HYDRA TPC and July beamtime results

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TECHNISCHE UNIVERSITÄT DARMSTADT

Physics Case

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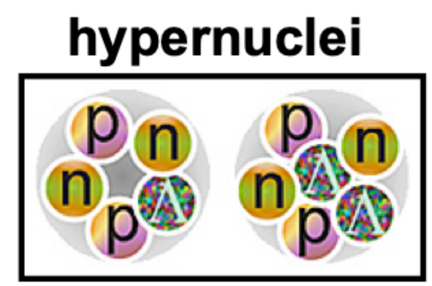
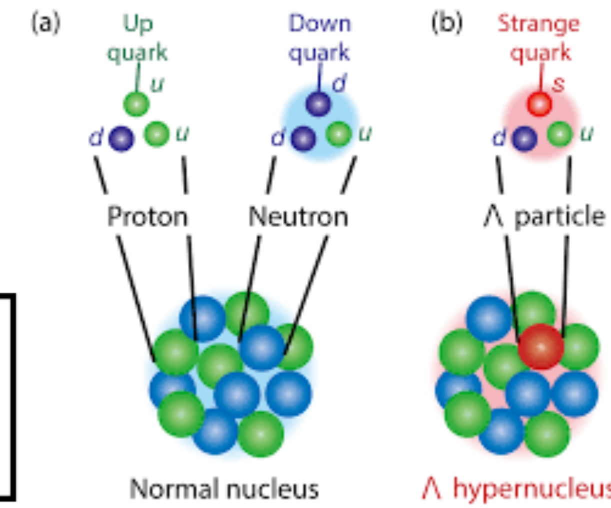
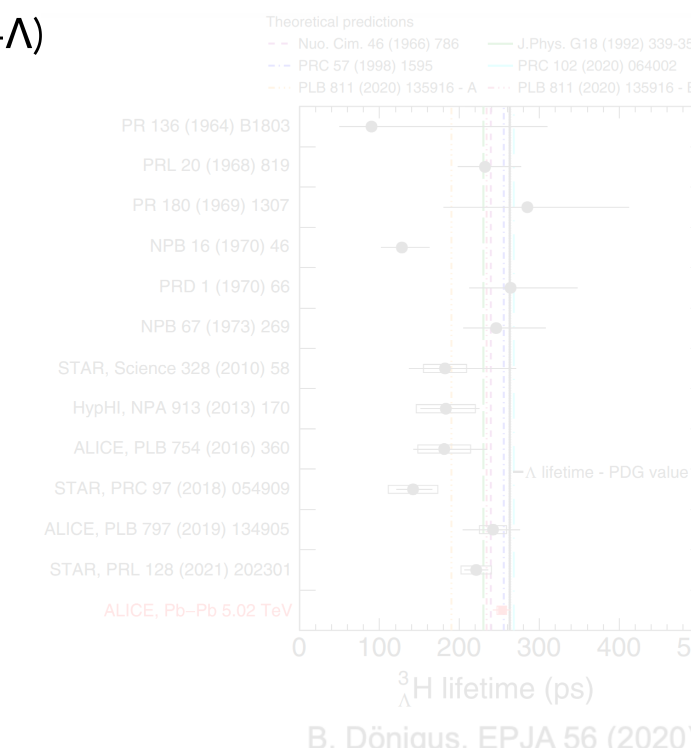
- **HYDRA** (HYpernuclei Decay at R^3B Apparatus) aims for hypernuclear invariant-mass spectroscopy and light hypernuclei.
- A **hypernucleus** is a nucleus containing one or more **hyperons** (Λ, Σ, Ξ, Ω).
- **Hyperons:** baryons that contain at least one **strange quark** (s):
  - **Λ (Lambda):** lightest hyperon (uds), τ ≈ 263 ps, decays weakly (Λ → πN).
  - **Σ (Sigma), Ξ (Xi), Ω (Omega):** heavier hyperons.
- First observed in **1953** in cosmic ray interactions.
- Experiments have identified about 40 single-strangeness (single-Λ) hypernuclear species to date.







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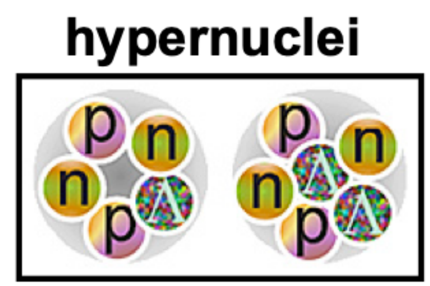
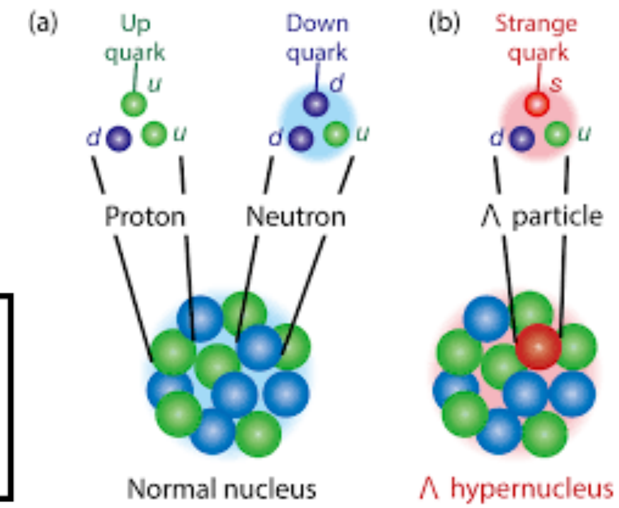
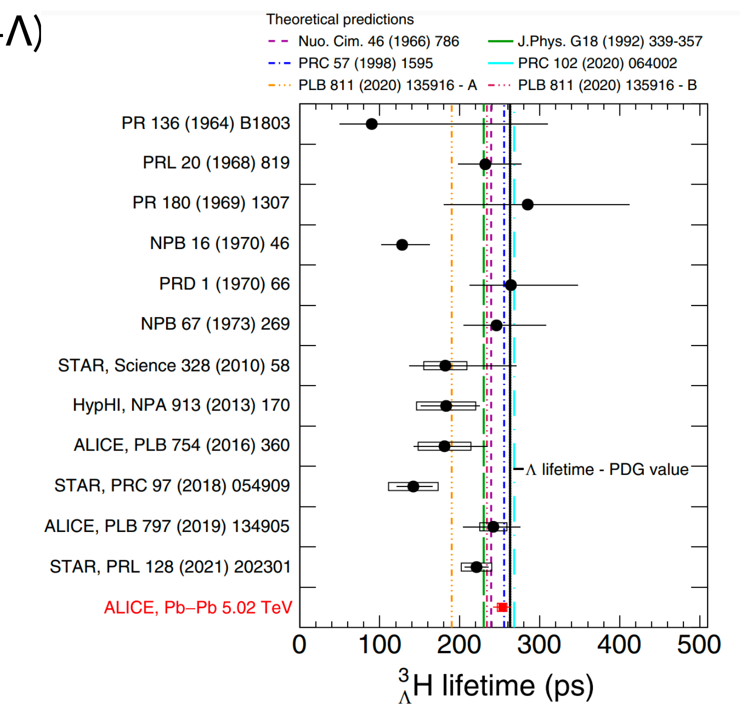
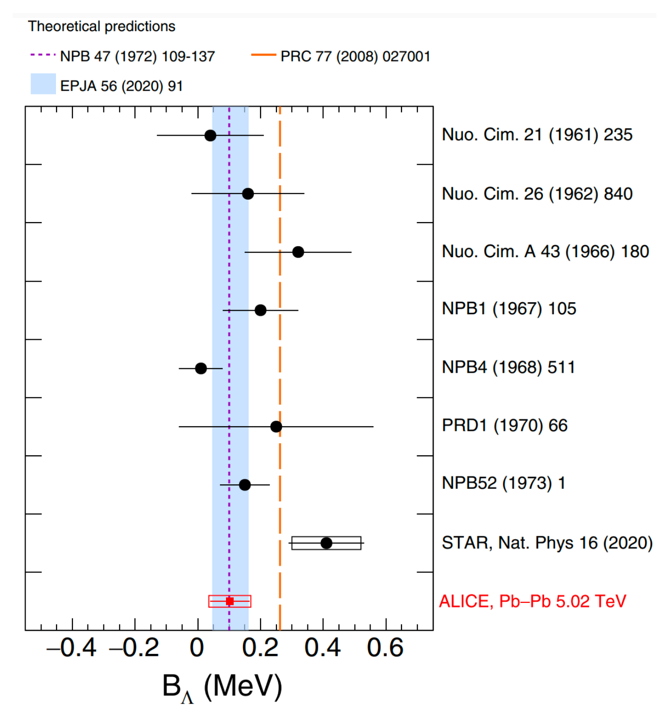




- Halo nuclei (e.g., ^{11}Li) established ~40 years ago; no direct experimental evidence yet for hypernuclear halos.
- $\Lambda - d$ rms distance in hypertriton ($^{3}_{\Lambda}H$) predicted at 10.8 fm (F. Hildenbrand, H.-W. Hammer, PRC 100 (2019)).
- Predictions for hypertriton matter radius vary between 4–10 fm depending on binding energy.



