A CONTINUOUSLY READ OUT TPC FOR ALICE

CERN Detector Seminar

24.06.2022

Robert Münzer on behalf of the ALICE Collaboration

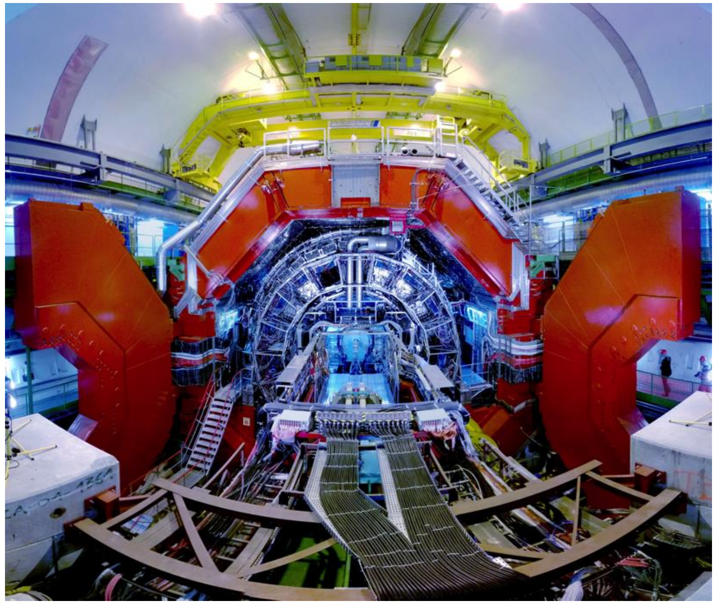
CONTENT

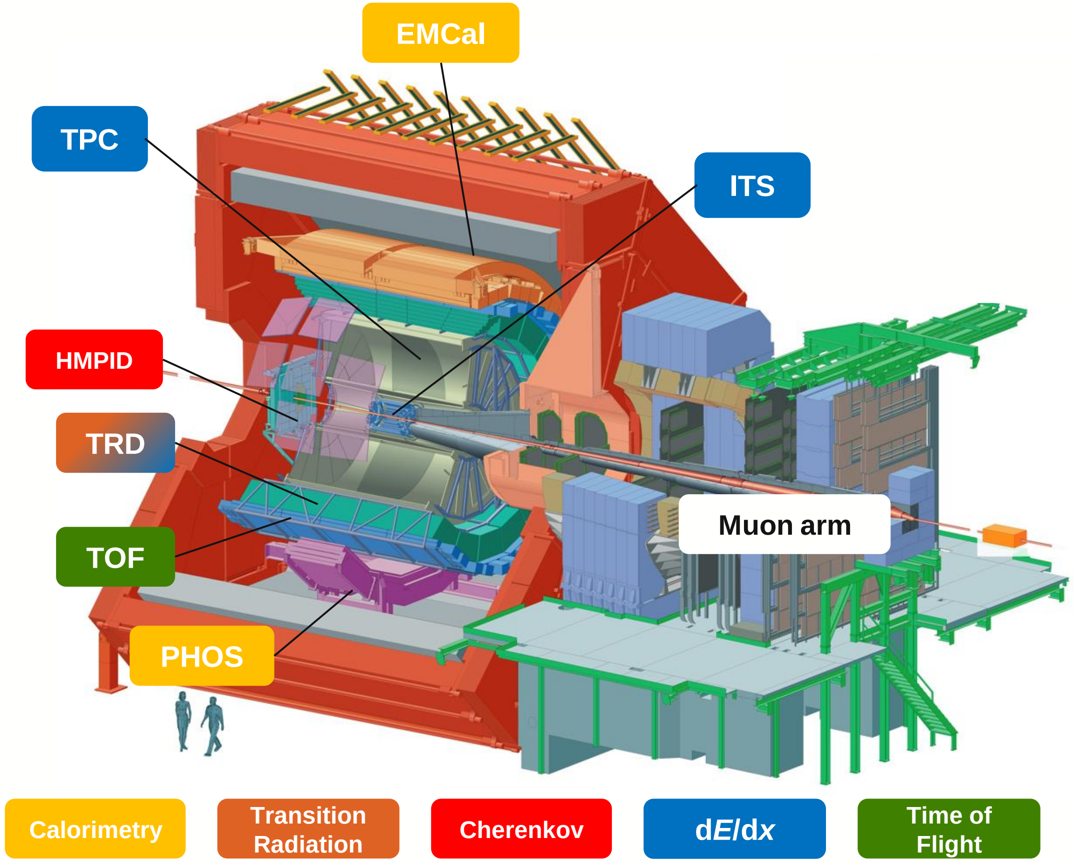
- Motivation for ALICE upgrade
- TPC upgrade
  - Read Out Chambers
  - HV system
  - Calibration system
  - Readout electronics
- Commissioning
  - Gain calibration
  - Chamber stability
  - Readout system
- Data from first collisions
- Summary and outlook

