Beam test results of the pixel-readout beam-particle monitor for the CSR external-target experiment

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Outline

1 Introduction

2 Beam-particle monitor of CEE

3 Readout electronics & Topmetal-CEEv2 ASIC

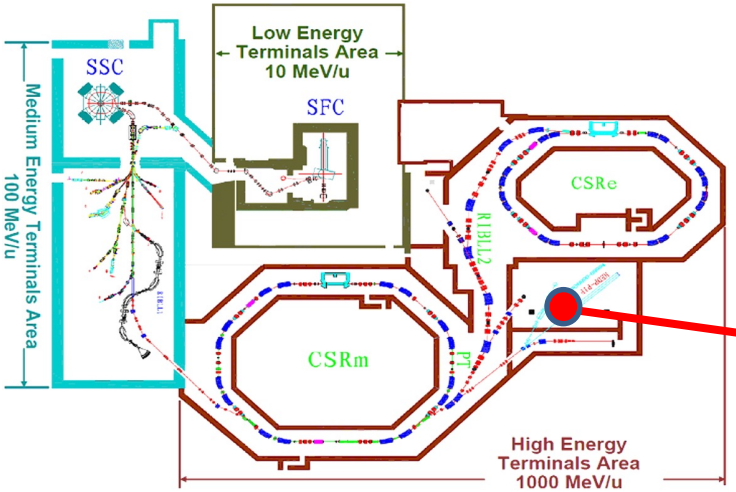
4 Beam-test results

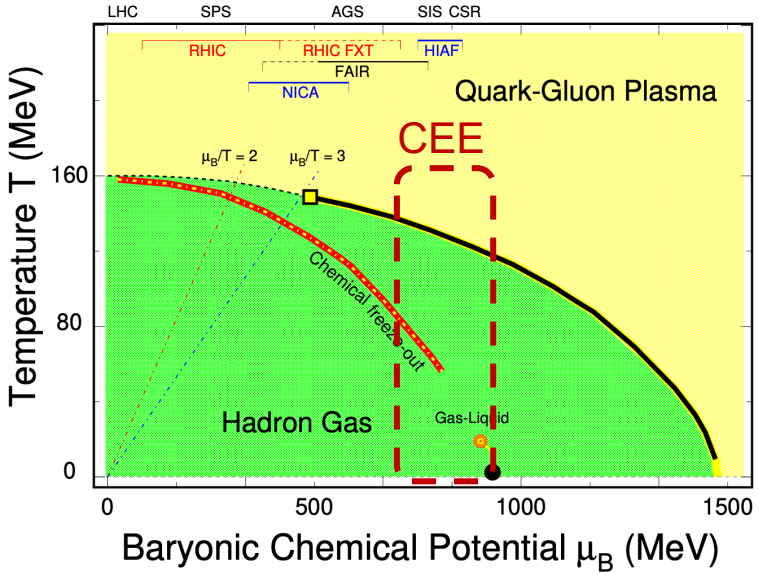
5 Summary & outlook

CEE at HIRFL-CSR

Heavy Ion Research Facility in Lanzhou

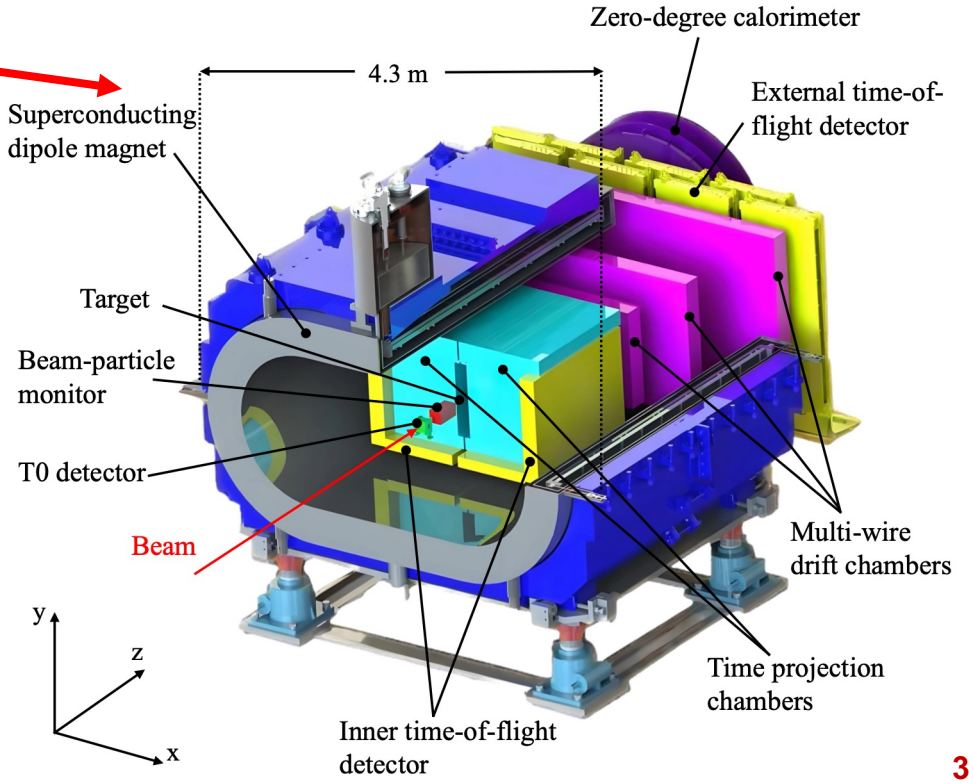
Cooler-Storage-Ring system





CSR External-target Experiment

- Study nuclear matter at high baryon density
- Fixed target, heavy-ion beam (up to U)
- Beam energy ~0.4 – 1.1 GeV/u
- Maximum event rate ~10^4 s^{-1}
- Commissioning planned for 2027