B. Dönigus, EPJA 56 (2020)

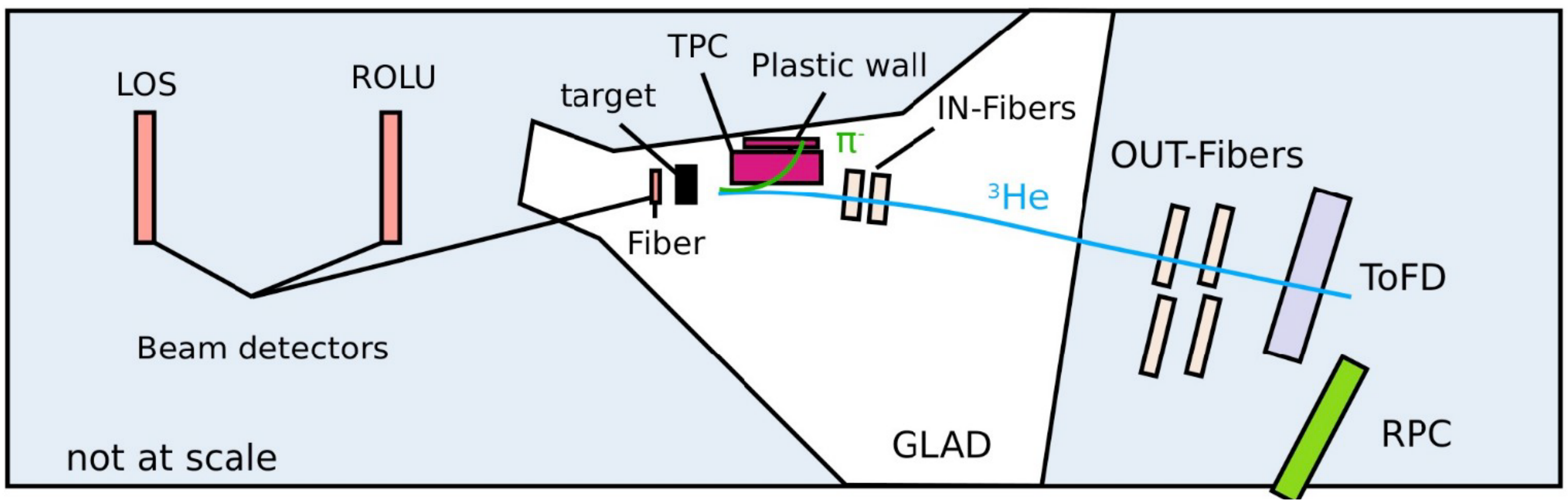


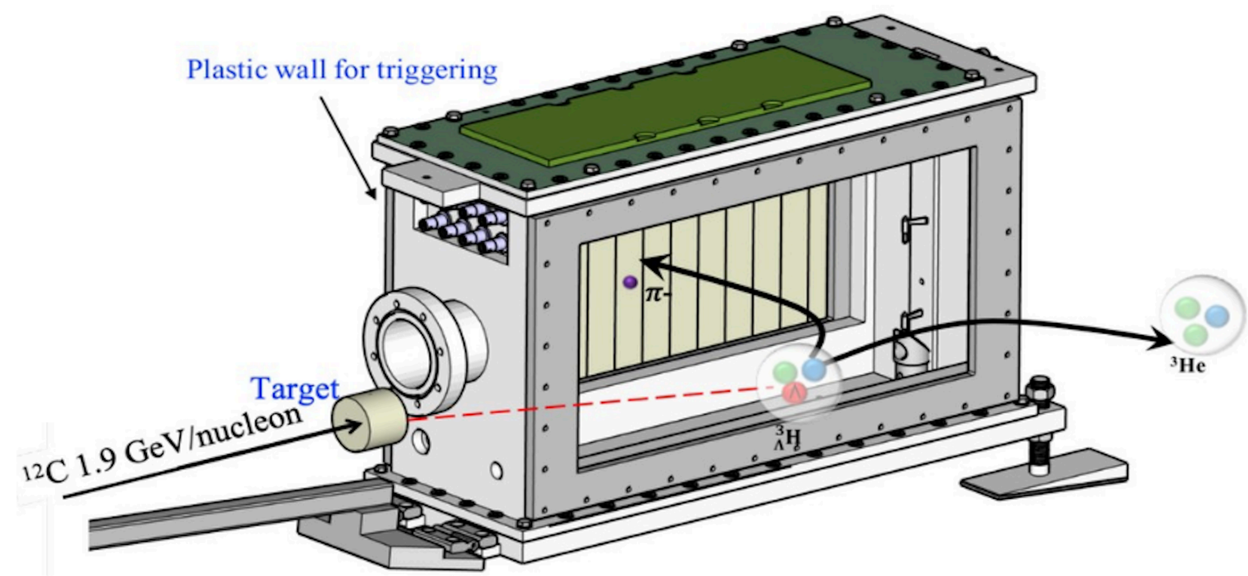
Hypertriton puzzle

- **Inconsistency** between several lifetime analyses (STAR, HyPHI0, ALICE).
- **Low binding energy** (130(50)(40) keV from nuclear emulsion).
- **Large spatial extension predicted** (unmeasured).

GSI Experiment 2026

- Measure the interaction cross section of **hypertriton-^{12}C** to deduce its size.
- Performed within the R^3B **collaboration at GSI/FAIR**.
- Reaction: **^{12}C + ^{12}C at 1.9 GeV/nucleon** → hypertriton production.
- **Reconstruction of invariant mass:** ${}^{3}_{\Lambda}H \to \pi^- + {}^{3}He$, resolution ~ 1.5 MeV/c^2 (σ).
- Production cross section unknown → **two-target method** (S. Verladita et al., Eur. Phys. J. A (2023)).
- GLAD dipole magnet at 2 T to bend low-rigidity decay pions.



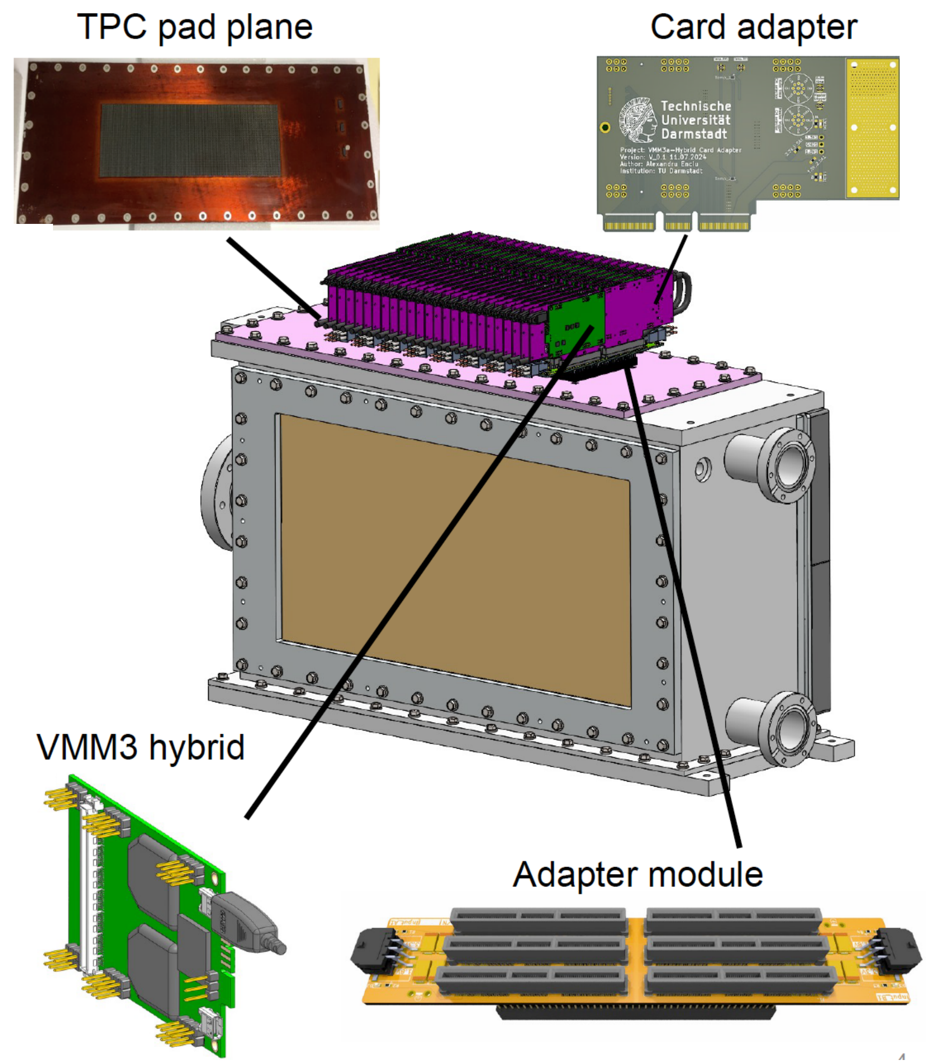


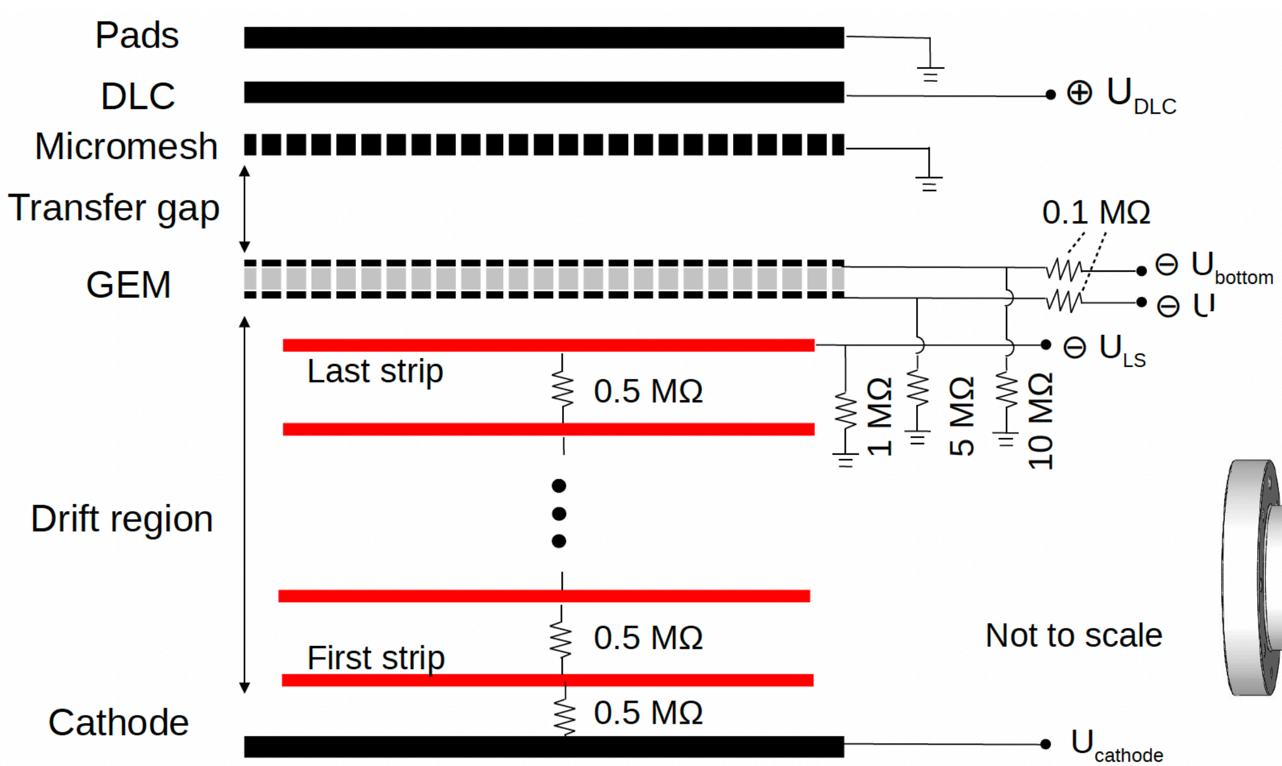
HYDRA detection systems:

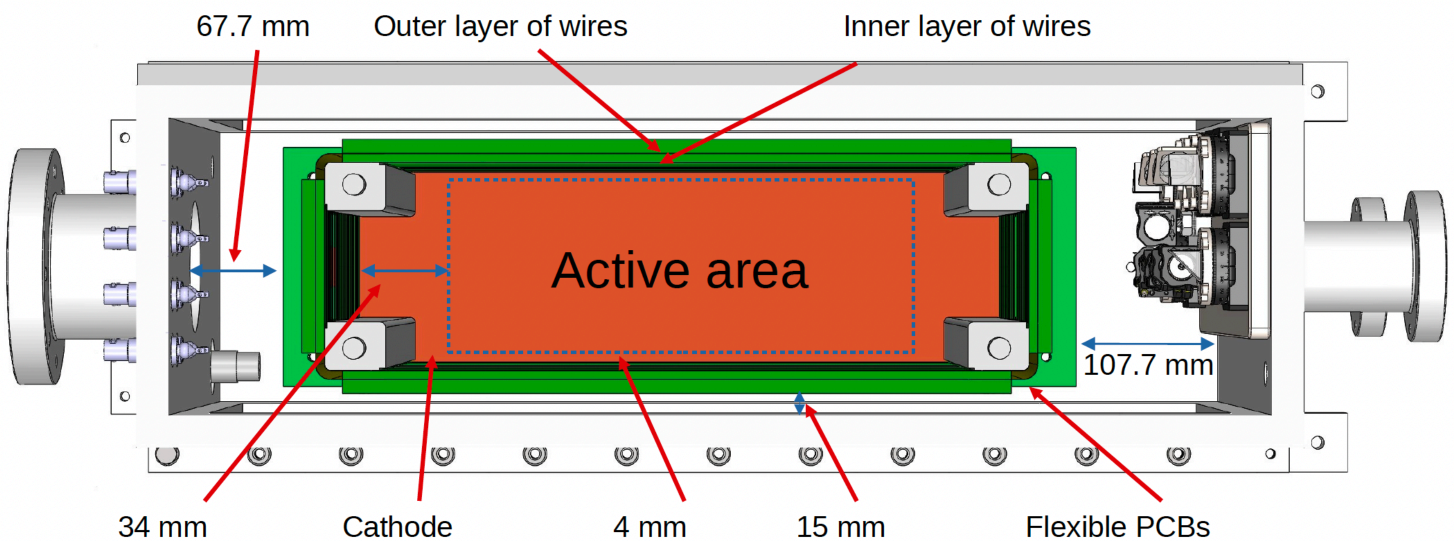
- **TPC** – pion tracking (VMM3a/SRS readout).
- **Scintillator wall** – trigger and timing (TRB-based reaout).
- **Fiber trackers** inside GLAD – recoil tracking (TRB-based readout).