MOTIVATION

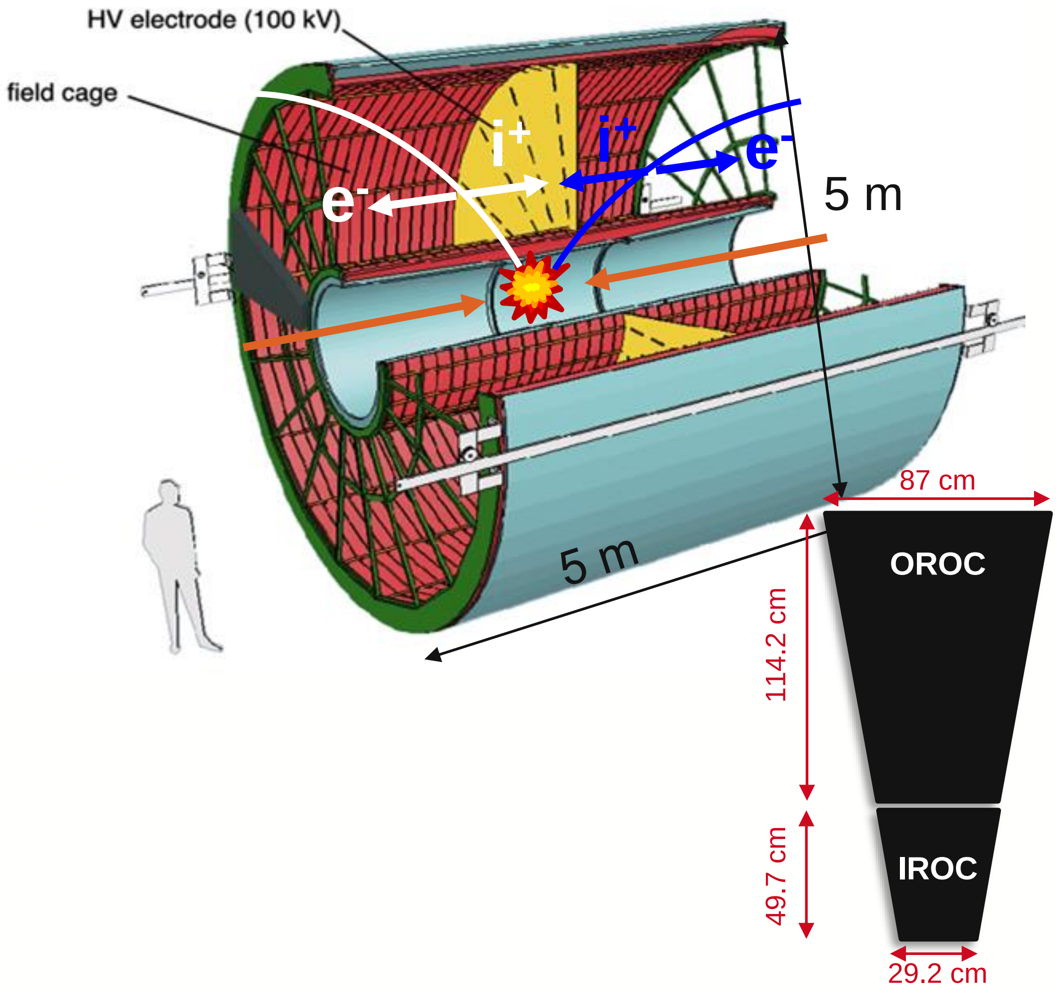
ALICE – A LARGE ION COLLIDER EXPERIMENT

- A dedicated heavy-ion experiment at the CERN LHC
- Study of a high-density, high-temperature phase of strongly interacting matter: quark-gluon plasma (QGP)
- **Unique PID capabilities** among all LHC experiments
- Covers broad kinematic range
- Many different PID techniques
- Excellent performance in Run 1 and Run 2