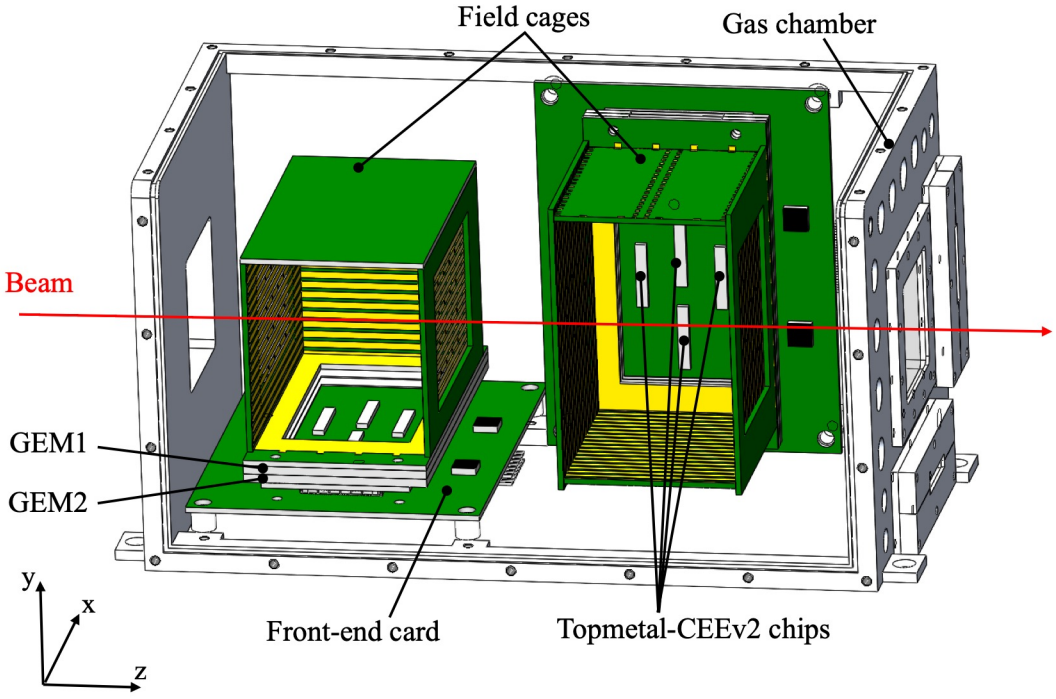


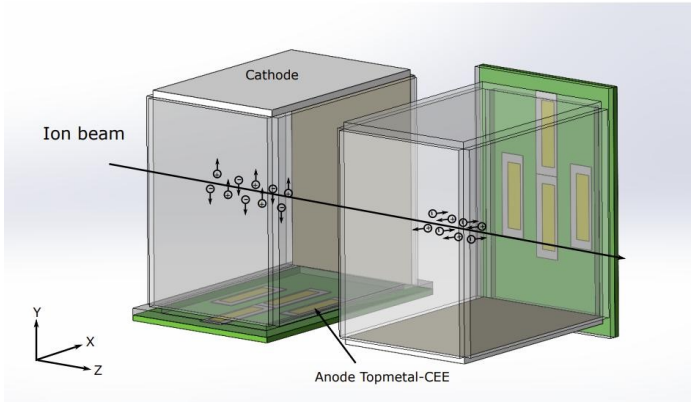
Beam-particle monitor of CEE

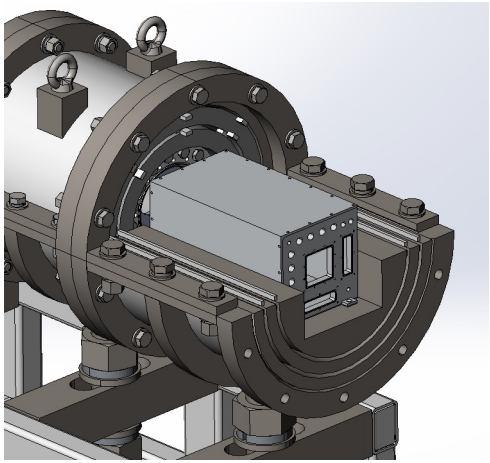
Placed upstream of the fixed target in a magnetic shield
- Overall size: 12 × 12 × 21 cm^3
- Measure the position and time of each beam particle
- Offline: primary-vertex reconstruction (with TPC & MWDC)
- Online: beam-status monitoring

Main design targets:
- Position resolution: <50 μm
- Time resolution: <1 μs
- Maximum event rate: ~1 MHz
- Sensitive area: ~ 3×3 cm^2

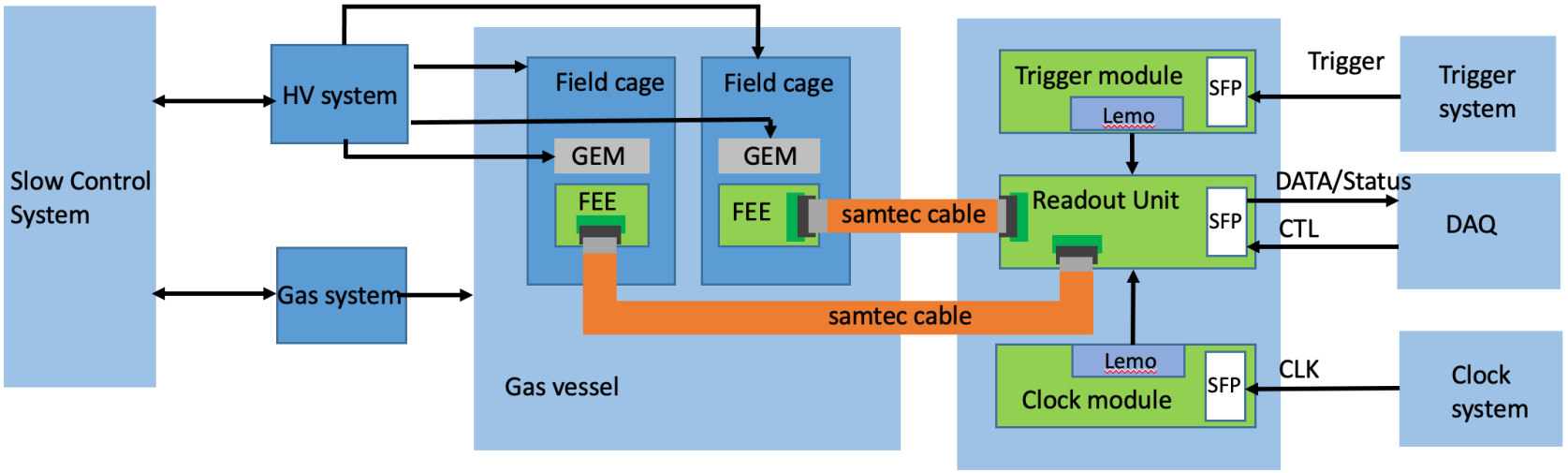
Two orthogonal GEM micro-TPCs provide X, Y, and drift-corrected (t0) reconstruction.