HYDRA TPC

- **Purpose:** Detect π⁻ from weak decay ${}^{3}_{\Lambda}H \rightarrow \pi^- + {}^{3}He$.
- **Active area:** 88 × 256 mm², 30 cm drift length, **5632 pads** (2×2 mm²).
- **Field cage:** double wire layers with a small offset → ~95% transparency.
- **Micromegas + GEM:** required amplification of 4000 to keep ion backflow <1% (Lian-Cheng Ji et al., NIM A 1082 (2026)).
- **Readout:** **VMM3a ASICs with SRS backend**, 48 hybrids to cover full TPC.
- **Drift velocity calibration** via UV laser (266 nm) + micro-mirror bundles generating reference tracks.







HYDRA TPC requirements

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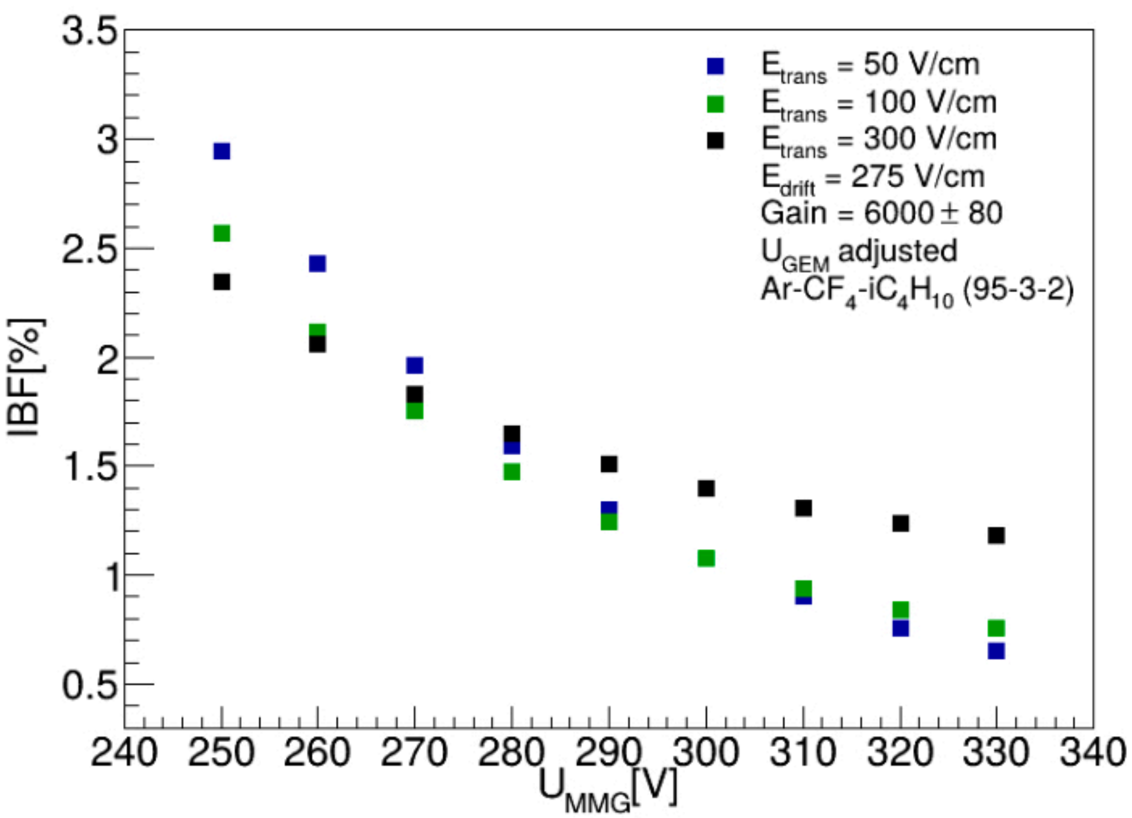
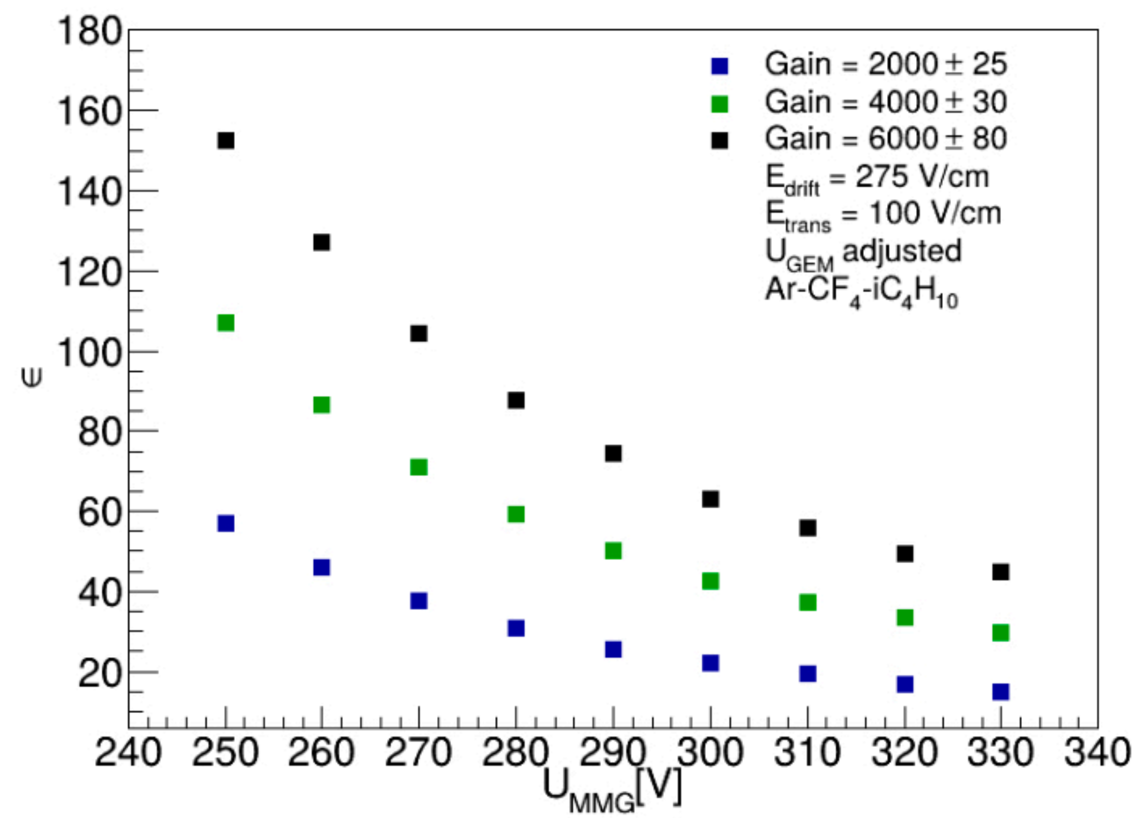
- Expected charge particles rate of **~200 kHz**.
- This rate results in a significant **space charge density** within the TPC's active volume due to the **ion back-flow**.
- To mitigate electric field distortions, an **ion back-flow of less than 1%** is necessary for a gain of 4000 for the amplification region.
- We track **ε = G × IBF** (ions escaping per incoming e⁻). Requirement: **ε < 40** ⇒ at **G = 4000** need **IBF < 1%**.
- Data show **G ≈ 2000** is safely within spec; viable settings exist at **G = 4000**, and a few at **G = 6000** but with reduced stability.
- Prioritize operation at **G ~ 4000** and verify performance at these gains.





From F. Horn (Bachelor's thesis)

HYDRA TPC readout

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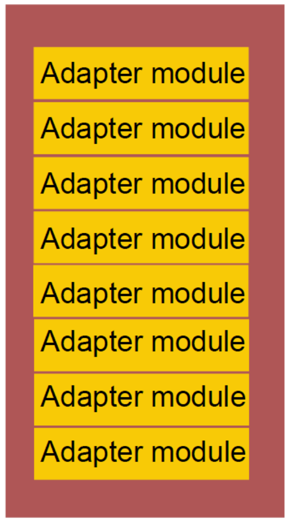
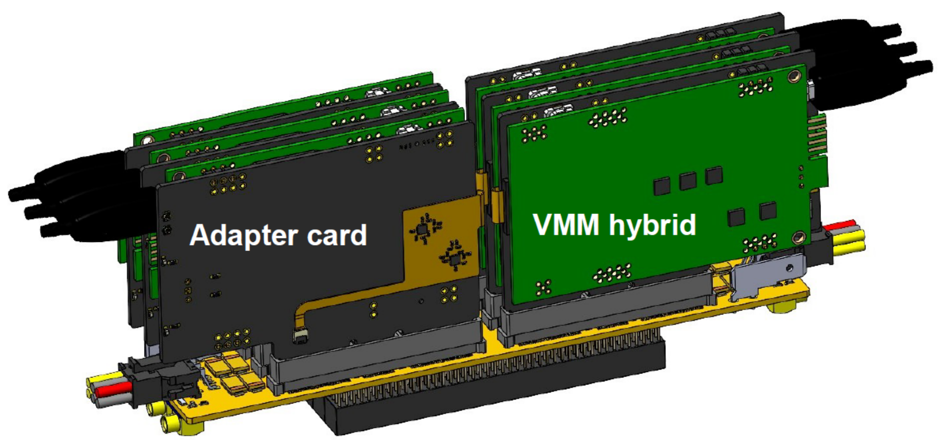
TPC pad plane



8 x Adapter module (v2)