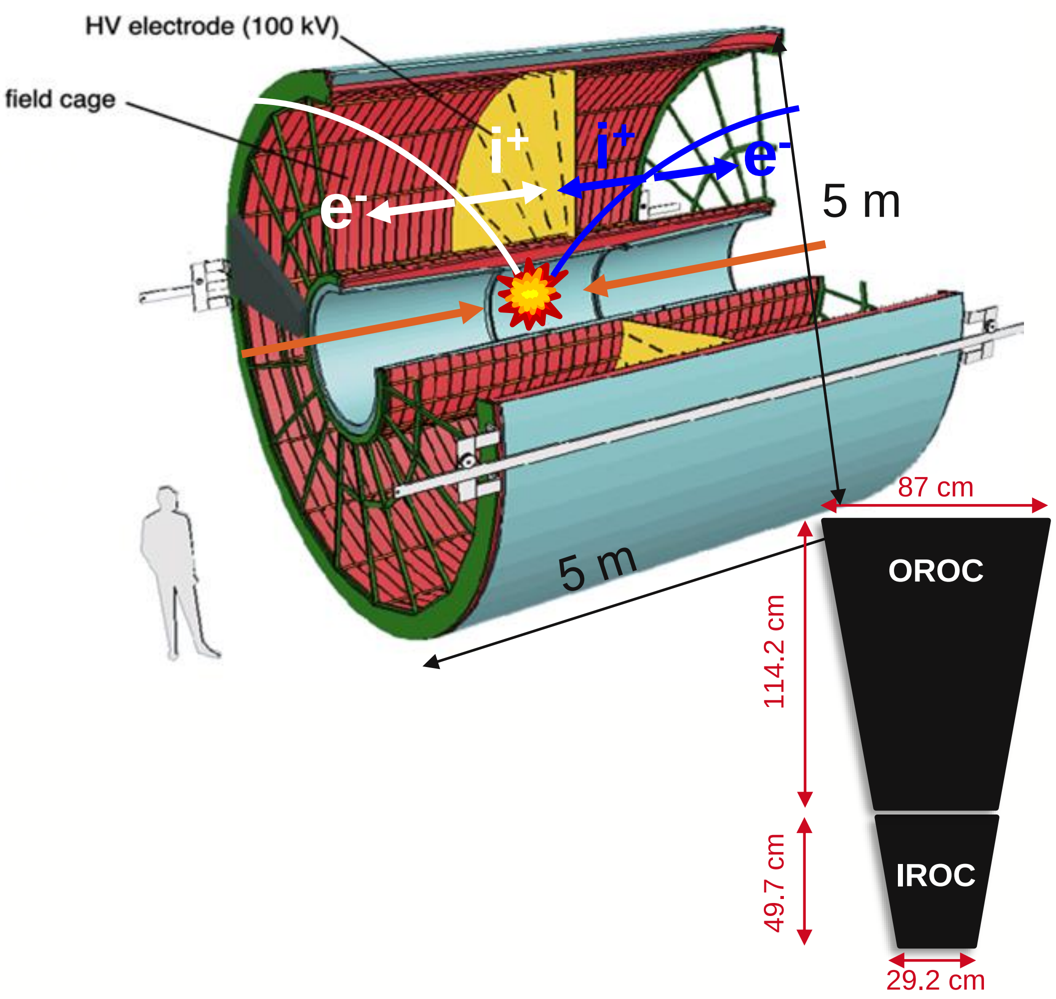


THE ALICE TPC



- Acceptance: $|\eta|<0.9$, $\Delta\phi = 2\pi$
- Low-mass, high-precision field cage
- ~90 m^3 active detector medium
- Gas:
  - Ne-CO_2-N_2 (90-10-5) in Run 1
  - Ne-CO_2 (90-10) in Run 1
  - Ar-CO_2 (88-12) in Run 2
  - Ne-CO_2-N_2 (90-10-5) in Run 2
- 100 kV at the Central electrode
  - E_{drift} = 400 V/cm
  - v_{drift} = 2.7 cm/μs
  - max t_{drift} = 92 μs
- 72 ROCs with pad readout
  - Employ gating grid
  - >550k pads in 152 rows
  - 2x18 Inner and 2x18 Outer Readout Chambers (ROCs)

