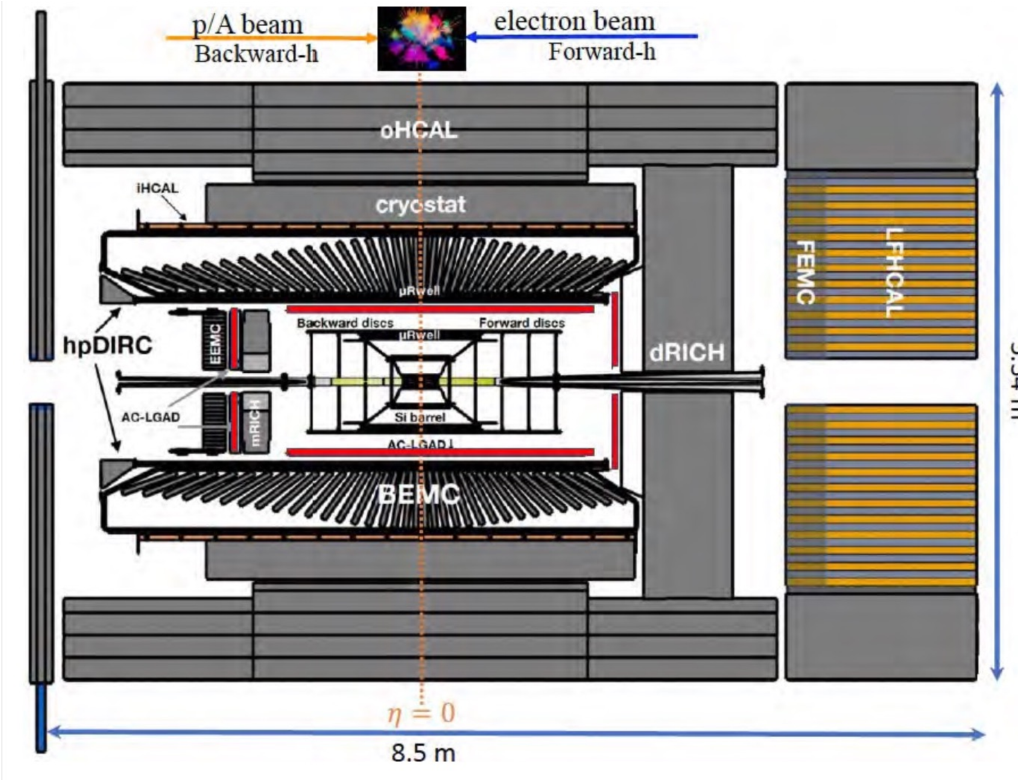
The FCFD ASIC for Detectors with AC-LGAD Strips

Artur Apresyan

EIC PDR for Electronics & DAQ

Timing for barrel Time-of-Flight detector



- Focus of this talk is on the development of the readout ASIC for the barrel section of the TOF
- Design is based on AC-LGAD sensors with 500 um pitch

Constant Fraction Discriminator ASIC (FCFD)

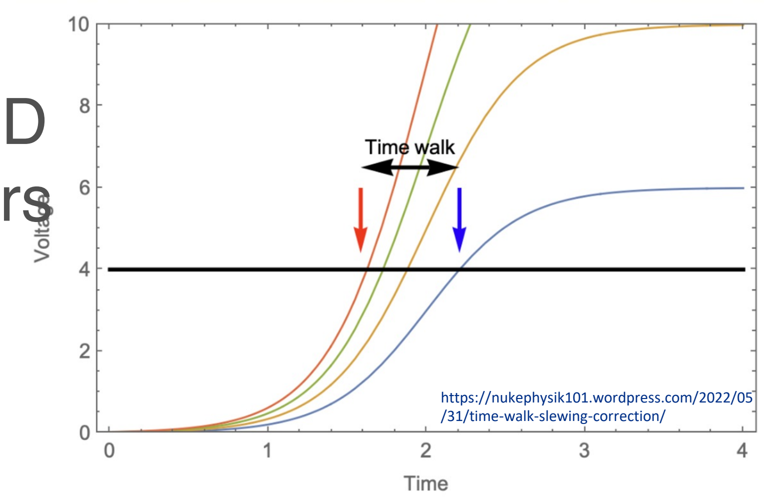
- A robust fast-timing measurement technique for LGADs
  - Easy to use and stable: no corrections, or calibrations and threshold adjustments
- CFD approach achieves better performance, especially for low S/N systems, such as LGADs **(NIM A 940 (2019), pp 119-124)**
  - CFD offers significant reduction 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…
- Power consumption for analog front-end LE and CFD comparable
  - Consumption for the digital parts is expected to be low, completed blocks exist

FCFD development history

- The first (FCFDv0) version was designed, produced and tested with DC-LGAD sensors
  - Developed in TSMC 65 nm technology node
  - Excellent performance demonstrated with charge injection, laser and beta source
- The next version (FCFDv1) was optimized with EIC sensor specifications
  - In close collaboration with the EIC detector experts and AC-LGAD developers
  - Specifications for sensors: 1 cm long AC-LGAD, 500 um pitch, 50 um thickness. Estimated capacitance ~5-10 pF

