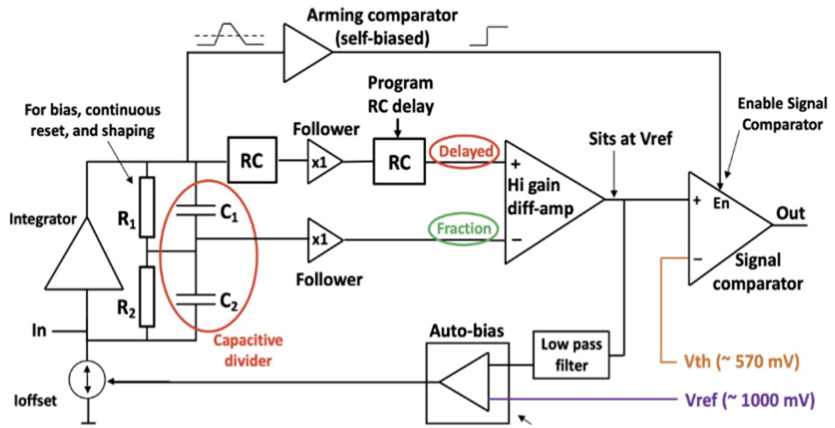

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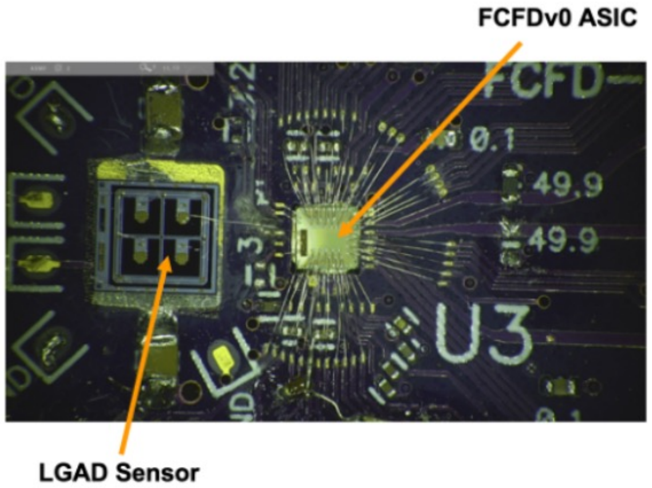
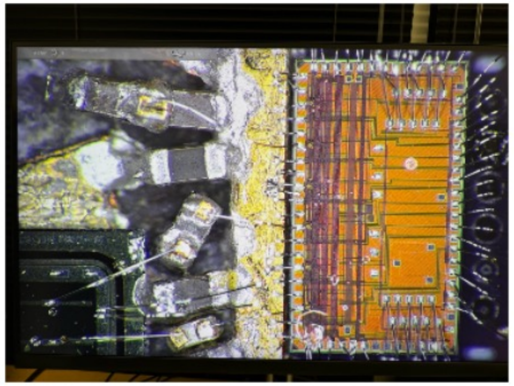
FCFD versions

- Developed in TSMC 65 nm technology node
  - Three versions produced over the years
  - V0 : demonstrate performance of the CFD on chip for DC-LGAD pixelated sensors
  - V1 : multi-channel chip specifically designed for strip AC-LGAD sensors readout
  - V1.1 : improvements and modifications to the V1 for strip sensors