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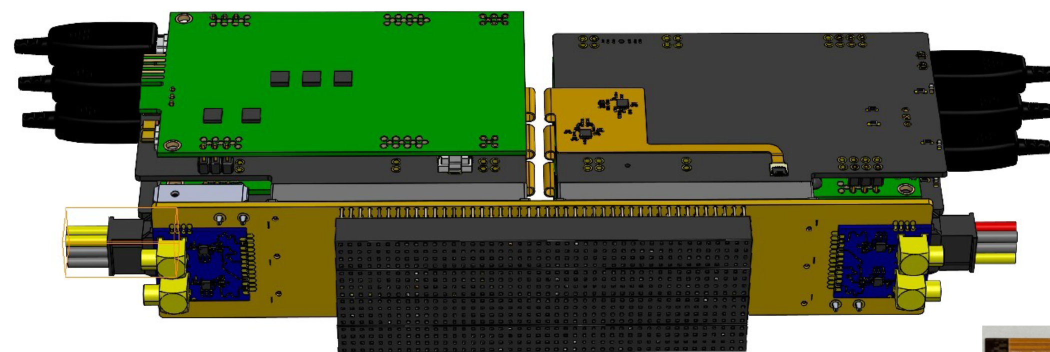
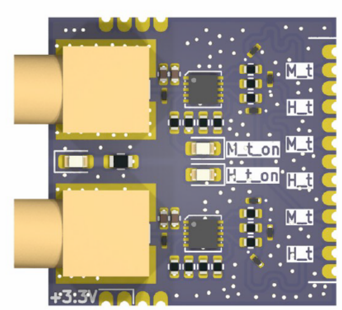
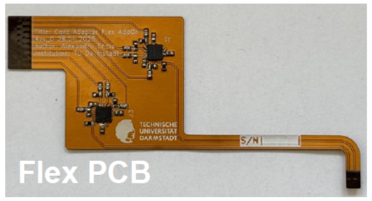


Clock buffers

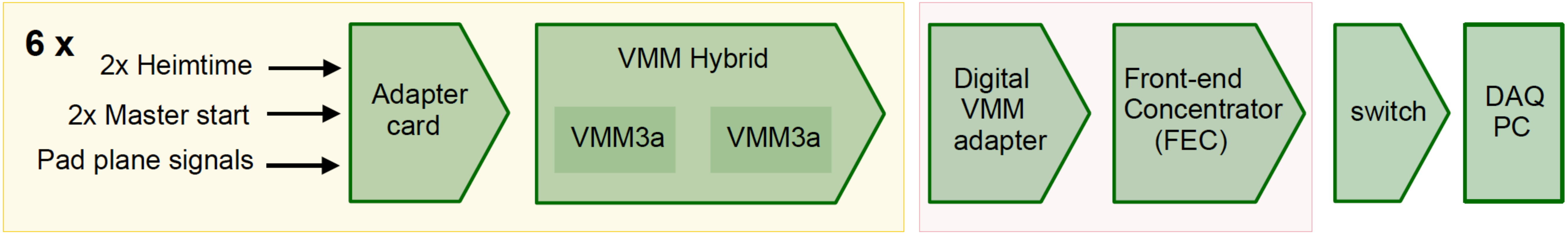
2 inputs to 6 outputs for
Heimtime & Master start





Adapter module

Backend SRS



HYDRA TPC readout

TPC pad plane

8 x Adapter module (v2)

8 x Adapter module (v2)

See Alexandru Enciu talk at 16:00 in WG5

Adapter module

Backend SRS

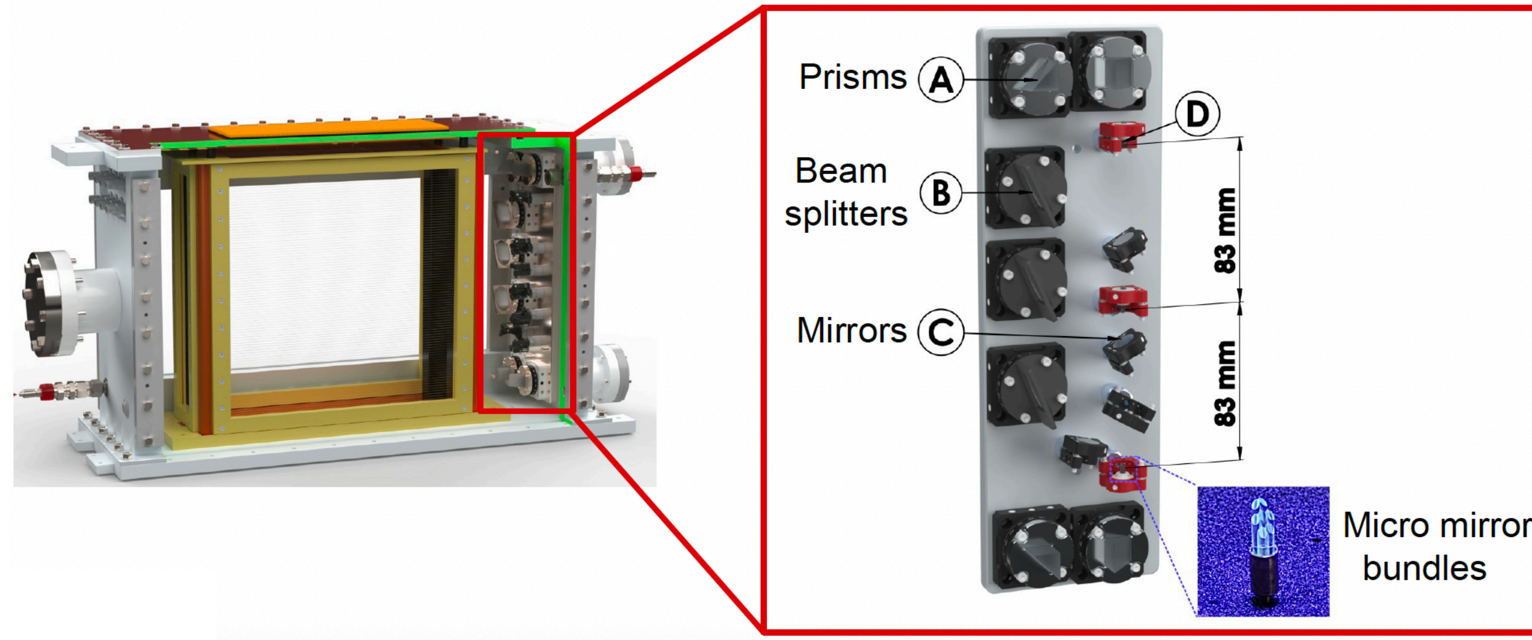
6 x

2x Heimtime →
2x Master start →
Pad plane signals →

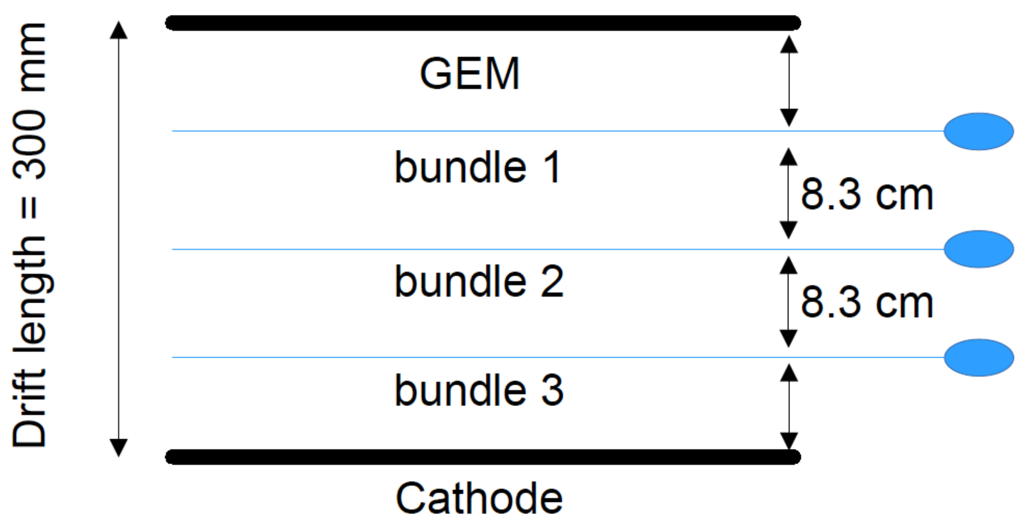
Adapter card → VMM Hybrid (VMM3a, VMM3a) → Digital VMM adapter → Front-end Concentrator (FEC) → switch → DAQ PC

Laser test at TUDa

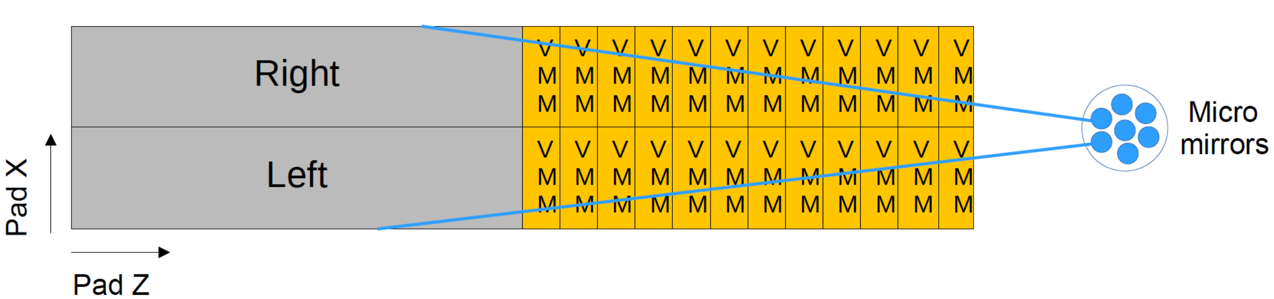
- VMM in continuous read-out mode.
- 1/2 of the TPC equipped with VMM readout, 24 VMM3a hybrids + cards 4 adapter modules.
- Test gas mixture: ArCO2 (92-8%).
- **Drift field:** 220 V/cm, **Amplification (gain):** ~6,000.
- 266 nm UV laser source, 20 Hz, 3 micros-mirror bundles at different heights.