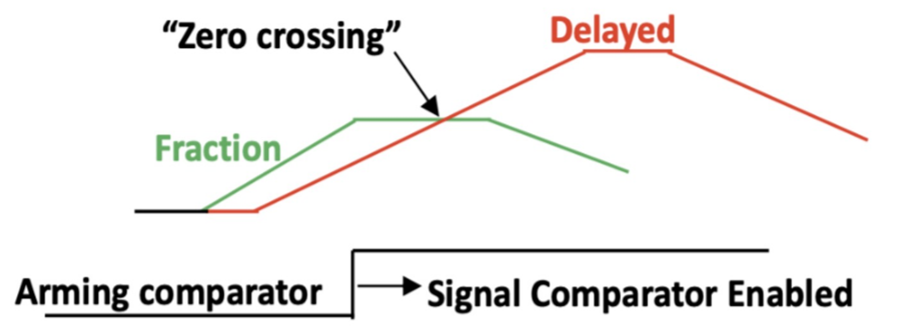
FCFD Readout for Timing Detectors

- 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



Fermilab CFD Chip Design

- 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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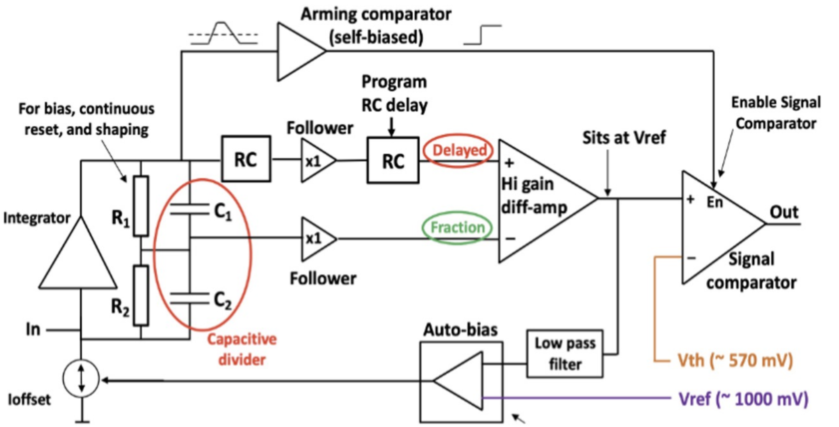

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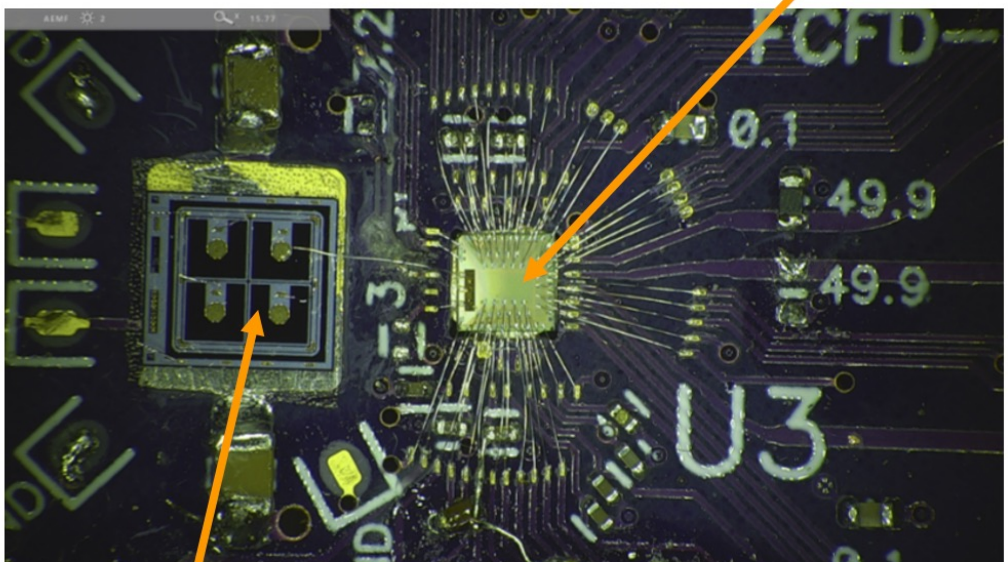
FCFD Chip Prototype v0

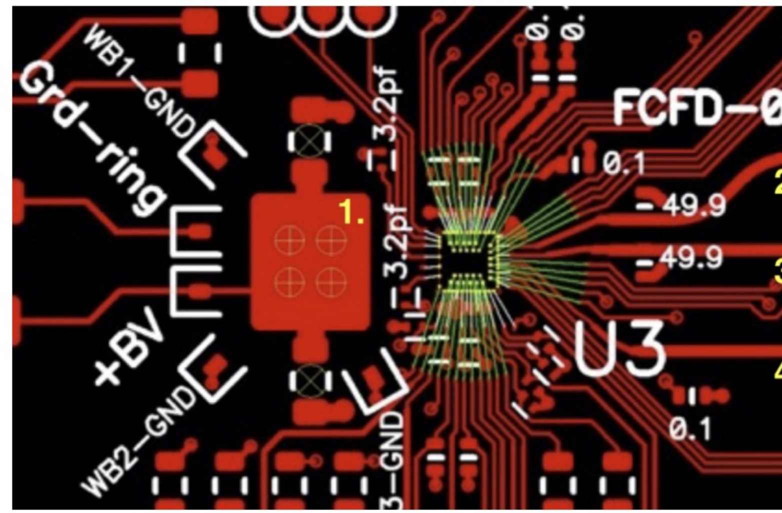
- First prototype designed and fabricated in 2021 & tested in 2022