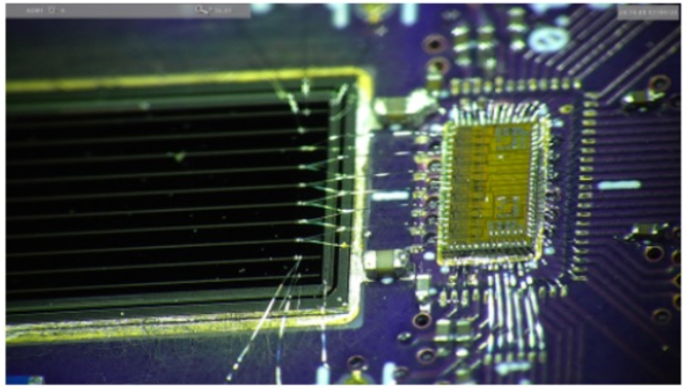
FCFD0



FCFD1

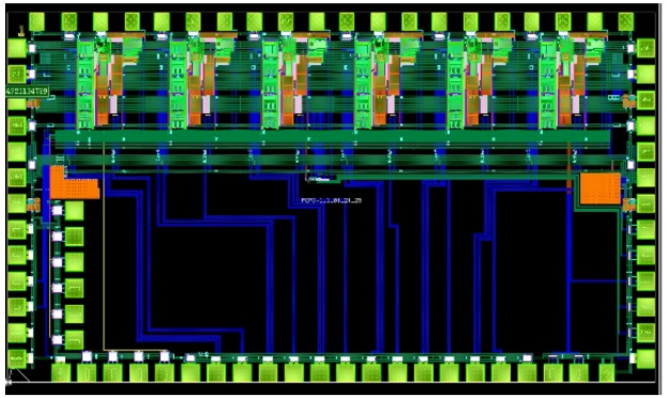


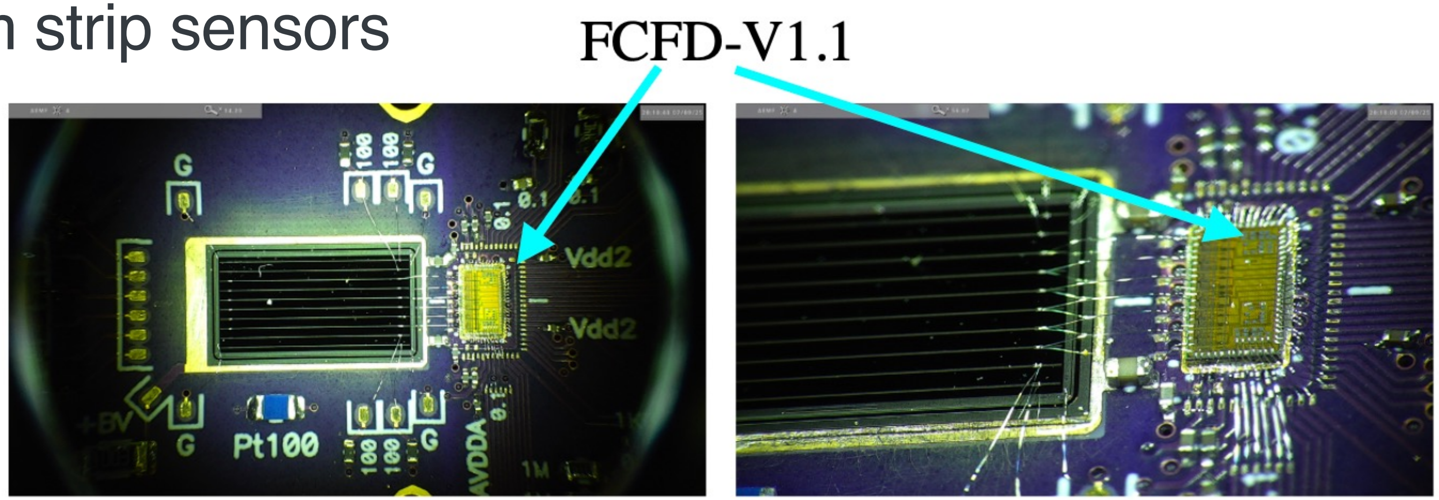
FCFD1.1



FCFD1.1 specifications

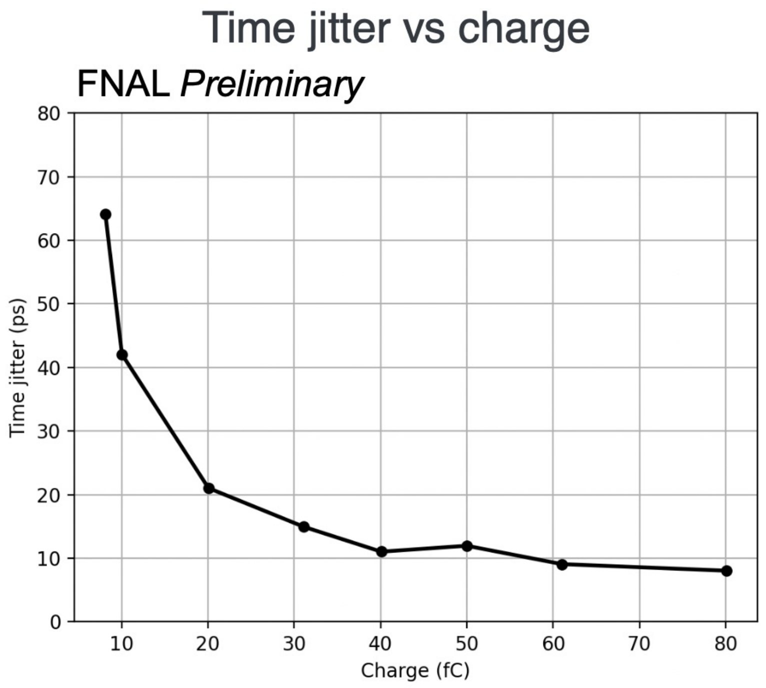
- **AC-LGAD sensors:**
  - Hamamatsu 1 cm long strips, 50 µm thick sensor
  - 500 µm pitch, 50 µm wide metal strips
  - Sheet resistance 1600 Ω/square
  - Dynamic range: 10 - 70 fC; signal MPV : 25 fC
  - Jitter at MPV : around 20 ps
- Chip **submitted on Feb 19, 2025,** received in **June 2025**.
- Wire-bonded to a HPK 1-cm strip sensors