THE ALICE TPC



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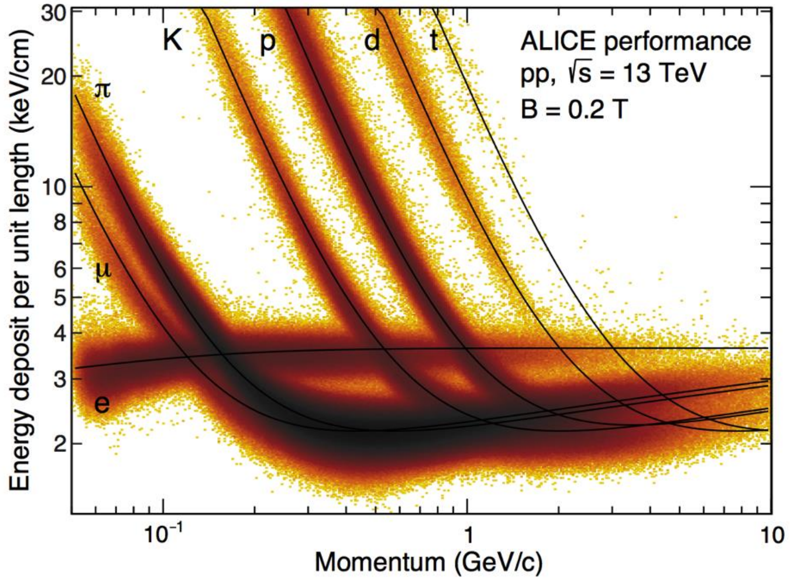
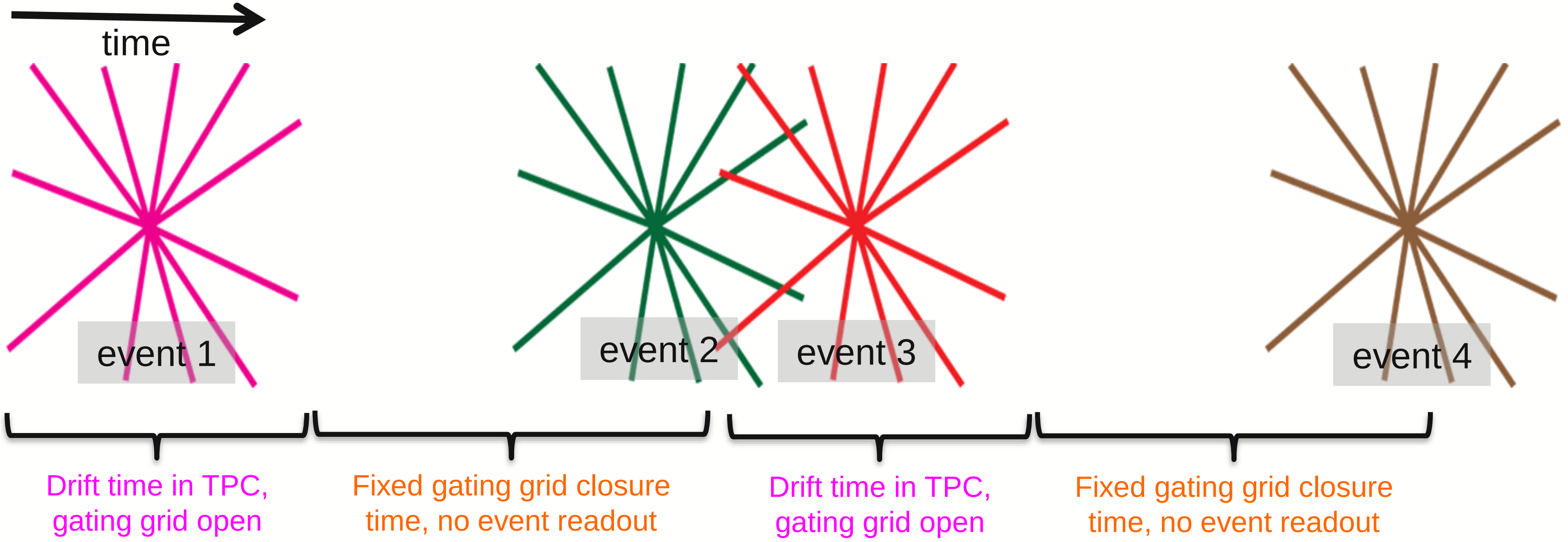