FCFDv0 ASIC



LGAD Sensor

Schematic Diagram



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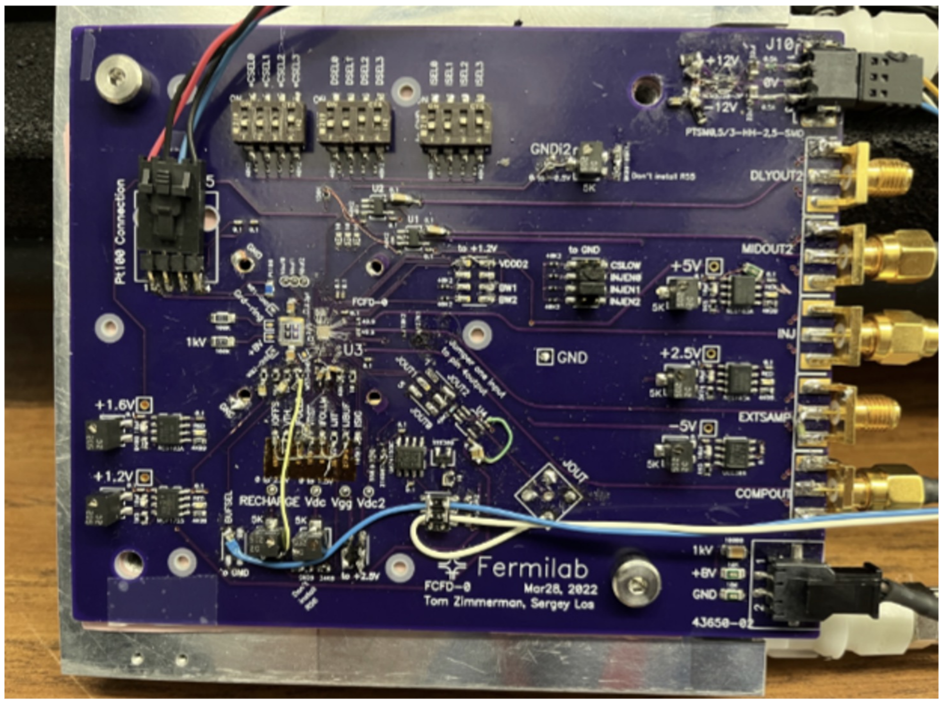


- Full test-board
- Key testing features:
  - Internal charge injection with 3-26 fC dynamic range
- Switch to enable spy on analog signal

Multi-Source Signal Testing Setup

- FCFD v0 performance evaluated using multiple types of signals:
  - Charge-injected signal
  - Picosecond Laser signal
  - Radioactive Source signal
  - Proton Beam signal

Charge Injection

- Inject range of signal sizes from 3-26 fC using built-in mechanism
- Time reference is clock signal used to trigger internal charge injection
- Injected waveforms are based on LGAD signals from simulation (confirmed by past measurements)
- Output waveforms look like this:
  - Spy waveform is small fractional copy of original signal
  - Discriminator waveform is CFD output and used for time-stamping