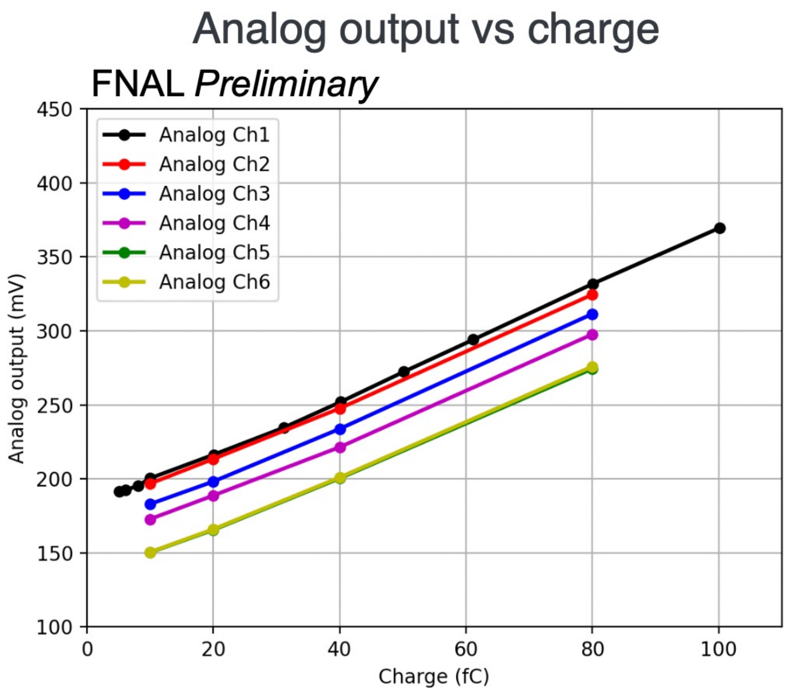




FCFD1.1 - Laboratory measurements

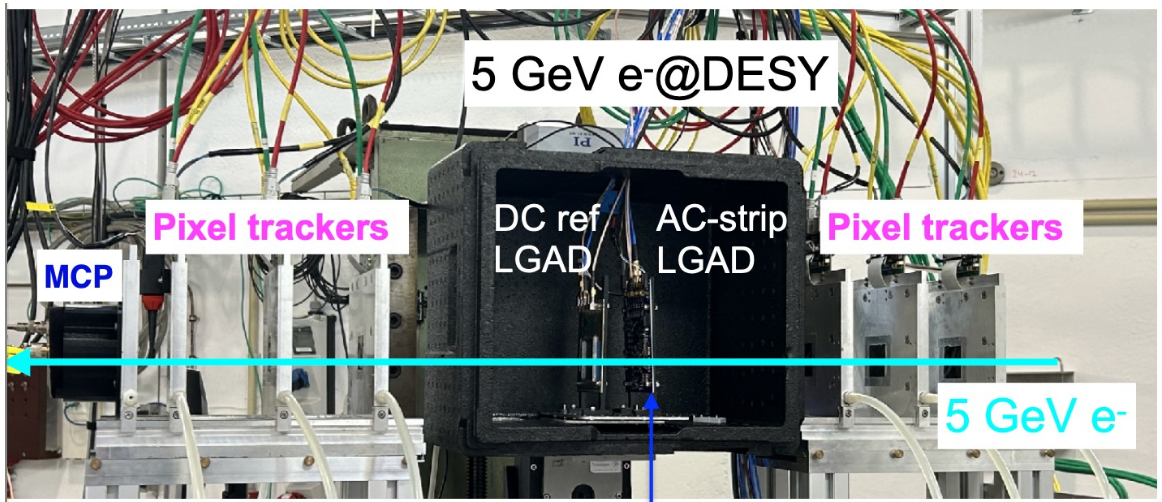
- Charge injection measurements:
  - Jitter measurements consistent with simulation and specs
  - Amplitude measurements: all channels behave as expected, linear in the range



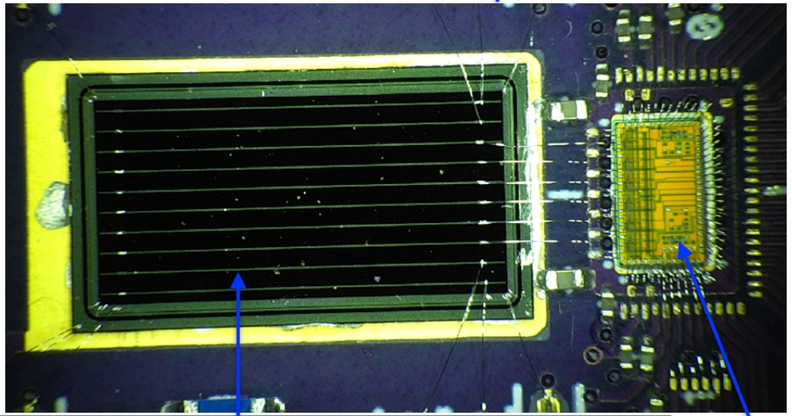


FCFD1.1 test beams in 2025

- 2 test beams in summer 2025 at DESY (5GeV e-) and CERN (120GeV p)



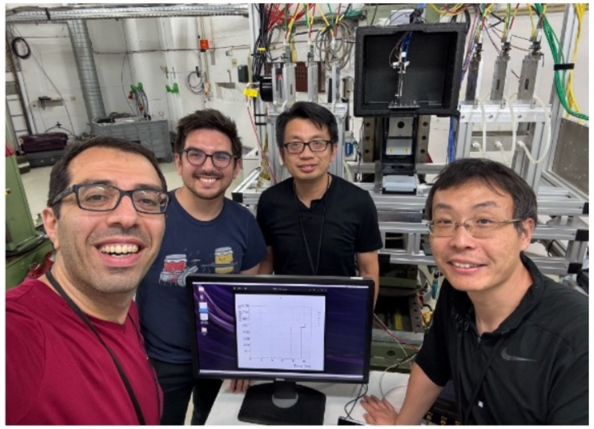
- Tracking with ~5 µm resolution
- Time reference detector with ~ 10 ps resolution (MCP)
- DAQ: high bandwidth, high ADC resolution 8-channel scope