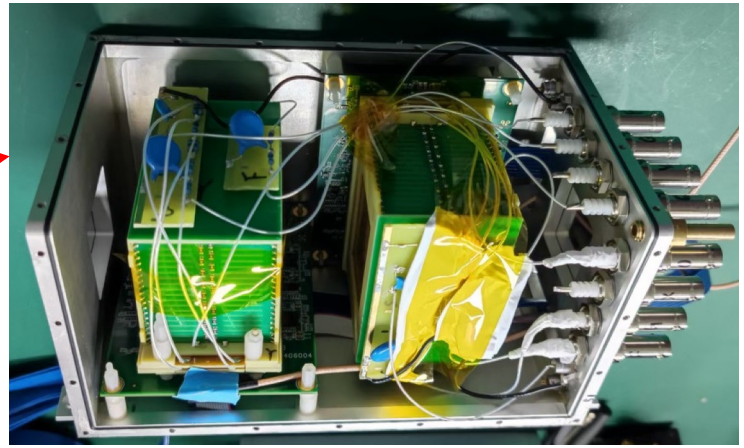






Detector system





Readout electronics

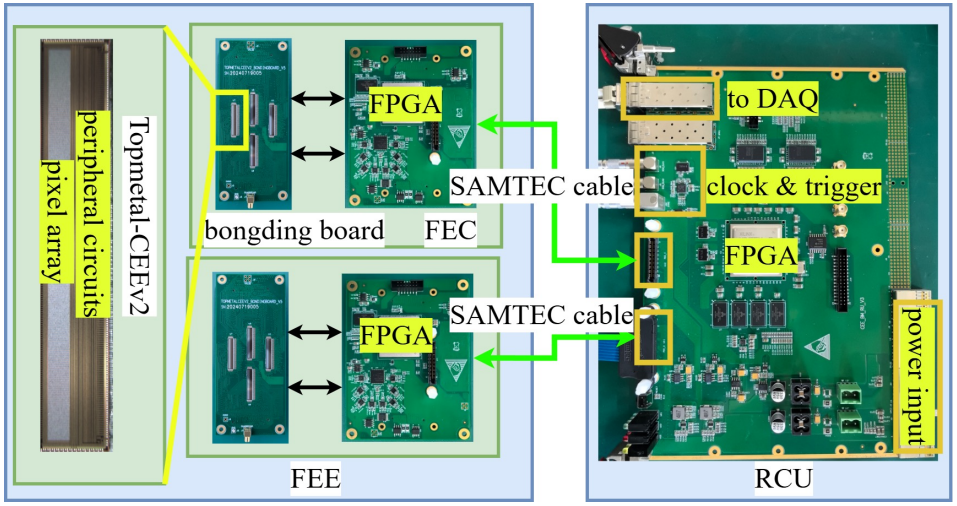
Data-rate

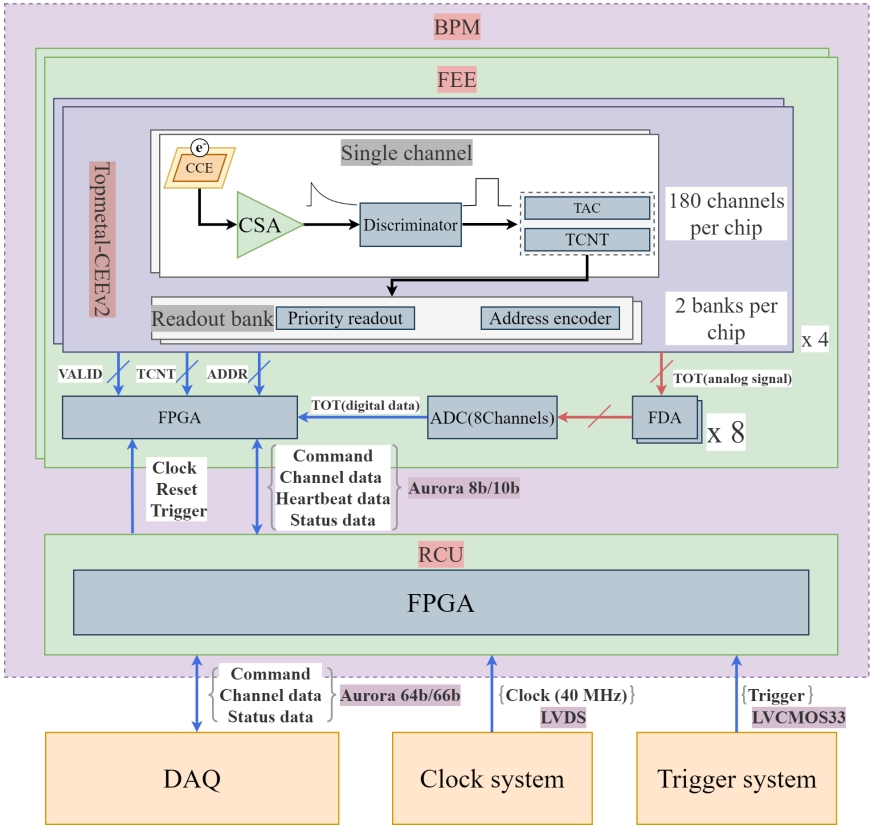
One FEE at 1 MHz particle rate:

· Continuous/raw upper-bound estimate: 30 hit pixels / particle / plane × 1 MHz × 8 bytes / pixel = 1.92 Gbps.

· Triggered scientific-data mode: average payload is reduced by the trigger-window factor ($R_{trigger} \times T_{window}$).

FEE → RCU: max. 3.2 Gbps (4.0 Gbps line rate with 8b/10b encoding).



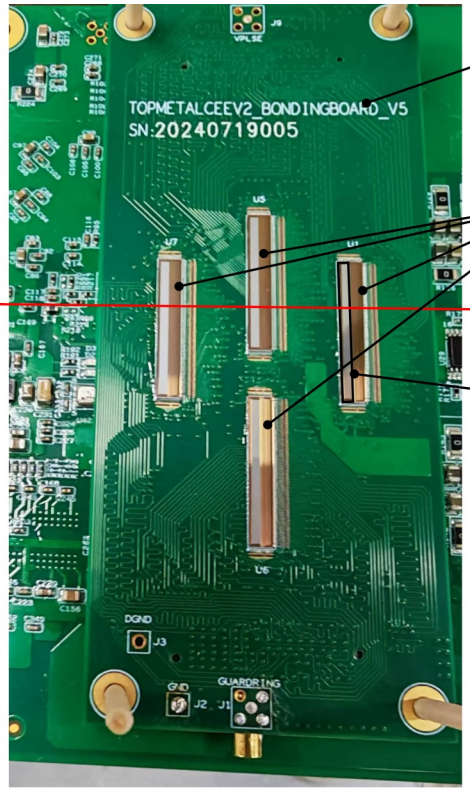


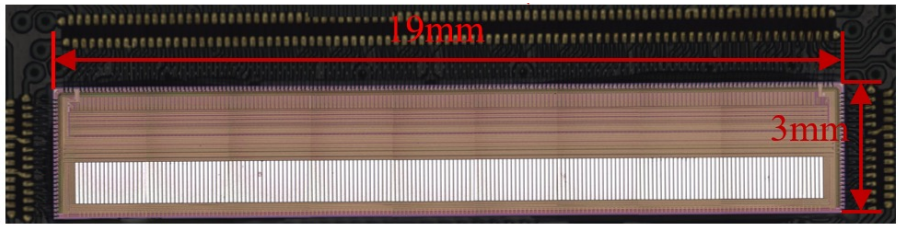
Topmetal-CEEv2 ASIC

130 nm CMOS · 180 × 1 pixels · 100 μm pitch
18 × 1 mm² active area; exposed top-metal charge-collection electrode.