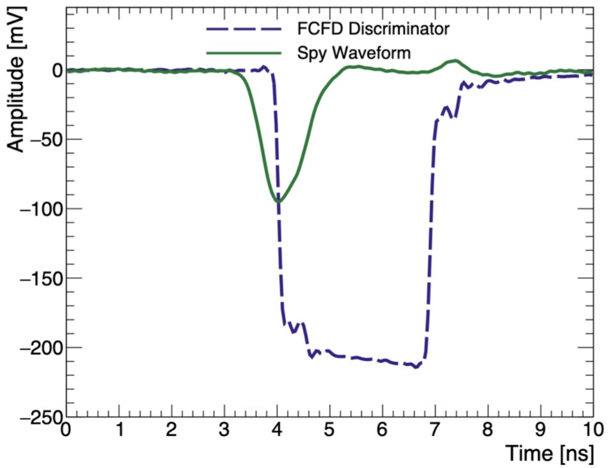
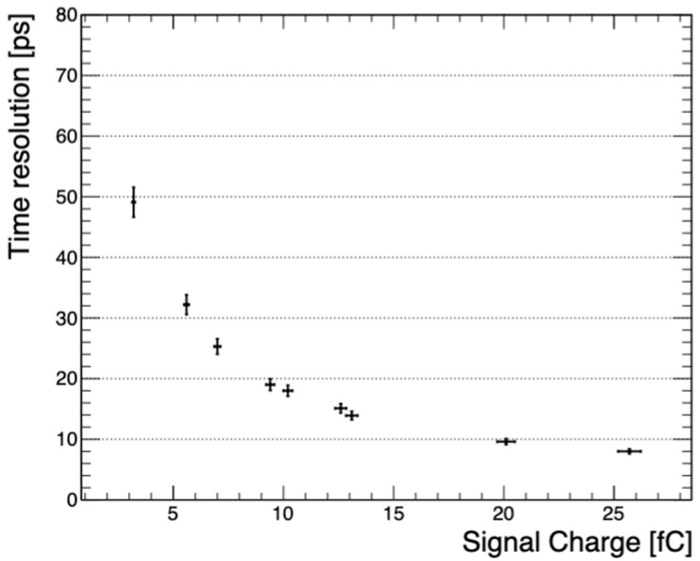
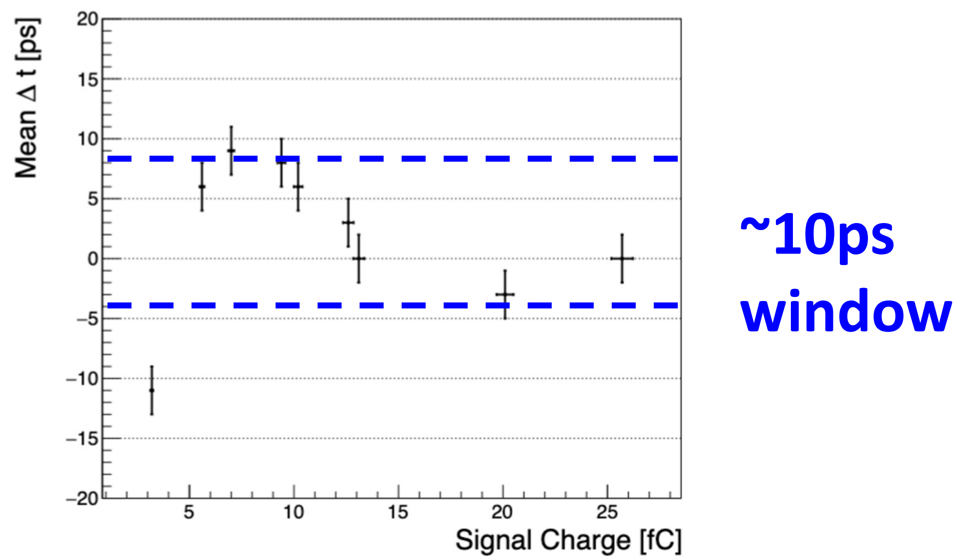


Figure 9: Candidate waveforms of the FCFDv0 discriminator output (blue) and the FCFDv0 input signal spy (green).

Charge Injection

- Time resolution performance as expected
- For largest signal (before saturation) get ~8ps time resolution
- Time walk effect is reduced from 100s of ps to a ~10ps window





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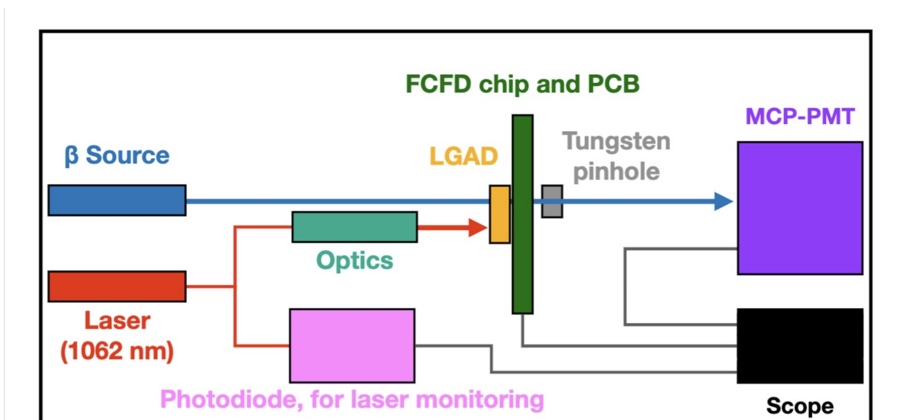
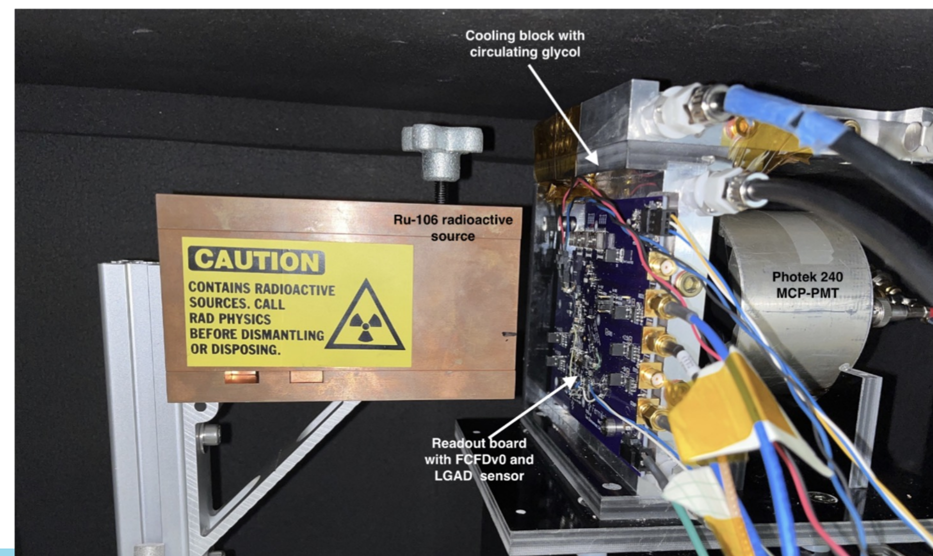
Picosecond Laser & Beta Source Setup