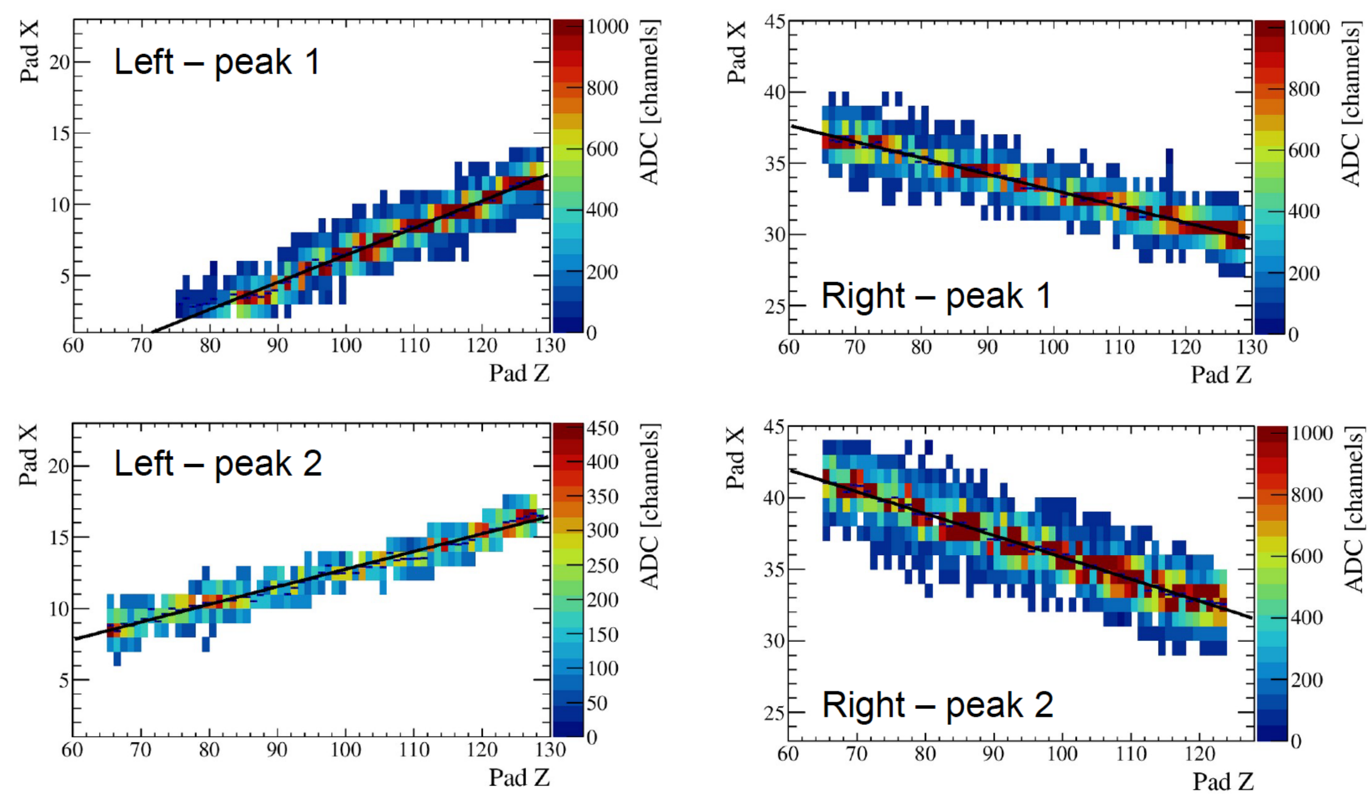


YZ drift plane



XZ pad plane





Calculate the centroid of charge for each Pad Z & fit linear tracks

July beamtime

Agenda: performance test for half of the TPC (24 hybrids).

Beam:

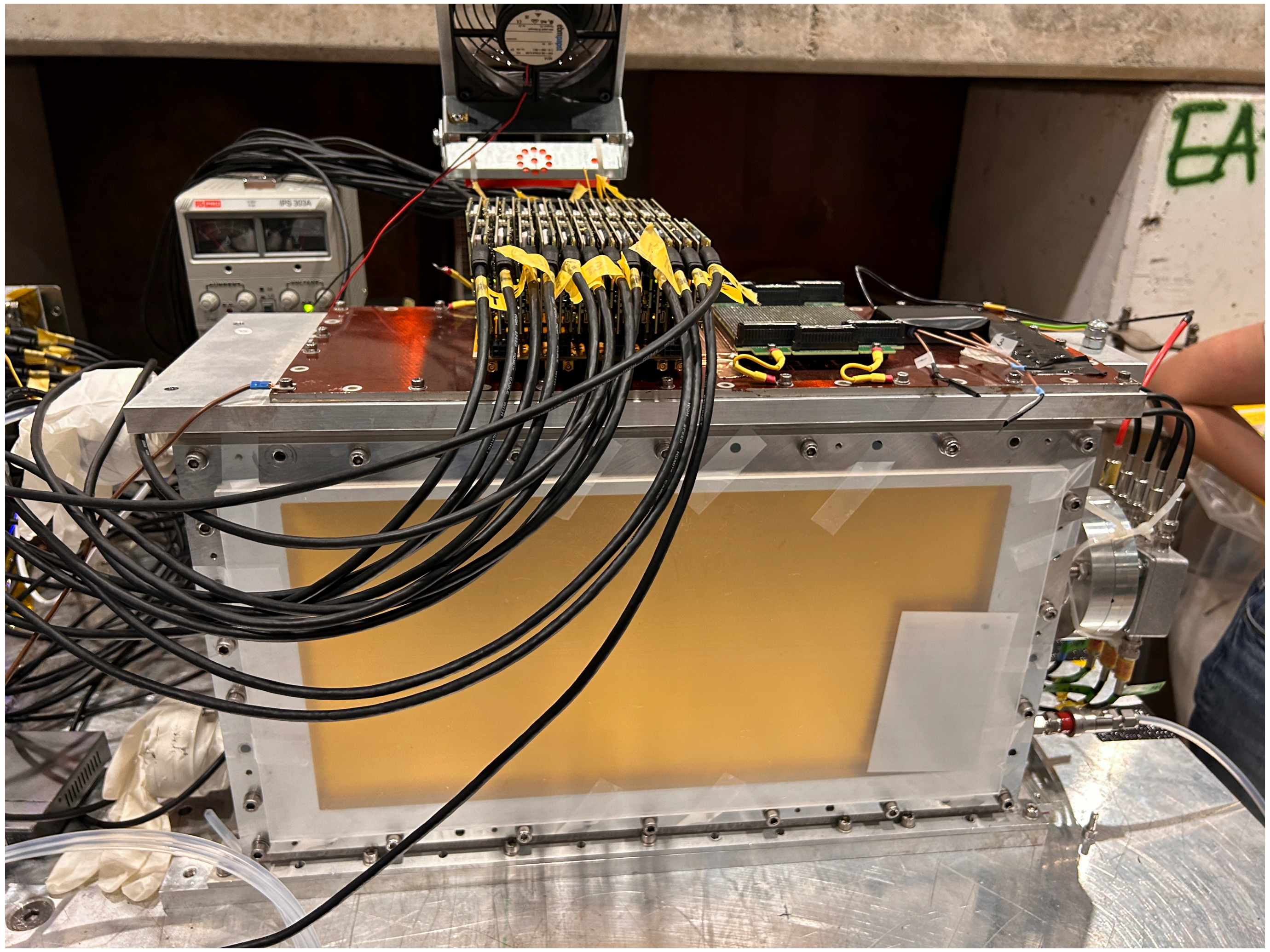
- π / μ beams.
- Intensity ~5×10^4–1.2×10^5 pps, 1–3 spills/cycle.

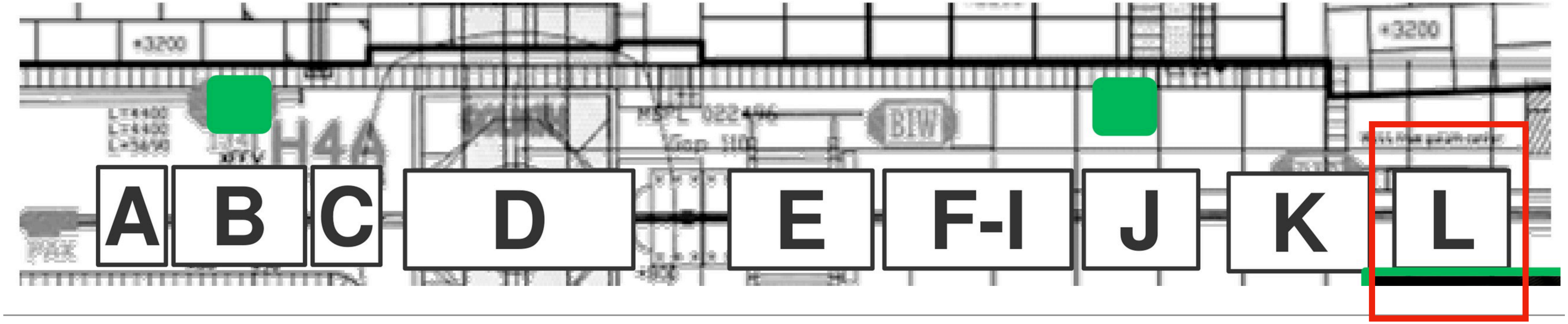
Muon beam:

- VMM settings: thresholds, gain.
- Gain (amplification) scan: 2,000 – 10,000.
- Ion-backflow settings.

Pion beam:

- Rate scan: $10^4 - 10^6$ pps.
- Gain scan, IBF settings.





HYDRA TPC Setup

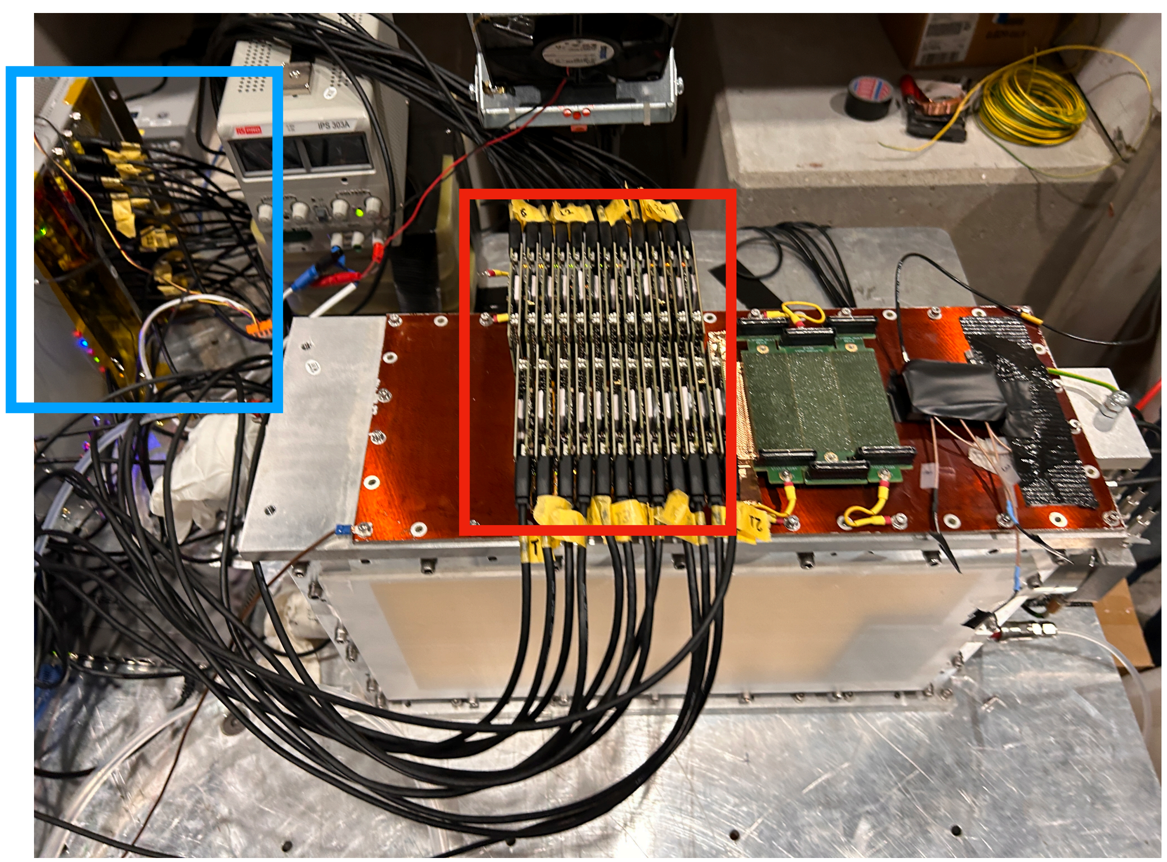
- **Detector:** HYDRA-TPC prototype with 24 hybrid front-end boards mounted on the pad plane.
- **Readout:** Hybrids grouped to 3× FECs; clock/trigger via CTFG.
- **High voltage:** HV crate for cathode, drift field, GEM, transfer field and HV module for Micromegas.
- **Cooling:** Simple air cooling with a top fan directed over hybrids/FECs.
- **Gas**: $ArCO_2$ (90-10 %).
- **DAQ & control:** FECs cabled to a network switch, then to the run PC for configuration and data taking.