Phys. Rev. D **98**, 030001 (2018)

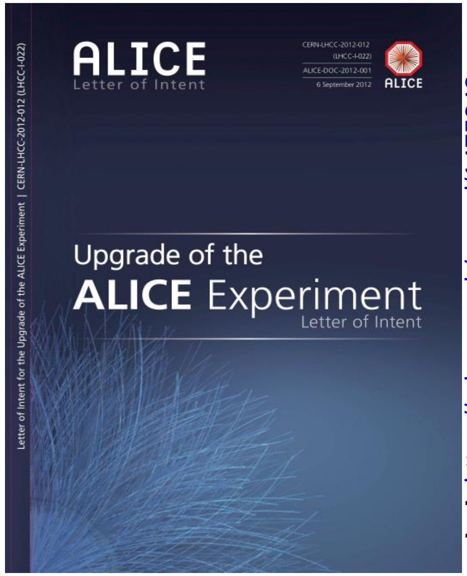
GATED OPERATION IN RUN 1 & RUN 2



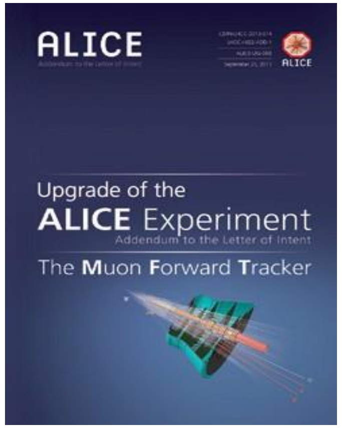
- **Multi Wire Proportional Chamber readout**
- A pulsed gating grid is used to prevent back-drifting ions from the amplification stage to distort the drift field (ion backflow (IBF) suppression ~10^{-5})
- 100 μs electron drift time + 200/400 μs gate closed (Ne/Ar) to minimize ion backflow and drift-field distortions
- **300/500 μs** in total limits the maximal readout rate to **few kHz** (in pp)
- Limitation of readout electronics: ~kHz in Run 2 **(2017 pp: 2040 Hz)**

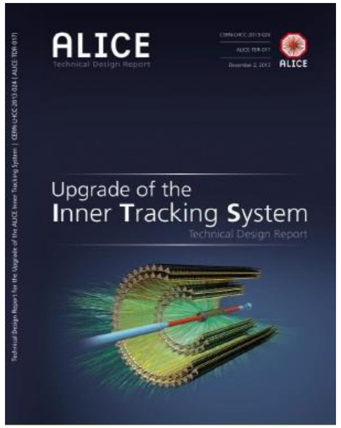
ALICE UPGRADE

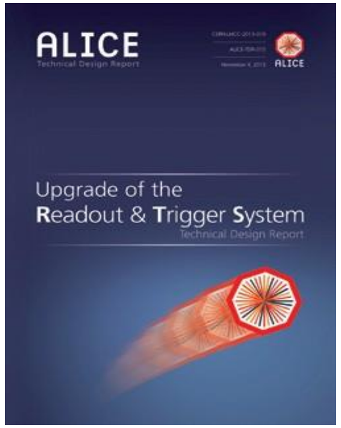
- **Motivation**: high-precision measurements of rare probes at **low p_t**
  - ✓ cannot be selected with hardware trigger
  - ✓ need to record large sample of events
- **Goal**: operate ALICE at high rate, record all MB events
  - ✓ 50 kHz in Pb-Pb (~10 nb^{-1} in Run 3 and Run 4)
  - ✓ no dedicated trigger, reduce data size (online reconstruction + compression)
  - ✓ preserve PID