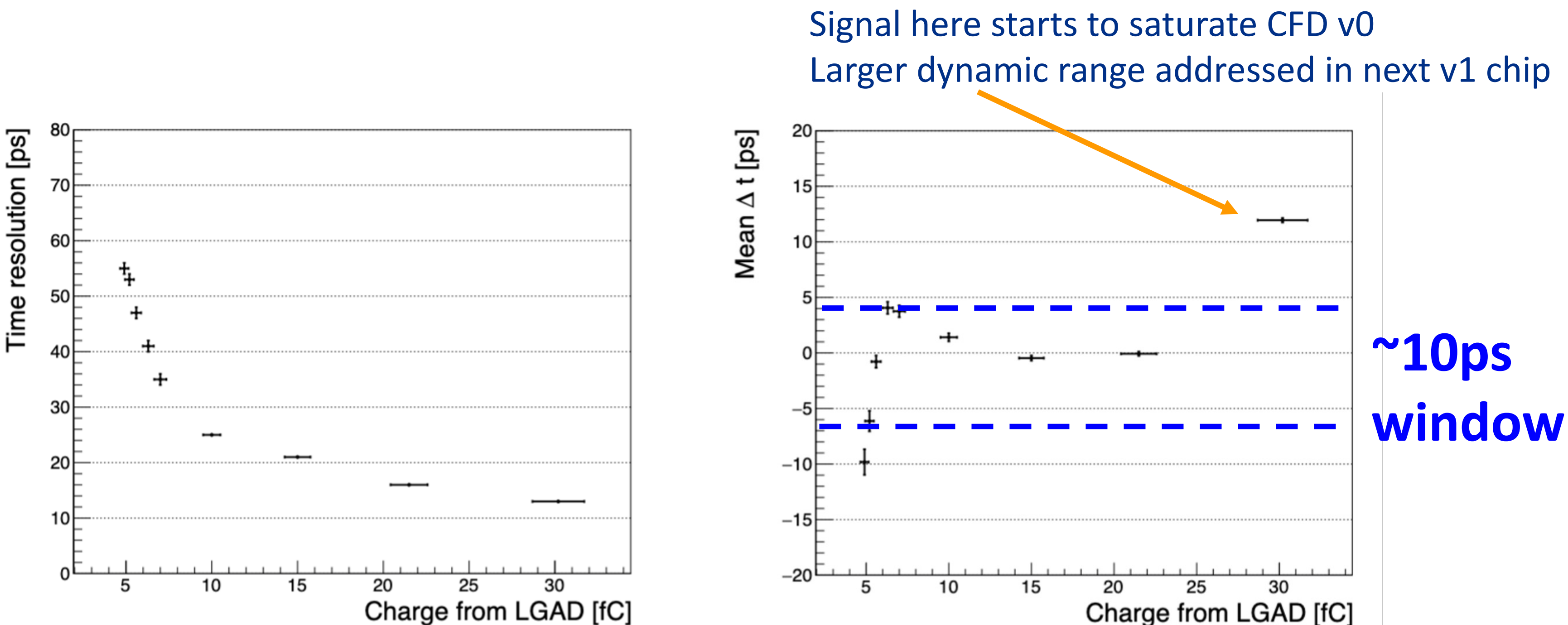
- Dark box with motorized stages, enabling laser injection and beta source
- Picosecond Laser trigger signal serves as time reference
- Collimator and MCP time reference detector ensures straight trajectories: get beta rates of about 2-3Hz at best alignment
- Temperature maintained at 20C by chiller and cooling block





Picosecond Laser Measurements

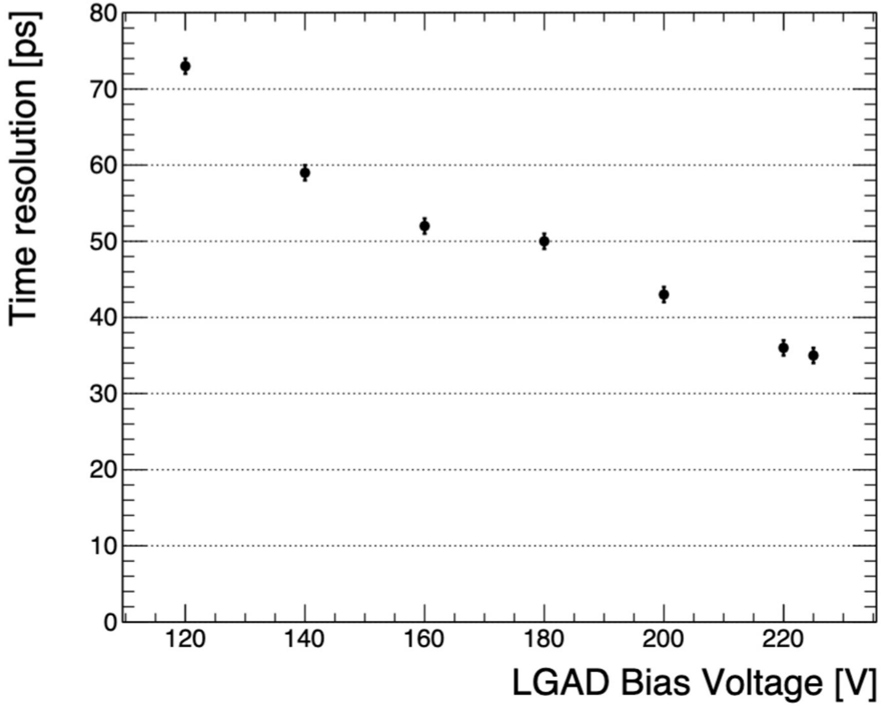
- Laser measurements confirm similar performance as charge injection