1cm strips, 500um pitch, 50um metal electrode, 50um thick

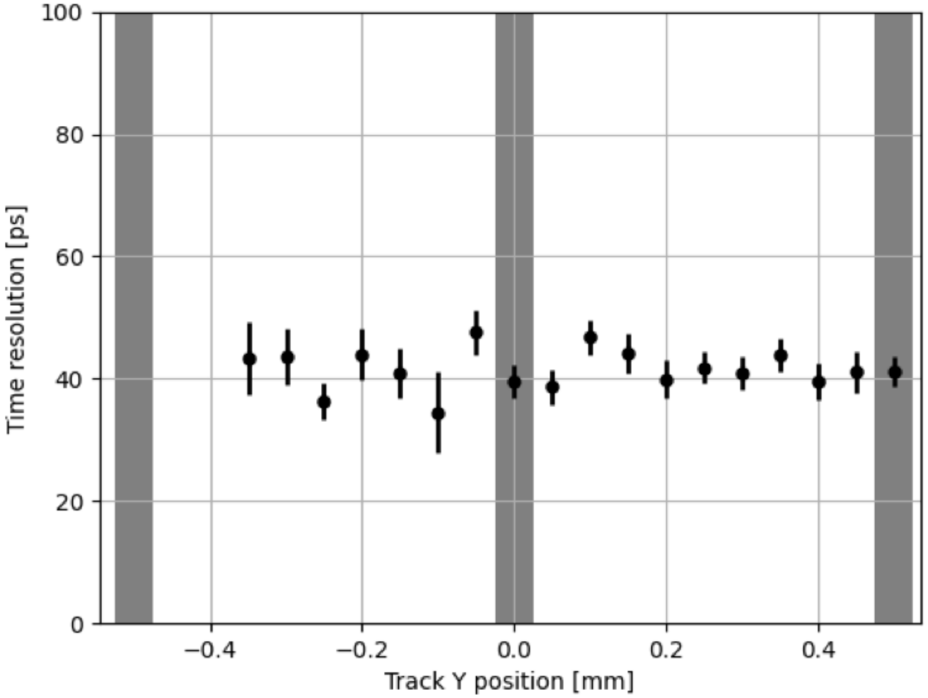
FCFD-V1.1

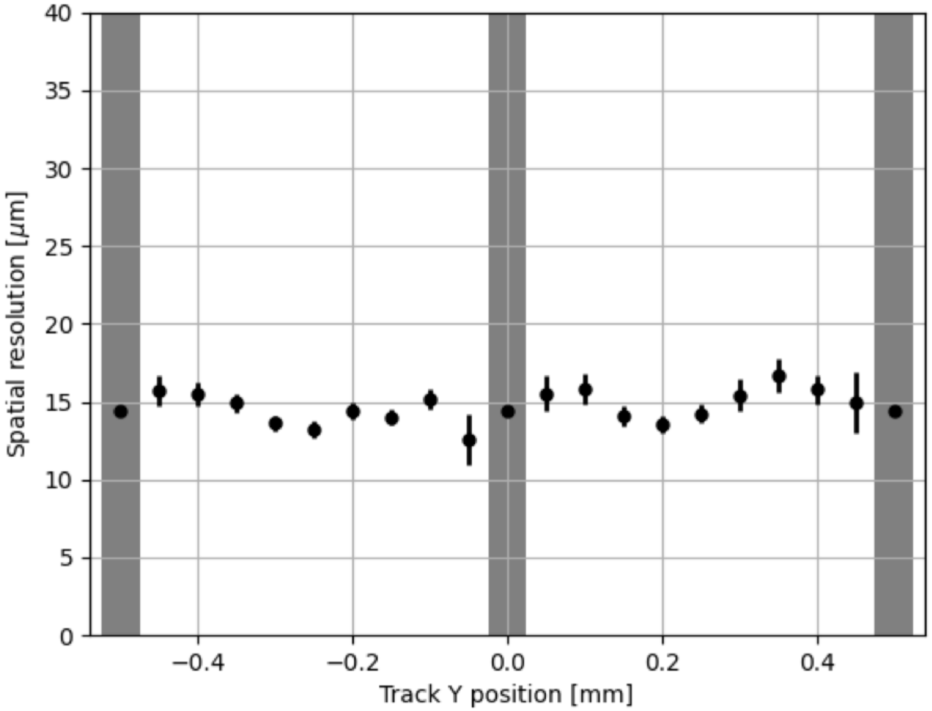
crew@DESY (July, 2025)



FCFD1.1 test beams in 2025

- Measurements of performance in DESY and CERN test beam
  - Measured **time resolution ~40 ps** across sensor surface
  - Measured **spatial resolution ~15-20 μm**
  - Fully efficient across the sensor surface