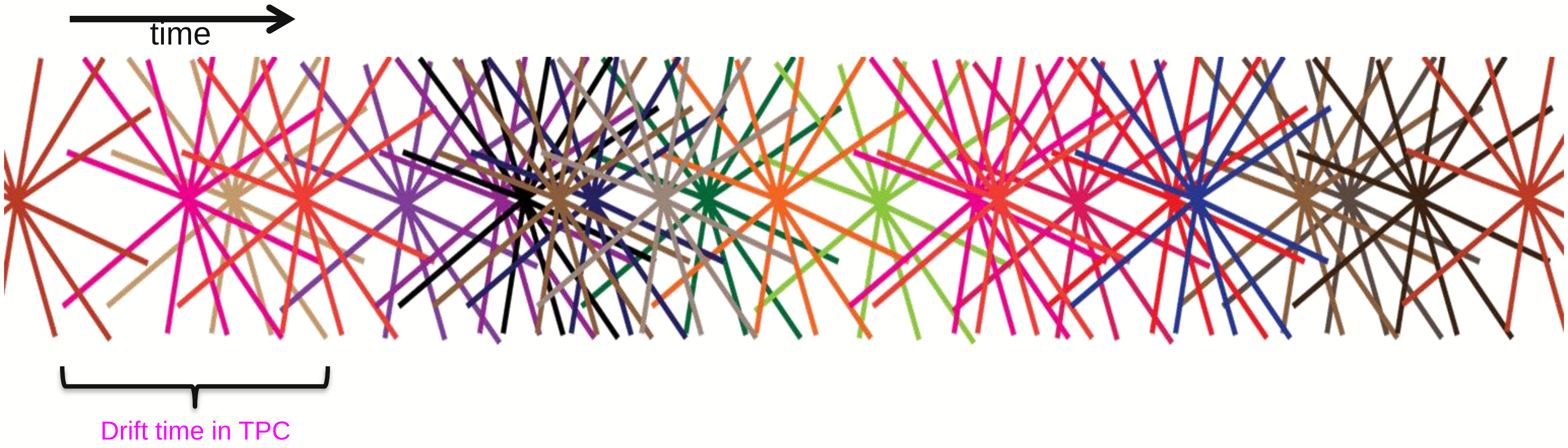
LoI: https://cds.cern.ch/record/1475243







CONTINUOUS OPERATION IN RUN 3 AND BEYOND



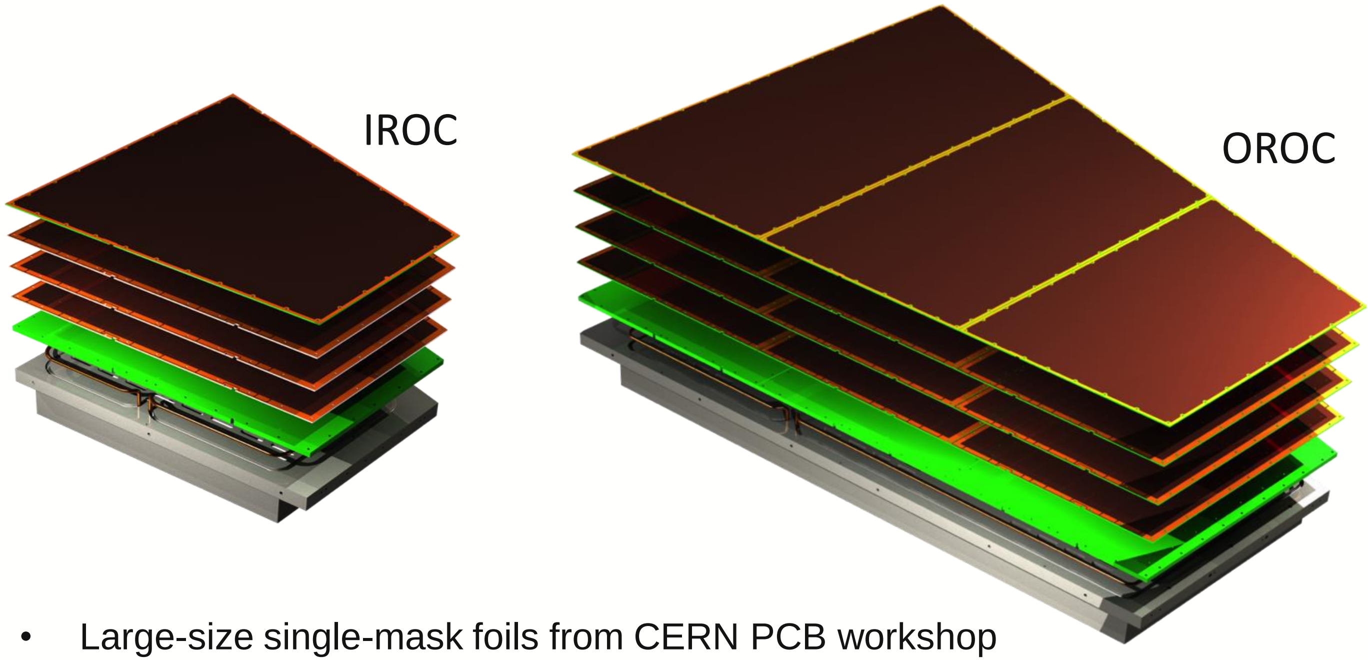
- Maximum drift time of electrons in the TPC: ~100 µs
- Average event spacing: ~20 µs
- Event pileup: 5 on average
- Triggered operation not efficient
- Minimize IBF without the use of a gating grid