Beta Source Measurements

- Similar performance is also confirmed with beta source

- The measured time resolution is consistent with a 8-10 ps contribution from the CFD chip, accounting for time jitter of LGAD sensor itself and imperfect collimator,



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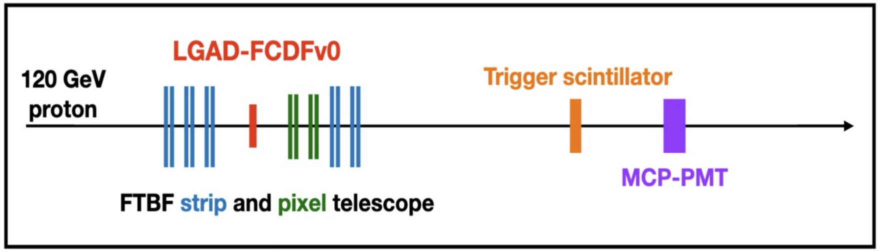
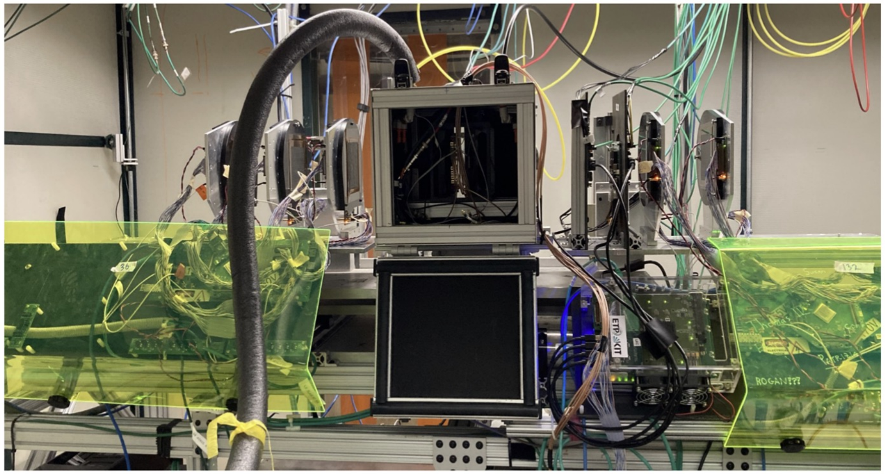
Proton Beam Measurements

- Use Fermilab Testbeam Facility to test CFD chip with 120 GeV protons

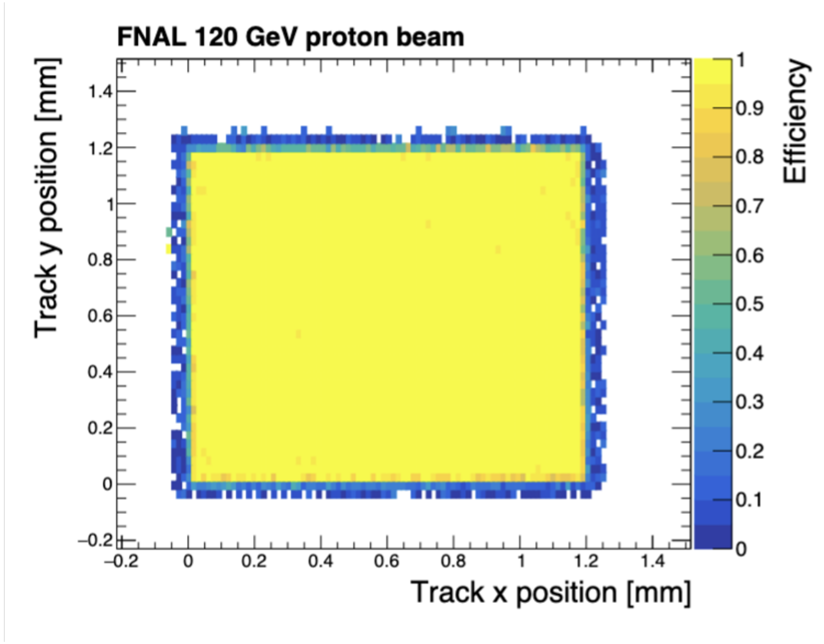
- MCP-PMT used as time reference detector
- Temperature maintained at 20C
- Tracking telescope used to measure hit positions and efficiency