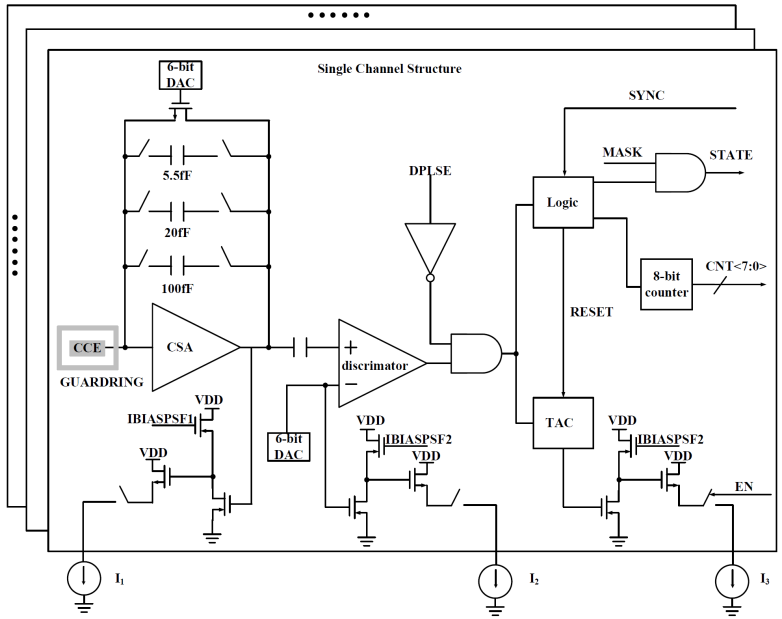
The main characteristics of the Topmetal-CEEv2 chip.

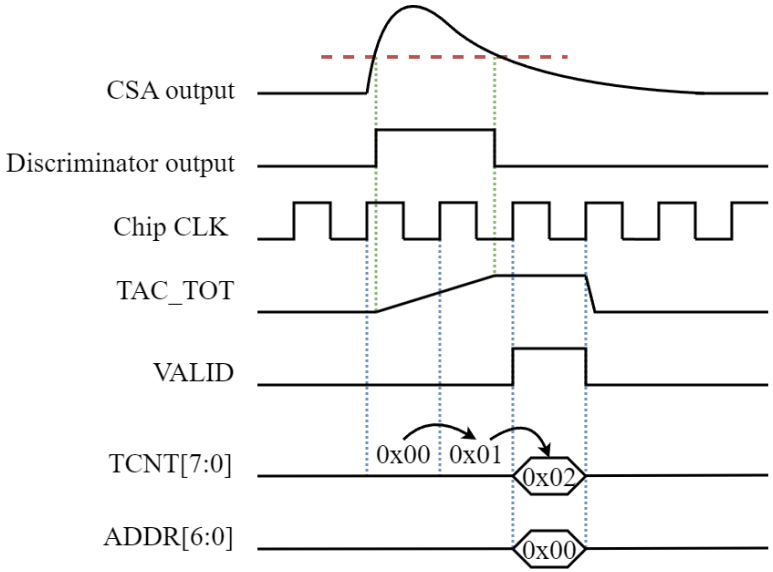
Technology	130 nm CMOS
Chip area	19 × 3 mm^2
Sensitive area	18 × 1 mm^2
No. of pixels	180 × 1
CCE size	89 μm ×1 mm
CCE pitch	100 μm
Equivalent noise charge	< 400 e^-
Min. threshold	~ 5000 e^-
Shaping time	~ 0.5 μs to 2 ms
Readout scheme	Data-driven zero-suppressed
Readout speed	Max. 40 MPixels/s
Readout	Pixel address, charge (TOT) and time (TOA)





Topmetal-CEEv2 — pixel circuitry





Per-pixel signal chain

1. Charge-collection electrode (CCE)
   collects drifting ionization electrons

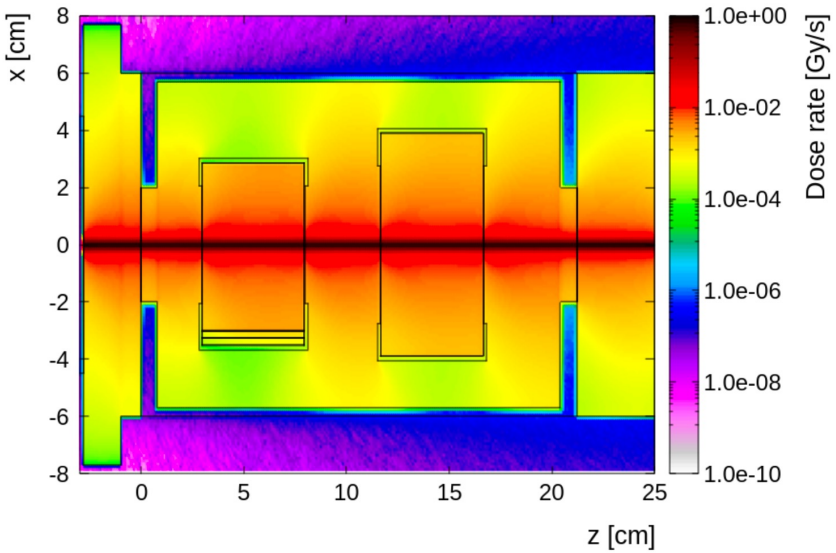
2. Charge-sensitive amplifier (CSA)
   selectable feedback C: 5.5, 20, 100 fF

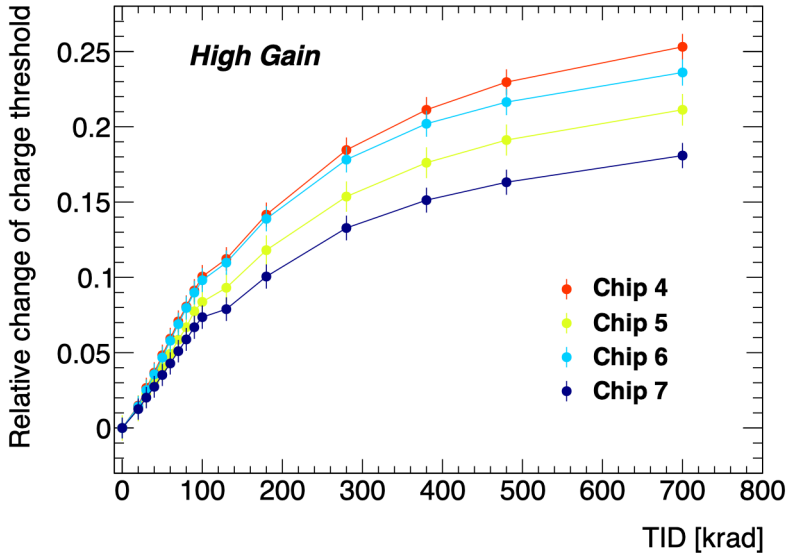
3. Discriminator + local 6-bit DAC
   sets the pixel threshold