Sensor specifications for FCFD1.2

- **AC-LGAD sensors:**
  - Hamamatsu 1 cm long strips, 50 µm thick sensor
  - 500 µm pitch, 50 µm wide metal strips
  - Sheet resistance 1600 Ω/square
  - Dynamic range: 10 - 70 fC; signal MPV : 25 fC
  - Jitter at MPV : around 20 ps

Timing/Position Specifications for FCFD1.2

- Let's review the components that go into overall timing:
  - $\sigma_T^2 = \sigma_{LGAD}^2 + \sigma_{Internal\ Clock}^2 + \sigma_{System\ Clock}^2 + \sigma_{TDC}^2$

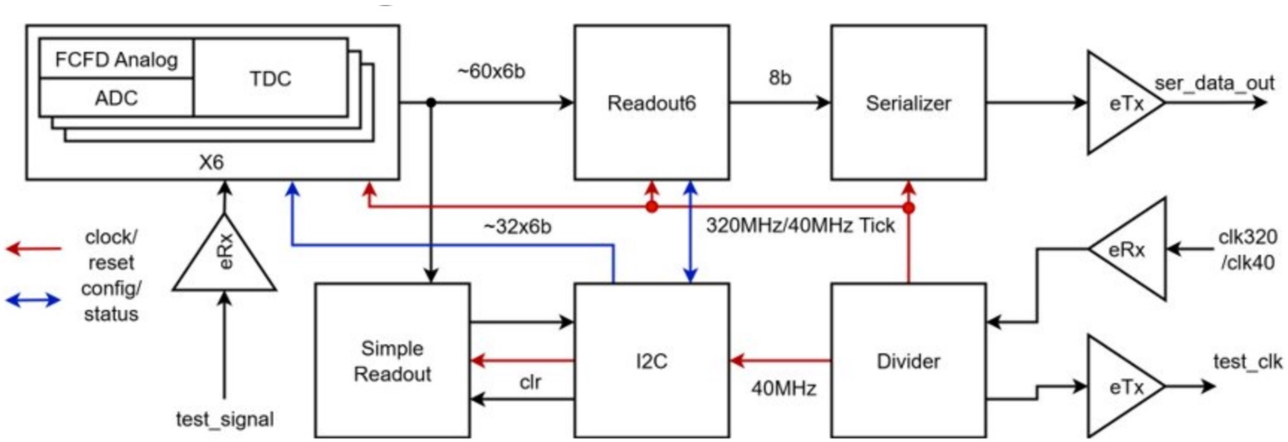
Component	Spec
σ_{LGAD}	~40 ps
$\sigma_{Internal\ Clock}$	< 10 ps
$\sigma_{System\ Clock}$	< 10 ps
σ_{TDC}	< 10 ps
Total	~ 45 ps