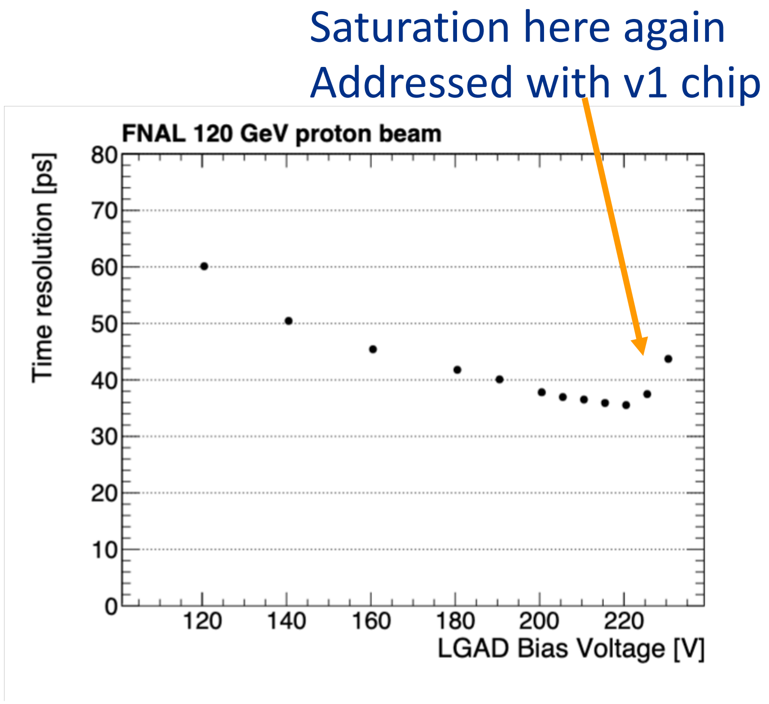




Proton Beam Measurements

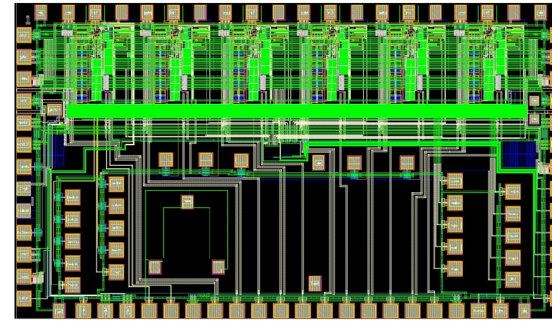
- 100% Efficiency is maintained over full LGAD pixel sensor area
- Time resolution performance consistent with Beta Source measurement

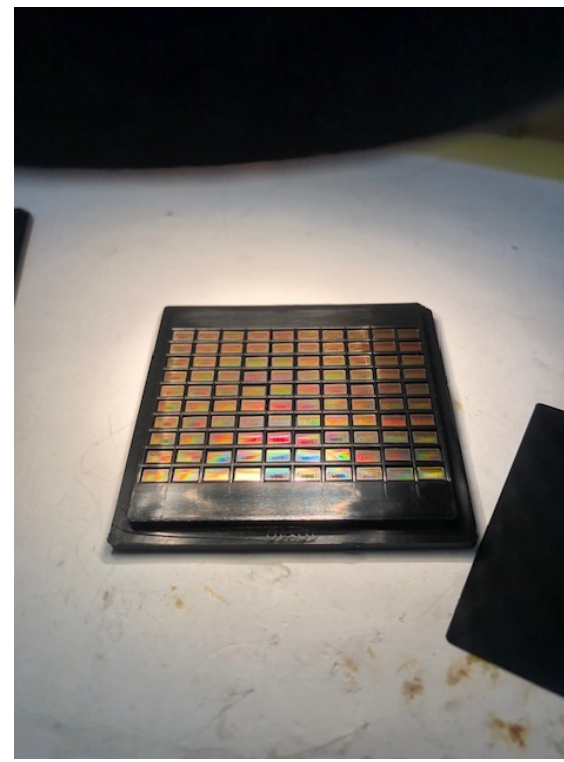




FCFDv1 status

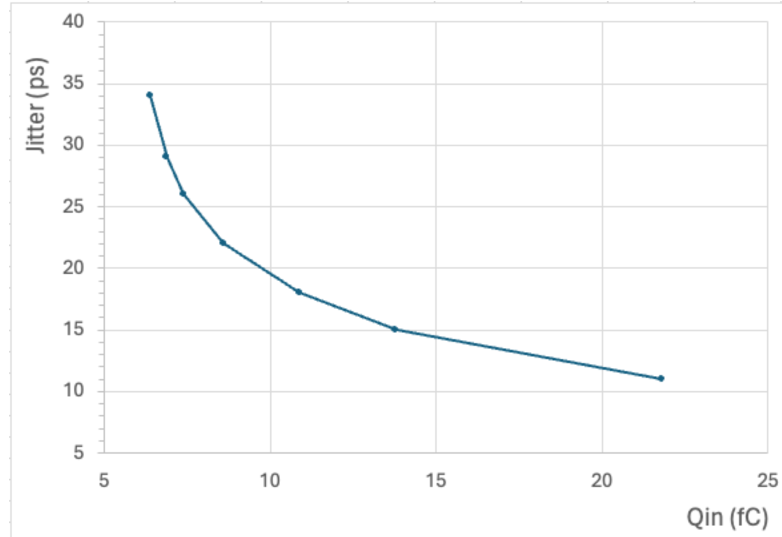
- Six-channel FCFDv1 submitted Sep. 2023
  - Wider dynamic range,
  - Sensitivity to smaller signals
  - Includes signal amplitude measurement for position measurement
- Received the chip back from TSMC in Jan 2024
  - Testing on bench started immediately
  - Preparations for test beam in Spring 2024