4. Time/charge measurement
   TOA + TOT-based charge measurement

5. Priority readout
   sends address, charge and time only for hits

Topmetal-CEEv2 — irradiation performance





	TID [kGy]		1-MeV-neq [$\times 10^{11}$ cm^{-2}]		>20 MeV had. [kHz/cm^2]	
	First cage	Second cage	First cage	Second cage	First cage	Second cage
Nominal setup	5.699 ± 0.002	7.409 ± 0.002	0.959 ± 0.002	1.541 ± 0.004	0.592 ± 0.009	1.919 ± 0.018
With shielding	5.732 ± 0.002	7.194 ± 0.002	0.981 ± 0.003	1.538 ± 0.004	0.565 ± 0.009	1.803 ± 0.018
Cage with less material	1.655 ± 0.001	1.560 ± 0.001	0.275 ± 0.001	0.299 ± 0.001	0.342 ± 0.004	0.686 ± 0.007
0 GEM layer	13.731 ± 0.003	16.272 ± 0.003	1.540 ± 0.003	2.324 ± 0.004	0.615 ± 0.009	1.962 ± 0.018
1 GEM layer	8.098 ± 0.002	10.138 ± 0.003	1.183 ± 0.003	1.861 ± 0.004	0.591 ± 0.009	1.946 ± 0.018
Beam FWHM = 1 mm	5.696 ± 0.002	7.409 ± 0.002	0.944 ± 0.002	1.520 ± 0.004	0.536 ± 0.009	1.741 ± 0.017
Beam FWHM = 4 mm	5.704 ± 0.002	7.407 ± 0.002	0.959 ± 0.003	1.544 ± 0.004	0.594 ± 0.009	1.935 ± 0.018
Beam FWHM = 6 mm	5.712 ± 0.002	7.406 ± 0.002	0.962 ± 0.003	1.554 ± 0.004	0.612 ± 0.009	1.973 ± 0.018
BM position	5.434 ± 0.002	7.388 ± 0.002	0.985 ± 0.003	1.616 ± 0.004	1.194 ± 0.015	2.492 ± 0.022

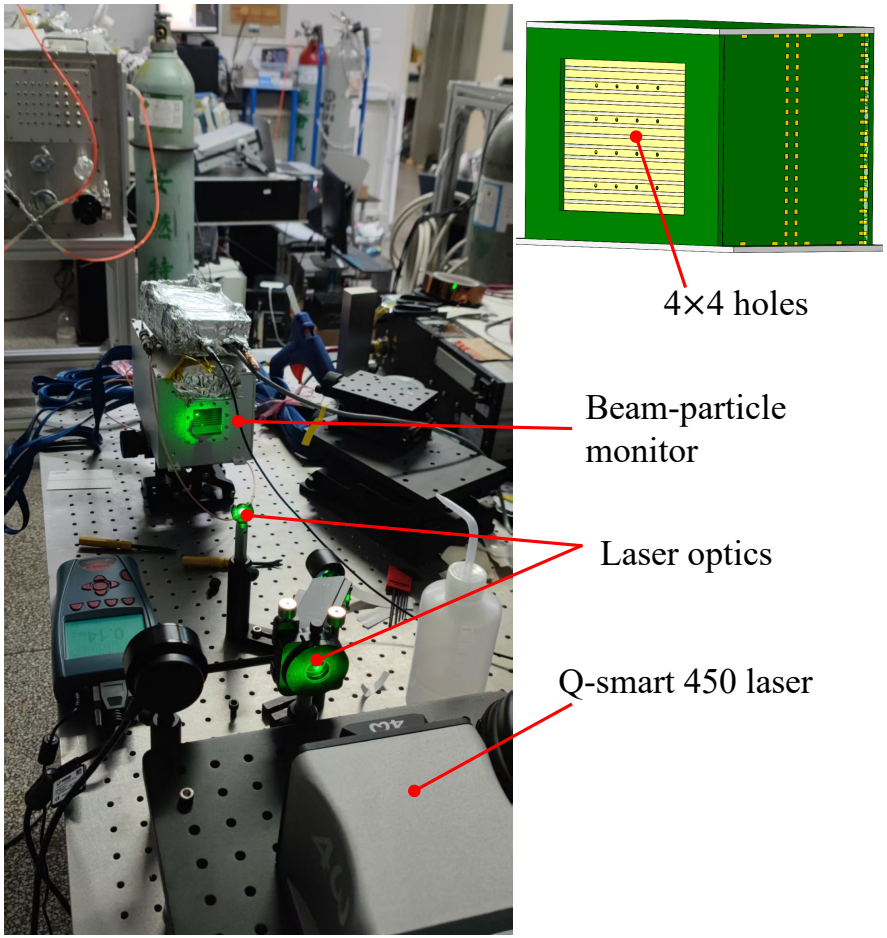
TID test: up to 700 krad

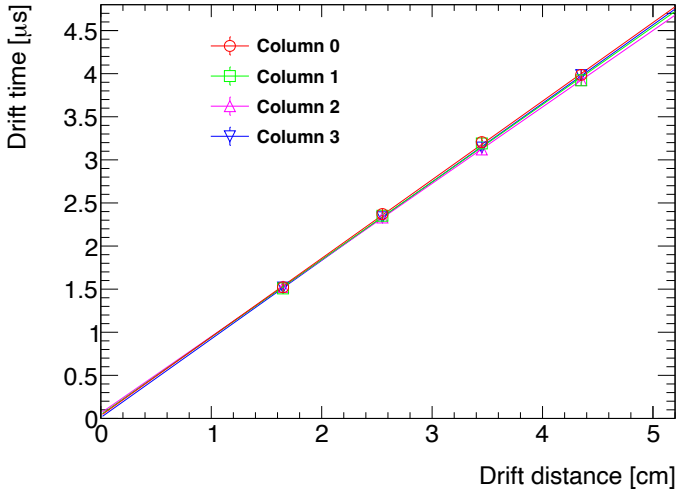
Threshold changes under irradiation and recovers toward baseline with room-temperature annealing.