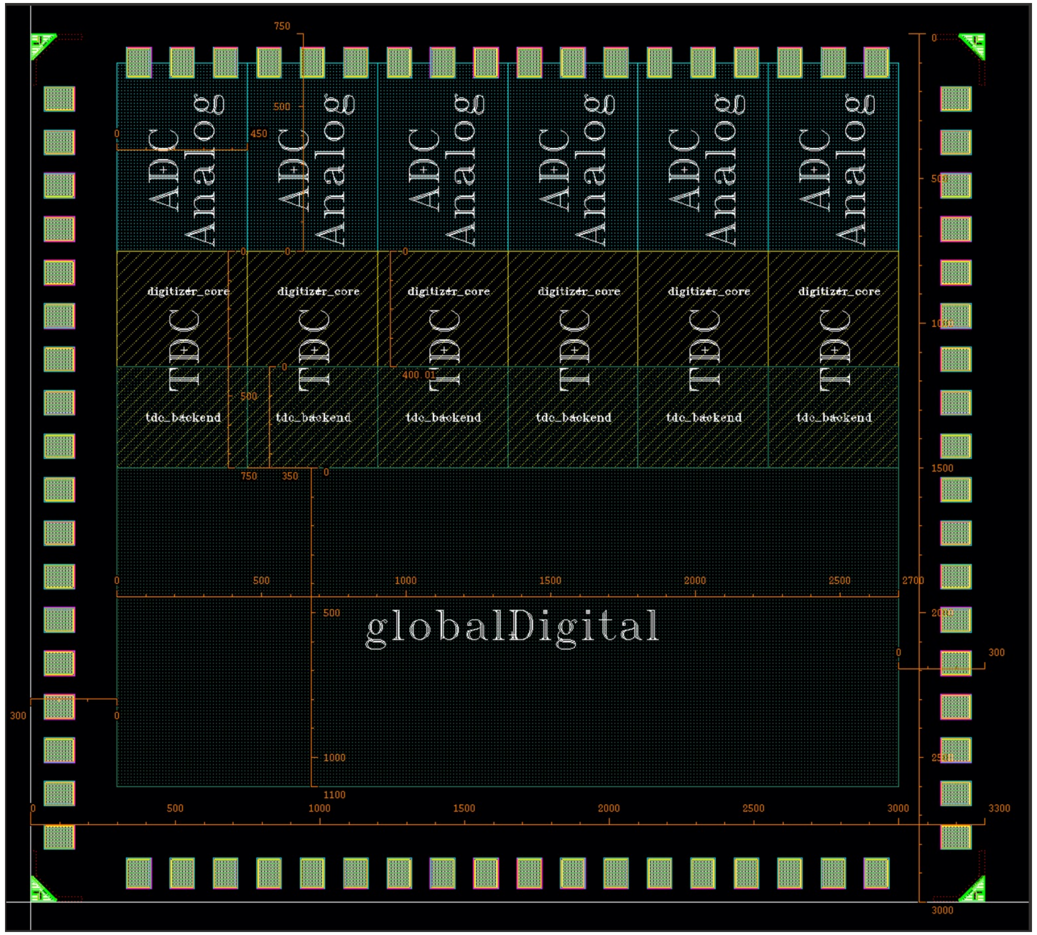
- Time resolution **$\sigma_T \sim$ 45 ps**

- Position resolution:
  - 30 µm in polar angle: **5-bit ADC for amplitude measurement**

FCFD1.2 status

- FCFD1.2 will implement TDC, ADC, I2C, and simplified readout on a 6-channel chip
- The whole team worked very hard through the holidays
  - All FCFDv1.2 RTL is completed now!
  - RTL is frozen now
  - Focus now on integration and verification
  - Tape-out in April on a mini@sic run





hpDIRC

- Signals are mostly one or two photon
- Signals on detector may vary due to gain variations and non-uniformity of the PMT

pfRICH

- Two groups of signals
  1. Single photons for Cherenkov ring imaging from aerogel
  2. Cherenkov hits from direct hits in the PMT window
- For category 1:
  - Single photon per pad: signal in ~ 10 pads per event per particle
  - Resolution about 30-40 ps for single photons
  - Gain may be 10^5 or 10^6, still need to be determined (Once the gain is selected, it will be the same for all devices)
  - The readout chip needs to handle gain variations of ~x2-3 due to MCP and field variations
- For category 2:
  - Localized within ~10 pads
  - Some pads will see signal an order of magnitude higher than Category 1

Specifications for pfRICH and hpDIRC

Detector	Channel Capacitance	Channel Rate	Time Resolution	Time Measurement Dynamic Range	Charge Measurement Dynamic Range	Charge Measurement Resolution
pfRICH	~10 pF	~10 kHz	~40 ps @ 100 fC	100-1,200 fC	100-10,000 fC	**TBD**
hpDIRC	~10 pF	~10 kHz	~40 ps @ 100 fC	100-1,200 fC	100-1,200 fC	**TBD**

- Assumptions that went into this table
  - Gain of 10^5 corresponds to 16 fC
  - pfRICH region of operation defined with RED arrow below.
  - Low end of 100 fC to account for ***x3*** gain variations
- We circulated the above proposal to the detector experts
  - Next steps would be to test with the upcoming prototypes and see how well the CFD approach works for these detectors
  - Modified version will be needed to accommodate for MCP signals

Applications for pfRICH and hpDIRC

- Copies of the FCFD1.1 were provided to be tested with HRPPD sensors
  - Would be great to get feedback on the testing and application
  - We will start working on the design of the FCFD1.2 variant, having results from these tests will be crucial to define the specs for the chip

Backup

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