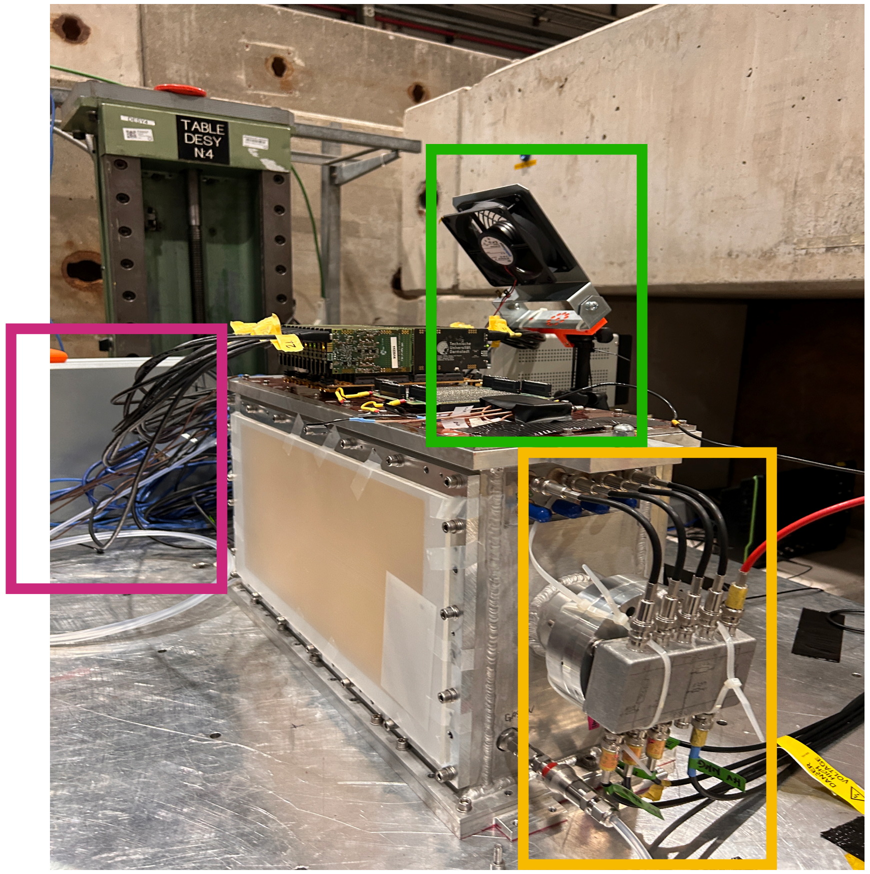
Front-end (VMM)

- **Gain:** ×3 mV/fC (scan focus; ×6 mV/fC also checked).
- **Peaking time:** 200 ns.
- **Thresholds:** 230 / 240 / 250 DAC (global).
  – plus calibrated points +30 mV, +40 mV above pedestal.
- **Continuous readout mode** for the VMMs.

Field settings for gain scans:

- E_t = 1000 V/cm, ΔU_{GEM} = 350 V, E_d = 220 V/cm.
- Amplification was tuned by scanning the MMG bias from 390 to 440 V.





Gain scan analysis: μ beam

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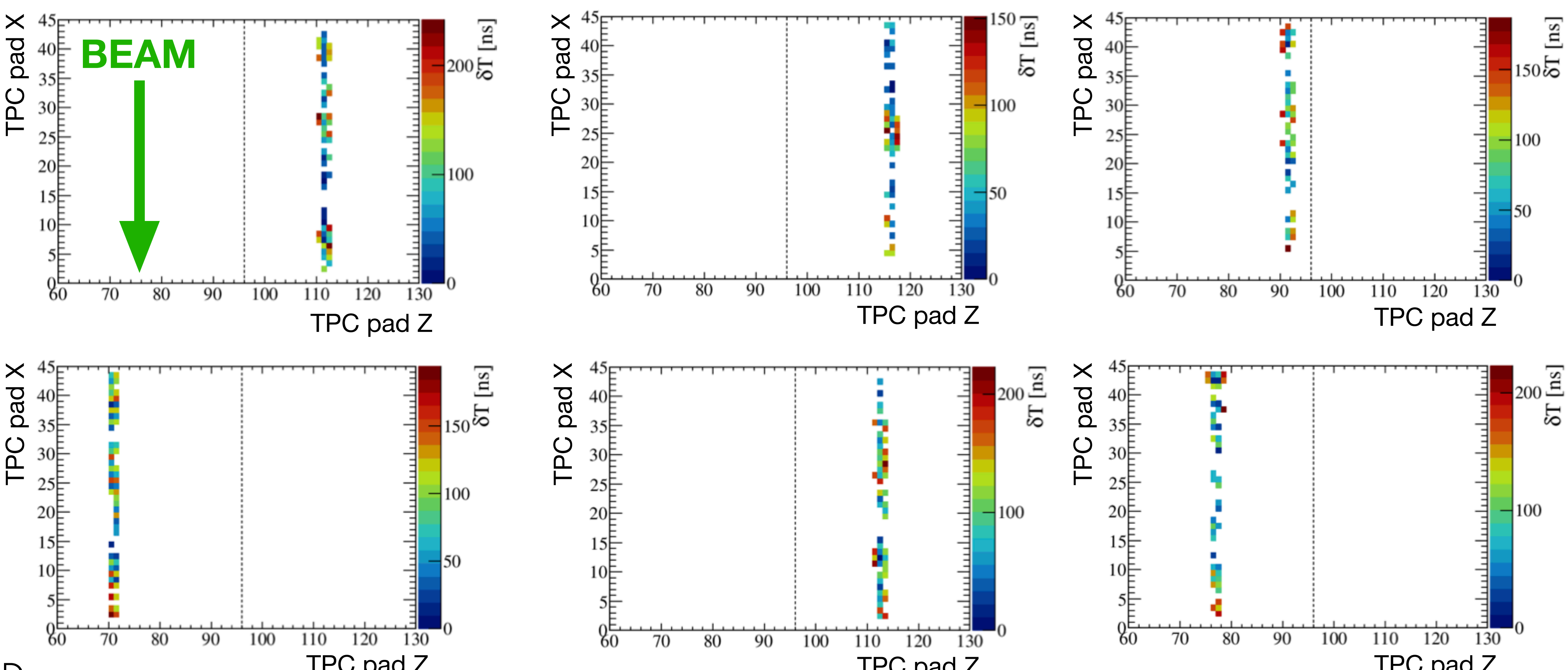
Gain scan - muon beam

Gain scan - muon beam:

- MMG 440V (gain 10k); thr. 30 mV, 240, 250; rate: ~0.63e5 pps.
- MMG 430V (gain 7k); thr. 240, 250; rate: ~0.63e5 pps.
- MMG 420V (gain 5.5k); thr. 240, 250; rate: ~0.5e5 pps.
- MMG 410V (gain 4k); thr. 240, 250; rate: ~0.5e5 pps.
- MMG 400V (gain 3k); thr. 240, 250; rate: ~0.5e5 pps.
- MMG 390V (gain 2.5k); thr. 240, 250; rate: ~0.5e5 pps.

Event and clustering reconstruction

- Event time window **30 us.**
- **Clustering in time** (within event) 250 ns.
- **Clustering in position** (Z) +-3 pads – at least 25 hits in a cluster.
- Considering only tracks with >5 pads along X.
- **Linear fit:** Pad X (centroid) = p0+p1*(Pad Z) – angular cut (p1).

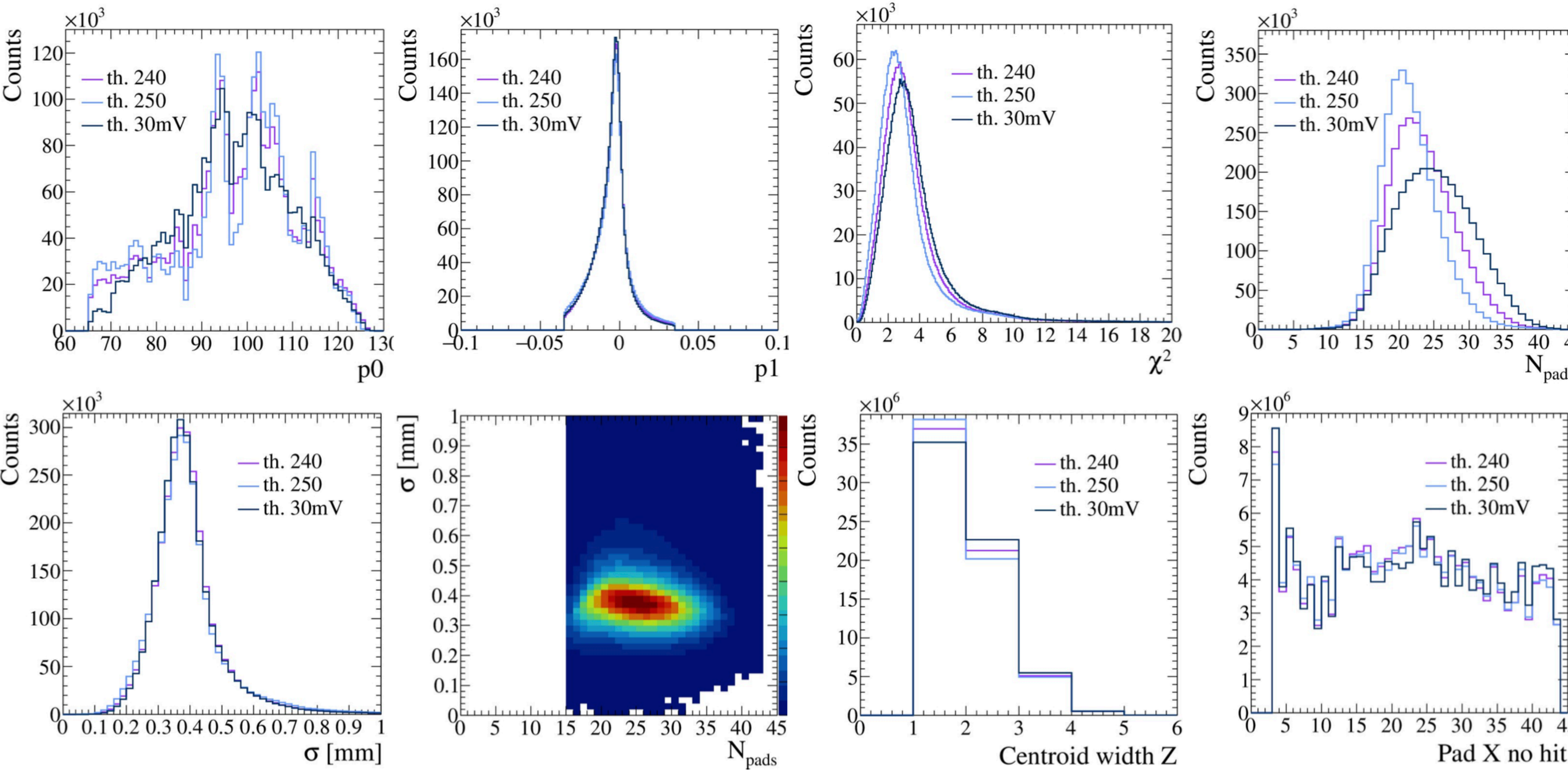


From M. Duer

Gain scan analysis: μ beam

- **Data: MMG 440V (Gain ~10k); threshold: 30mV, 240 DAC, 250 DAC.**
- **Linear fit:** Pad X (centroid) = p0+p1*(Pad Z) – angular cut (p1).