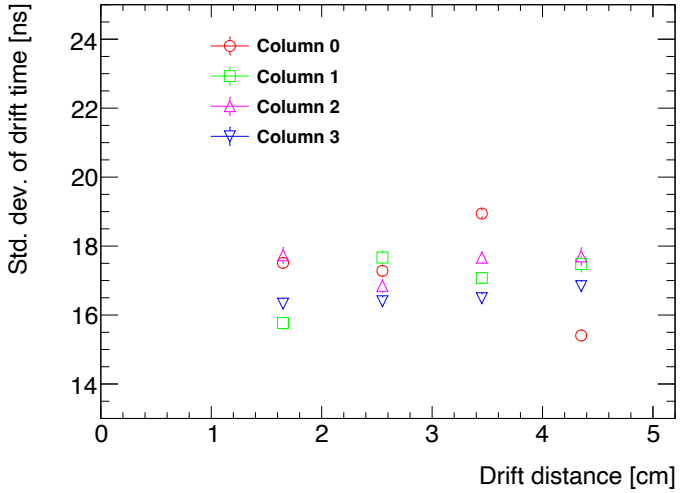
Operational strategy: periodic threshold calibration.

Laser test

Controlled laser ionization validates the charge, timing, and clustering response before heavy-ion tests.



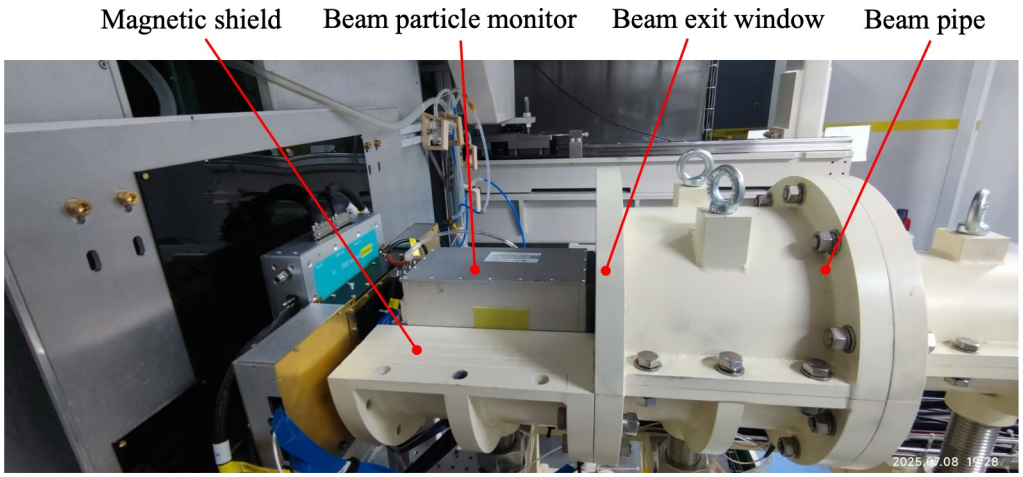




Carbon beam test (Jan. 2026)

1.1 GeV/u C beam, no magnetic field.
Beam-rate scan: ~ 0.01 - 1 MHz.

Baseline validation of detector response and the full reconstruction chain.



Event reconstruction

Pixels

address + charge + arrival time

↓

Clusters

charge-weighted centroid per row

↓

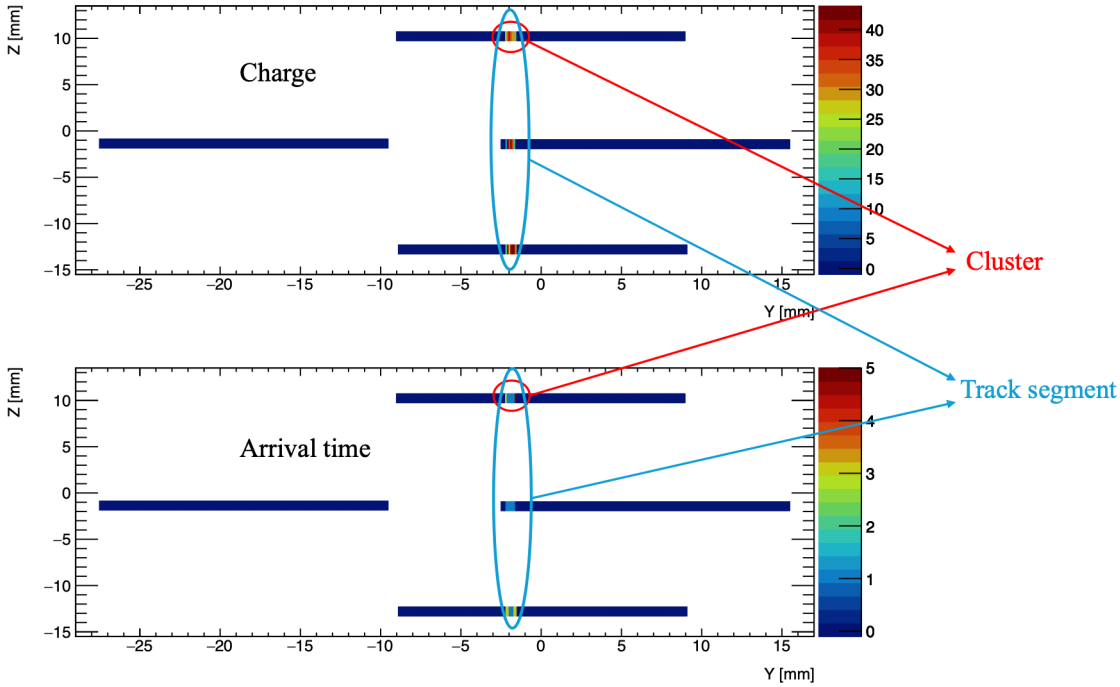
Track segments

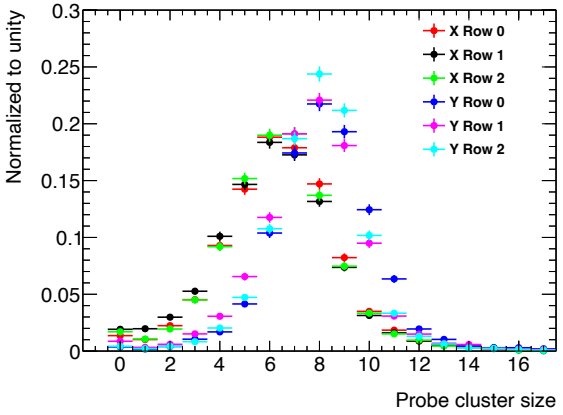
X,Y and arrival time per micro-TPC

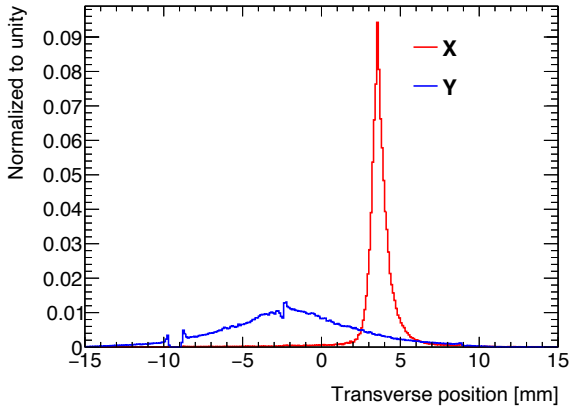
↓

Matched pair (Track)