Status and Next plans

- FCFDv1 chip is now being tested
  - Measurements with internal charge injections performed with an LGAD-like signal being injected.
  - With input capacitance ~3.5 pF we achieve around 11 ps time resolution
  - The analog output works linearly over the range of input charge from 7 fC to 60 fC, the discriminator flip time output stays constant within around 10 pS

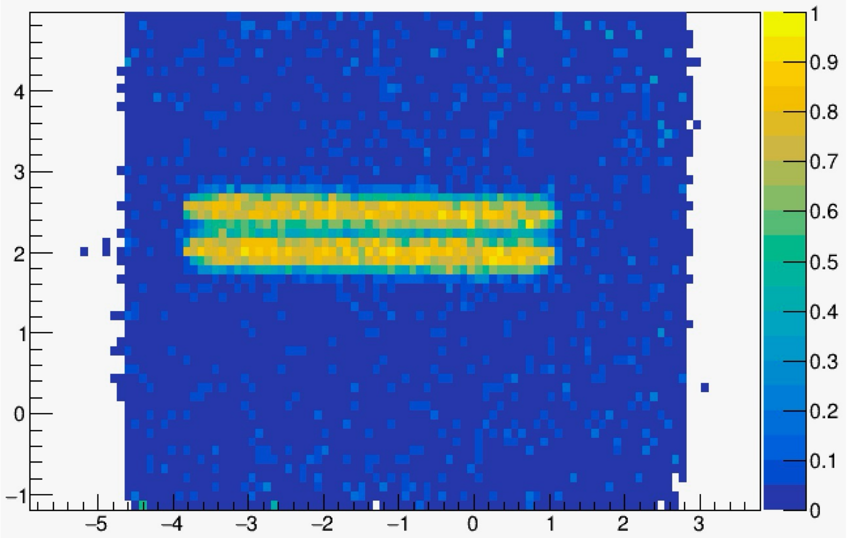


Jitter measurements with 3.5 pf input capacitance and charge injection

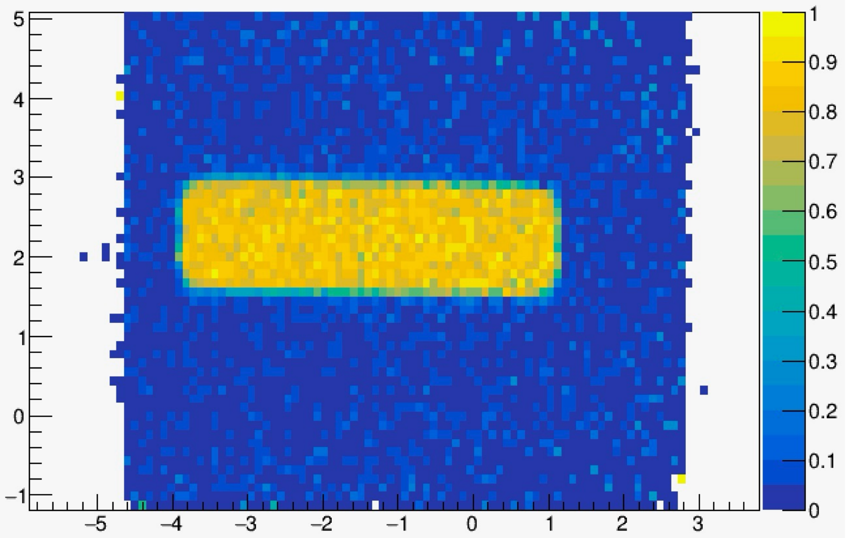
- Our measurements of the AC-LGAD strip sensors showed the complex CR-network which complicates operation of the ASIC
  - Additionally, the capacitance for some of the sensors is a lot larger than we originally specified
  - Hamamatsu 5 mm E-type strip sensors behave the best so far, and we have adapted the readout board for this sensor

FCFDv1 test beam results

- Testing in the Fermilab beam this week
  - Connected to a 5 mm strip AC-LGAD sensor, 500 µm pitch, 50 µm thickness
  - Main goals to measure timing and position resolution with particles
- Optimizing the readout board grounding, power supplies, noise
  - Two-strip efficiency demonstrated to be 100%
  - Continuing the characterization of the ASIC and timing performance, results soon



Efficiency with 2-strip



Two-strip efficiency

Development plans in 2024 and 2025

- Complete the testing of FCFDv1
  - Characterize the system performance for timing and position measurements using AC-LGAD strip-sensors
  - Initial tests showed new features of AC-LGAD sensors that impact performance
  - Would like to re-optimize the chip with the final-spec AC-LGAD parameters as tested with FCFDv1 version, for a minor revision FCFDv1.1
- Next focus on the full chip: full-size FCFD v2
  - Finalize the geometry and sensor key parameters (strip length, sheet resistance and thickness)
  - Complete ASIC with readout that would interface with the EIC experimental DAQ
  - Implement the interfaces with RDO, comments on rad-hardness and power consumption
- The final ASIC to be produced and tested during FY25

Summary