- Sigma = 2*sqrt(chi2/NDF).
- chi2= ∑(y_i-p1*x_i-po)*(y_i-p1*x_i-po).



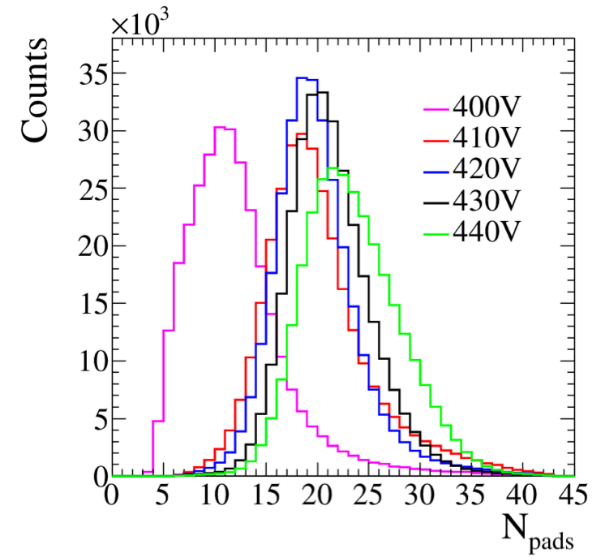
From M. Duer

Rate comparison: μ beam

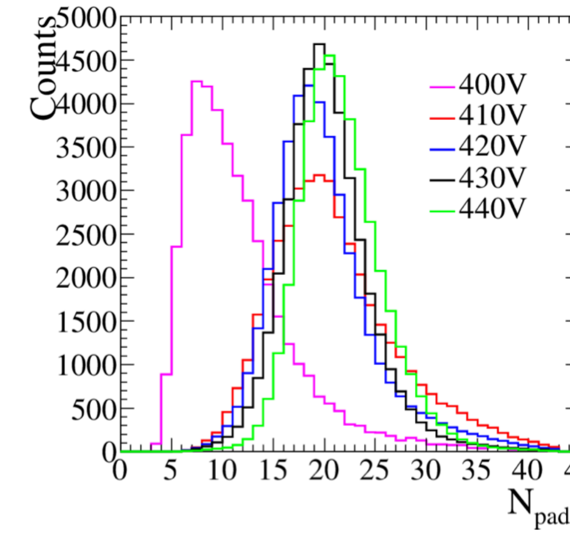
Rates

- **Data: MMG 440V;** threshold: 30mV, 240 DAC, 250 DAC.
  - Rates: 30mV – 0.65e5 pps, 240 – 0.62e5 pps, 250 – 0.29e5 ops.
- **Data: MMG 430V;** threshold: 240 DAC, 250 DAC.
  - Rates: 240 – 0.21e5 pps, 250 – 0.07e5 pps.
- **Data: MMG 420V;** threshold: 240 DAC, 250 DAC.
  - Rates: 240 – 0.3e5 ups, 250 – 0.1e5 pps.
- **Data: MMG 410V;** threshold: 240 DAC, 250 DAC.
  - Rates: 240 – 0.03e5 pps, 250 – 0.005e5 pps.
- **Data: MMG 400V;** threshold: 240 DAC, 250 DAC.
  - Rates: 240 – 0.02e5 pps, 250 – low.

Threshold 240

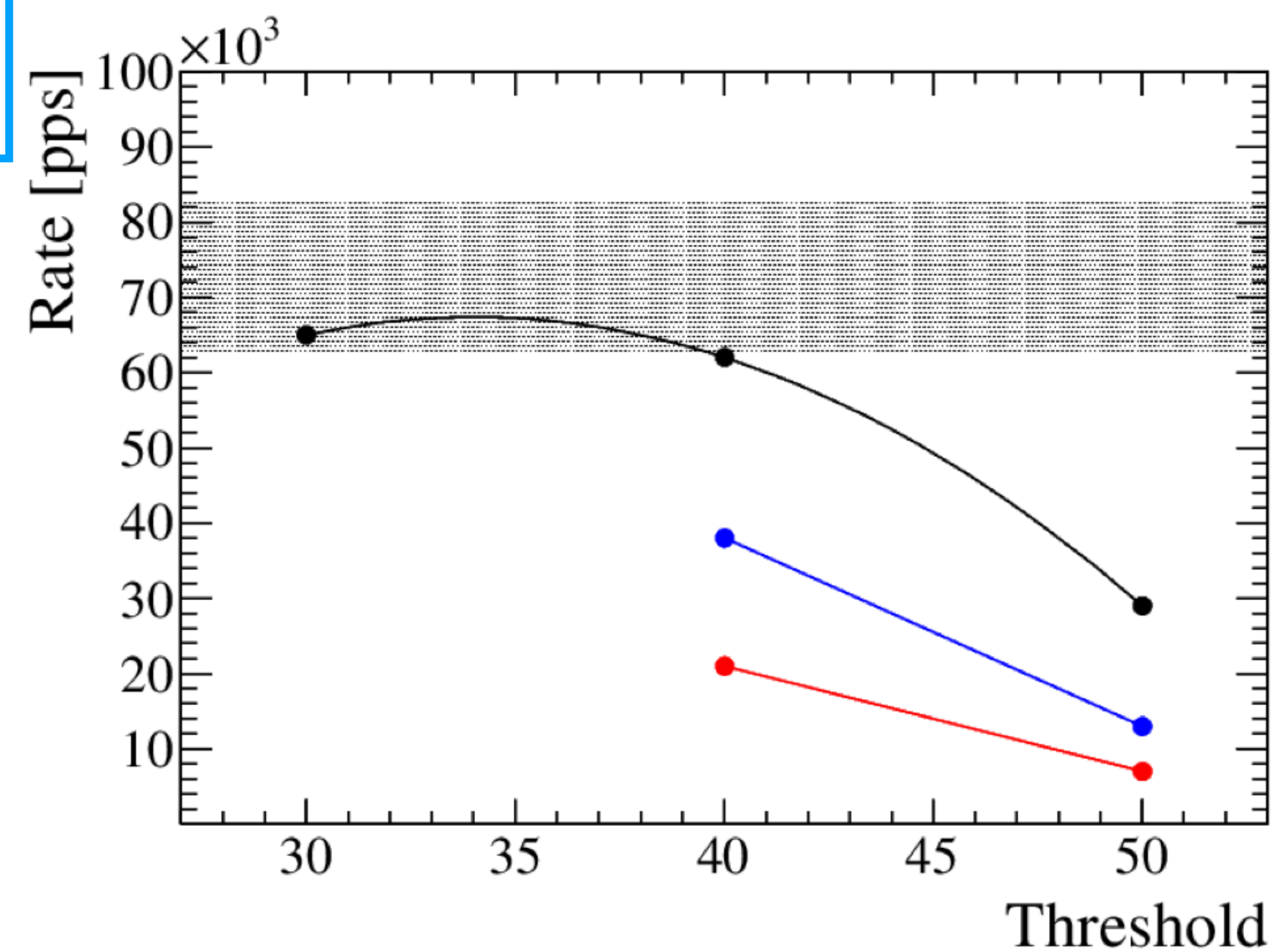


Threshold 250



Rate comparison - muon beam

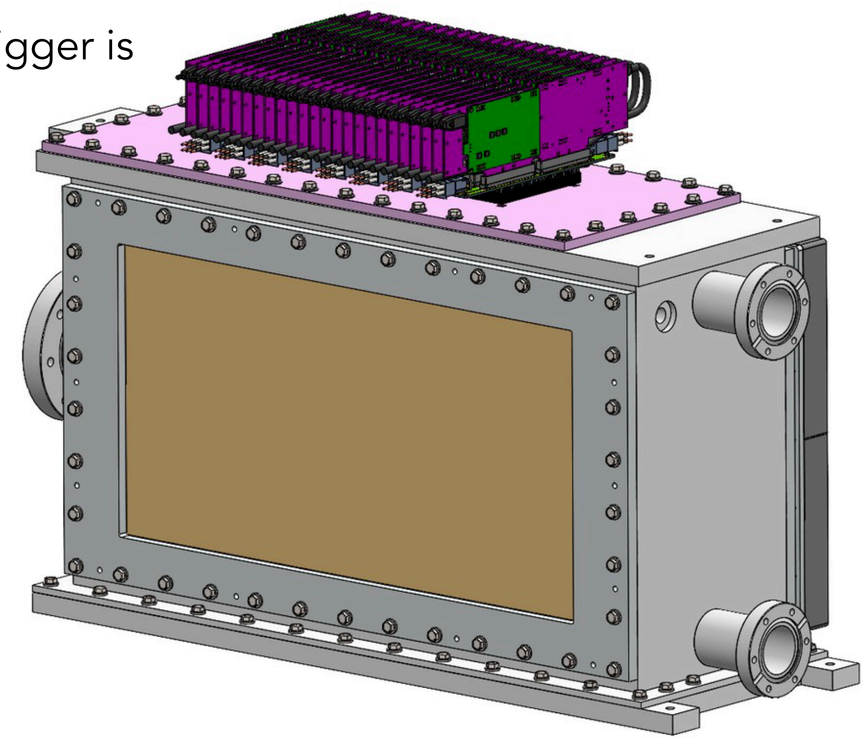
- **Black band** = beam rate at 440 V, 430 V measurements. 420V measurement is normalized according to this rate.
- **MMG 440V (gain ~10k).**
- **MMG 430V (gain ~7k).**
- **MMG 420V (gain ~5.5k).**