correlate orthogonal micro-TPCs → X, Y, t0







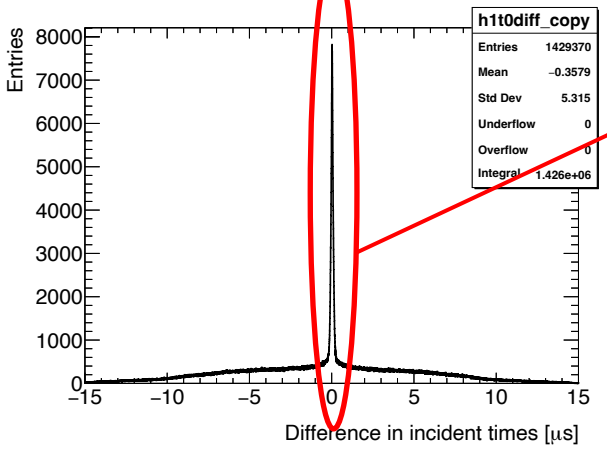
Track matching and t0 reconstruction

Track segment X + Track segment Y

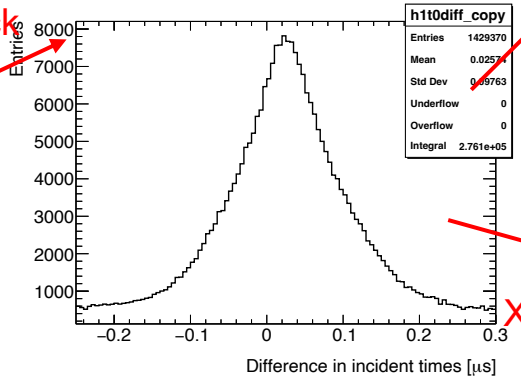
$t0_{XZ} = t_{XZ} - L_{driftY}/v_{driftY}$, $L_{driftY}=|y_{YZ} - y_{planeXZ}|$

$t0_{YZ} = t_{YZ} - L_{driftX}/v_{driftX}$, $L_{driftX}=|x_{XZ} - x_{planeYZ}|$

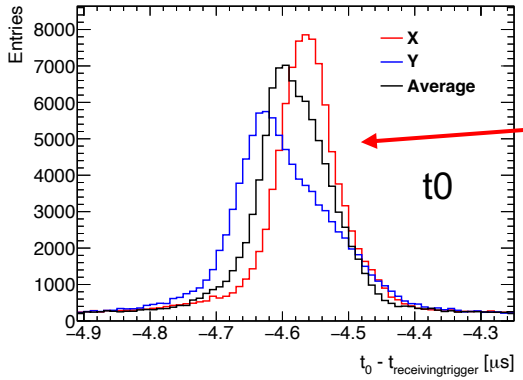
$t0_{XZ} - t0_{YZ}$

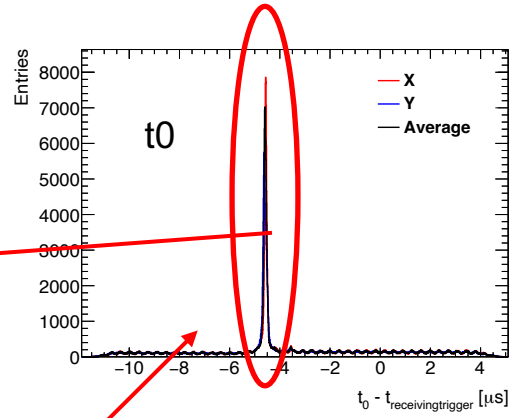


Track

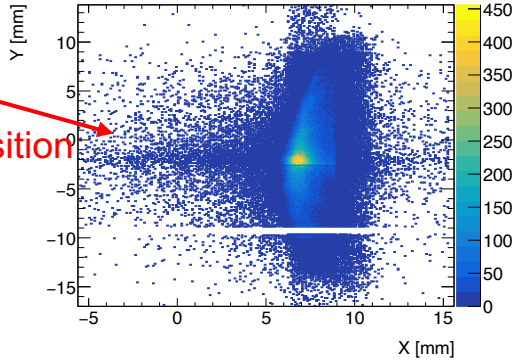


time





X,Y position

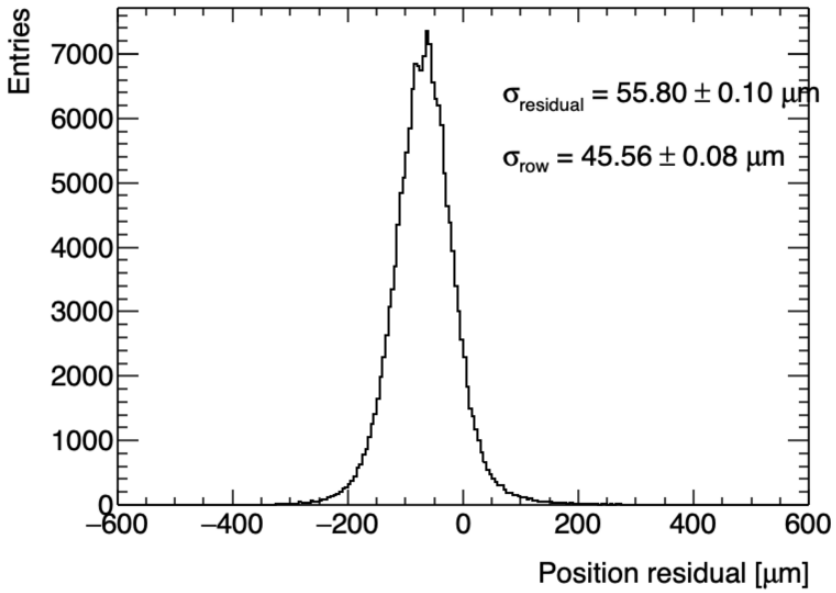


Correct X/Y segment pairs satisfy $t0_{XZ} \approx t0_{YZ}$

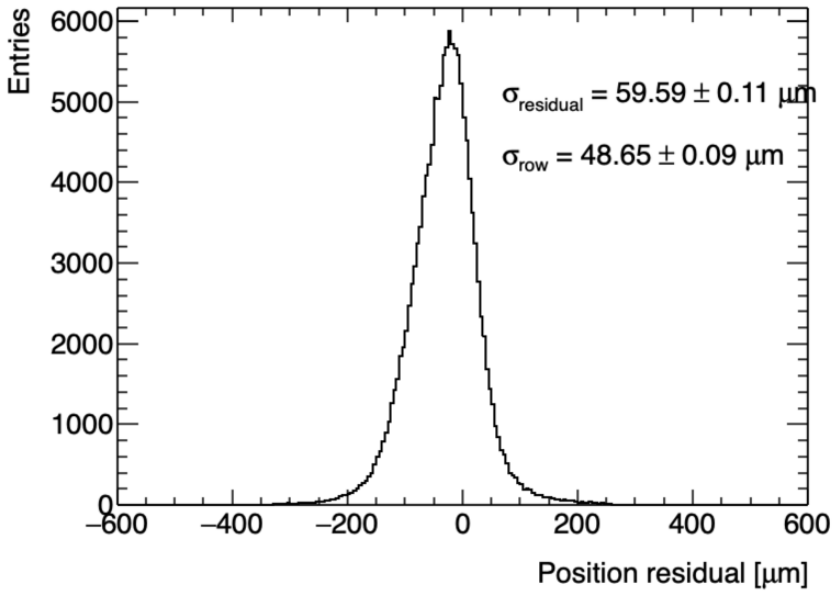
Transverse position resolution

· To evaluate the resolutions of transverse position and arrival time, track segments containing clusters in all three pixel rows are utilized.
· A reference track is defined by the clusters in two of the three rows, and the reference-track residual is then calculated.
· Single-row resolutions, σ_{row}, are inferred from the reference-track residual.

Both single-row resolutions meet the 50 μm target.



X-direction position residual

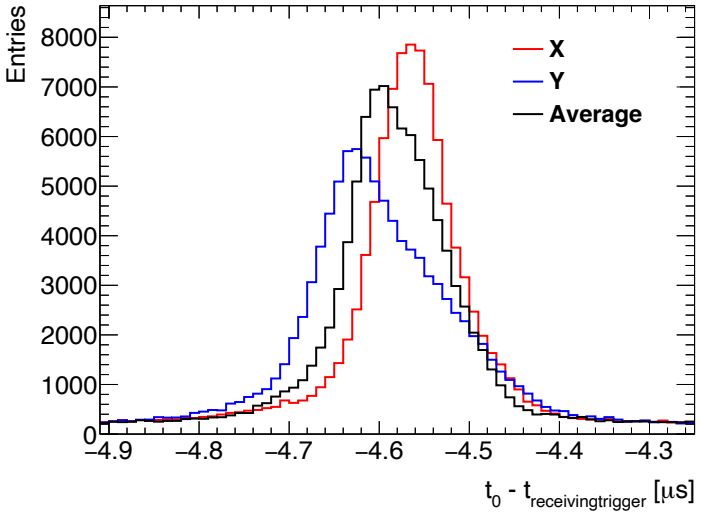


Y-direction position residual

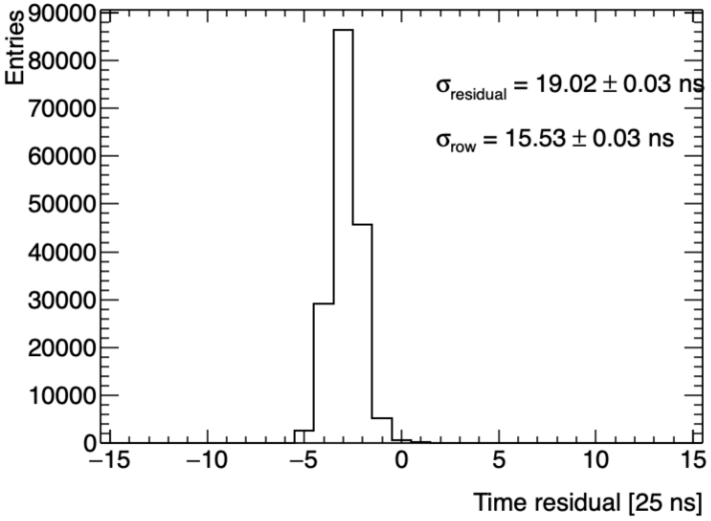
Time resolution

Arrival time resolution: ~15 ns.

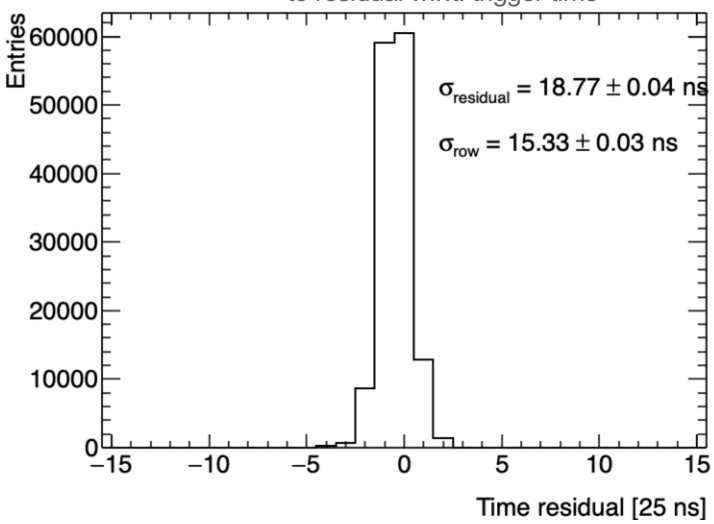
Incident time (t0) resolution: < 100 ns.



t0 residual w.r.t. trigger time



X-direction arrival-time residual



Y-direction arrival-time residual

Summary and Outlook

A dual micro-TPC/GEM beam monitor with Topmetal-CEEv2 chips reconstructs the X–Y position and absolute incident time of individual beam particles.

The carbon beam test demonstrates <50 μm transverse precision and <100 ns incident-time reconstruction.

Next steps:

· Integrate timing, tracking and trigger with other CEE sub-detectors
· Continue radiation calibration and long-term stability tests
· Improving the rate capability (currently validated up to ~0.5 MHz)

References:
· Nucl. Instrum. Meth. A 1089 (2026) 171561 (350 MeV/u Sn-beam study, July 2025)
· IEEE Trans. Nucl. Sci. 73 (3) (2026) 671–679
· JINST 20 (2025) P09020

Thank you

Hulin Wang, on behalf of the CEE Beam Monitor Group

Questions welcome