From M. Duer

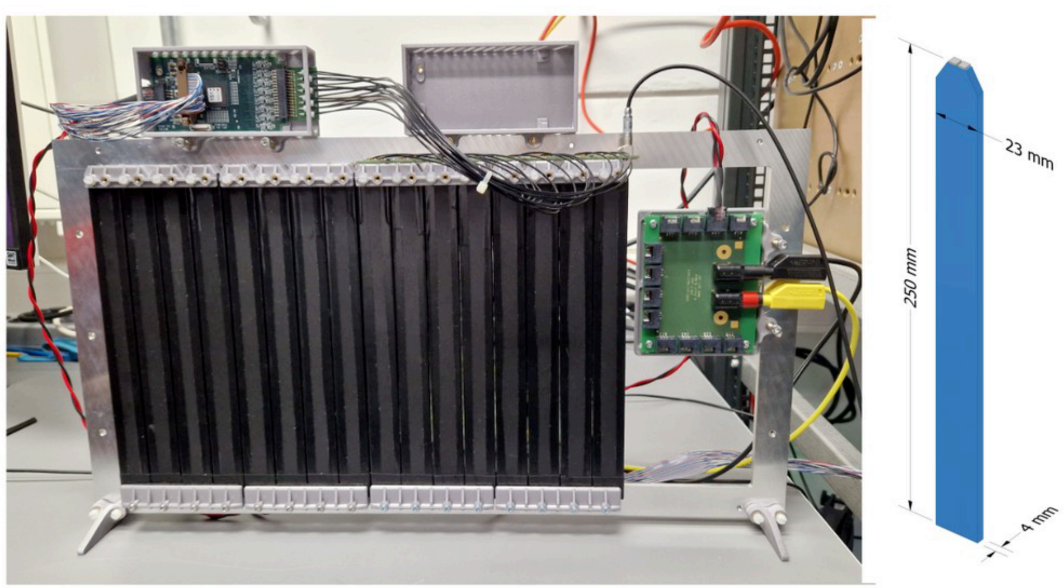
Plans for November beamtime

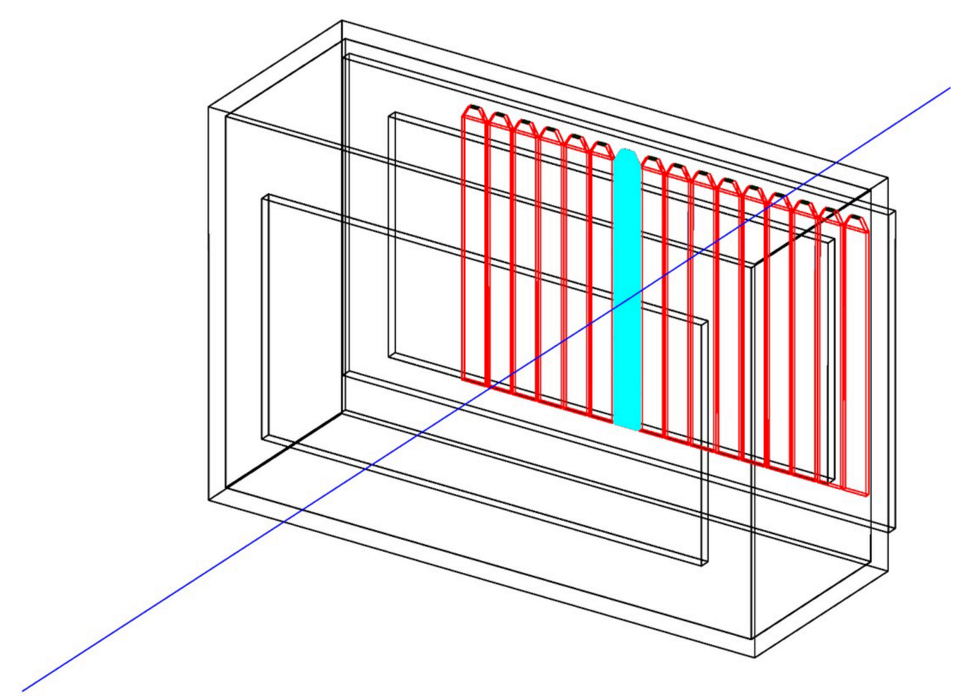
- **TPC – VMM3a/SRS readout.**
- **Scintillator wall for trigger and timing – TRB readout (GSI).**
- **Trigger source:** signals from muons/pions in the plastic scintillator wall; the resulting trigger is fanned into the TPC (SRS/VMM3a) as the event start.
- **Beam:** muons & pions.
- **Gases:**
    - **Ar–CO_2** (90–10 %).
    - **T2K mix Ar–CF_4–i-C_4H_{10}** (95–3–2 %).



Planned measurements:

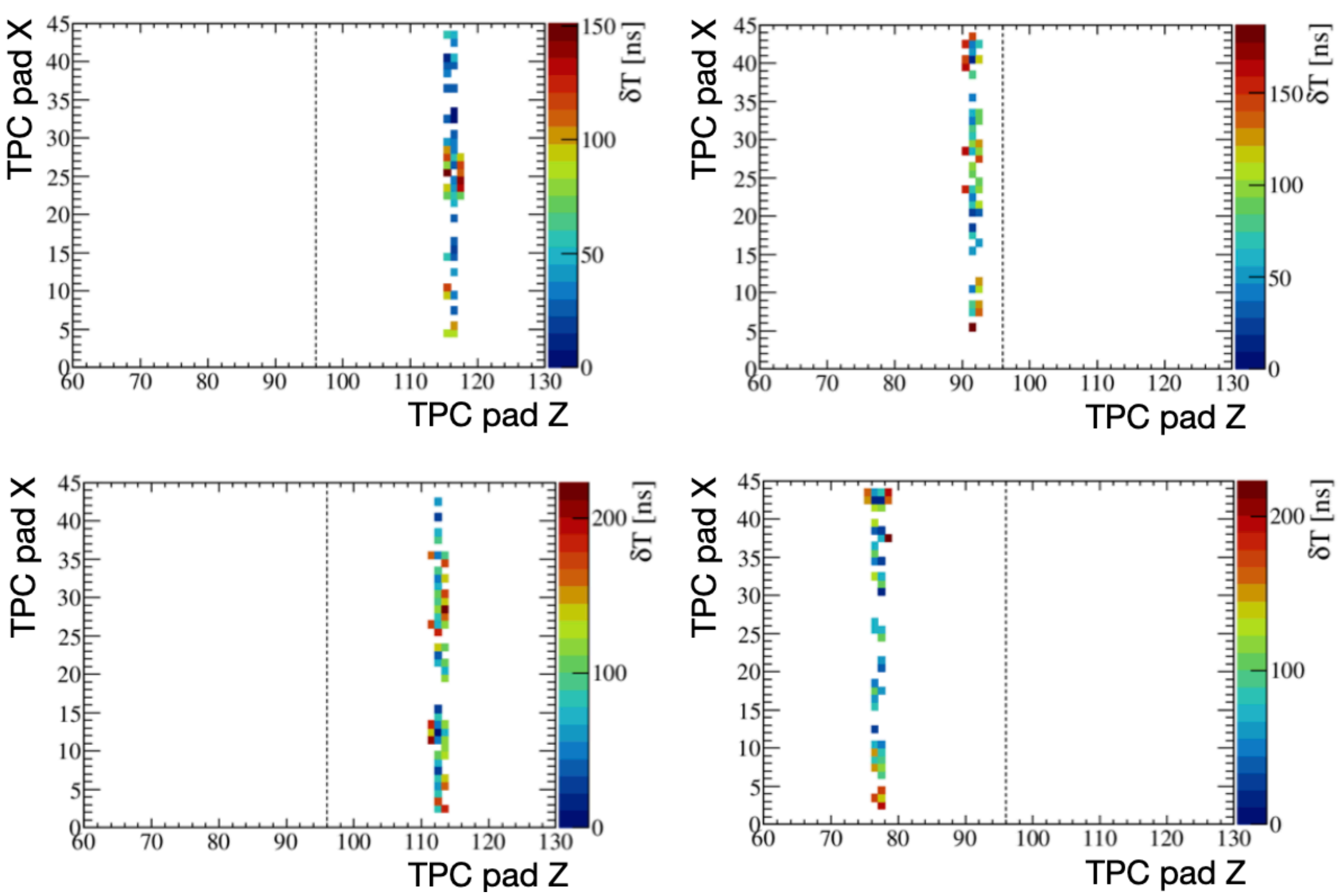
- Performance test for half of the **TPC (24 VMM hybrids)+ scintillator wall.**
- DAQ test – **time synchronization** of detectors.
- **Rate capabilities:** scan up to a few 100 kHz.
- **Optimize HV and electronics settings** (test higher VMM gains).

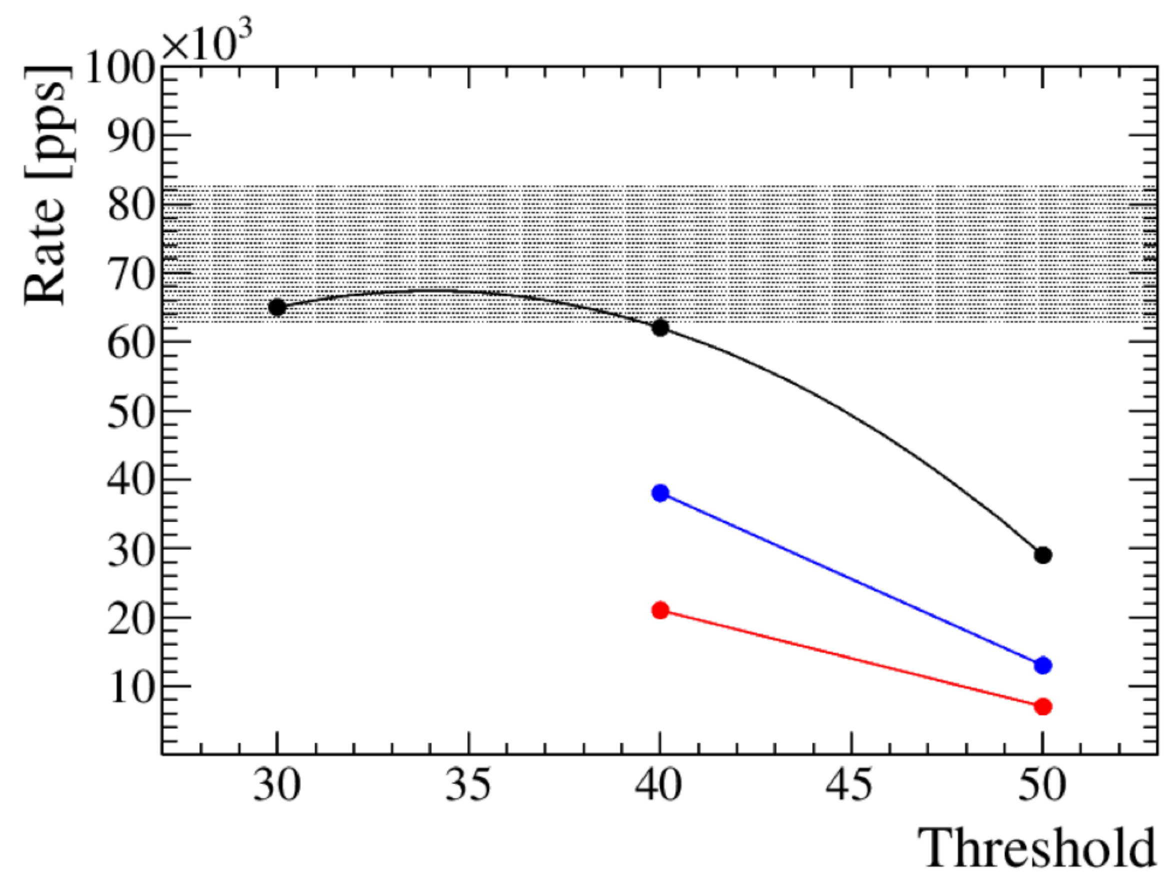




Conclusions

- A **characterization of SRS/VMM behavior** (gains, thresholds, limits) was achieved.
- The **operating region** of the TPC was outlined from gain–rate scans (MMG, GEM, ..).
- The **amplification chain** (GEM + Micromegas) was mapped with MMG scans.
- **Muon/pion tracking** was validated with clean events.
- It emerged that **higher VMM3 gain** and **testing an alternative gas** could improve amplification while reducing IBF.
- To achieve good detection capabilities with minimum IBF (<10k TPC amplification) **we need to increase the VMM gain** (>3 mV/fC).
- If we see we cannot operate at gain 4000 or similar, we may need to consider another gas (**T2K**).
- Space charge effects are still to be evaluated: this will be done with high rate runs.





HYDRA collaborators

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HYDRA core team:

- M. Duer (YI group leader), A. Lagni(PD), A. Enciu (PD), L. Ji (ex PhD), A. Obertelli, T. Aumann, D. Rossi, L. Fonseca (ex PD) S. Velardita (ex PhD), F. Horn **TU Darmstadt, Germany**
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- L. Fabbietti, R. Gernhaüser **TU Munich, Germany**
- H. Tornqvist **Chalmers University of Technology**
- Y. Wang **University of Cologne**
- S. Ota **University of Osaka, Japan**

HYDRA

Thanks for your attention!