- **Continuous readout with GEMs (Gas Electron Multiplier, F. Sauli 1996)**

F. Böhmer et al., NIM A 719 (2013) 101

TPC UPGRADE

GEMS FOR THE UPGRADE



- Large-size single-mask foils from CERN PCB workshop
- 1 stack in IROC, 3 stacks in OROC

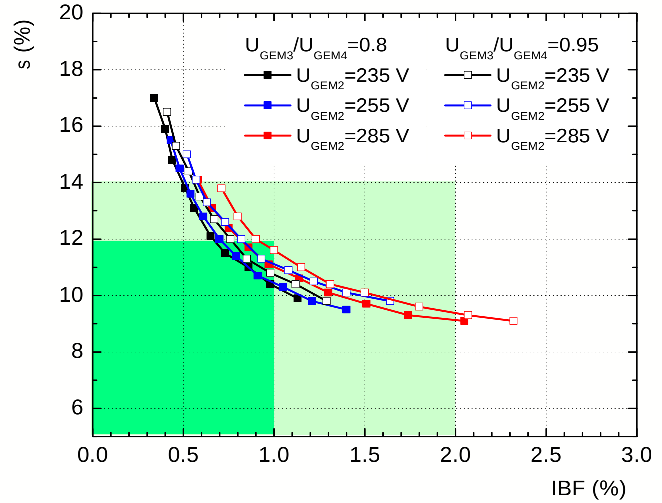
Requirements:

- Operate at the gain of 2000 in Ne-CO_2-N_2 (90-10-5)
- IBF < 1% at gain = 2000 → $\varepsilon = 20$
- Local energy resolution $\sigma_E/E < 12\%$ for ^{55}Fe
- Stable operation under LHC conditions

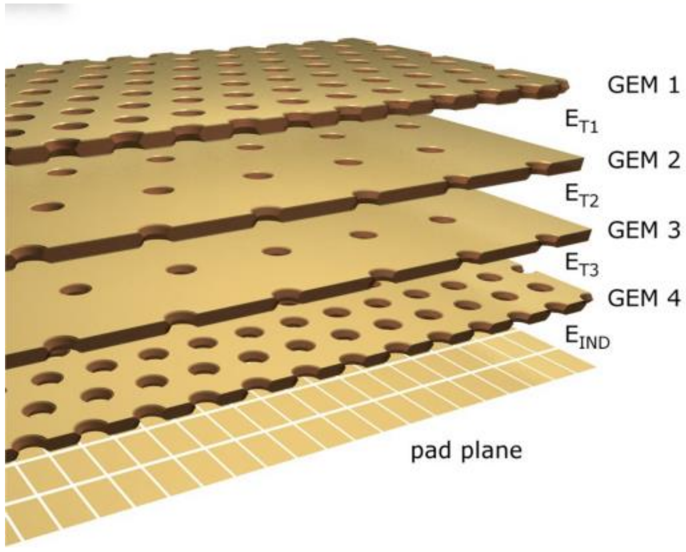
ALICE

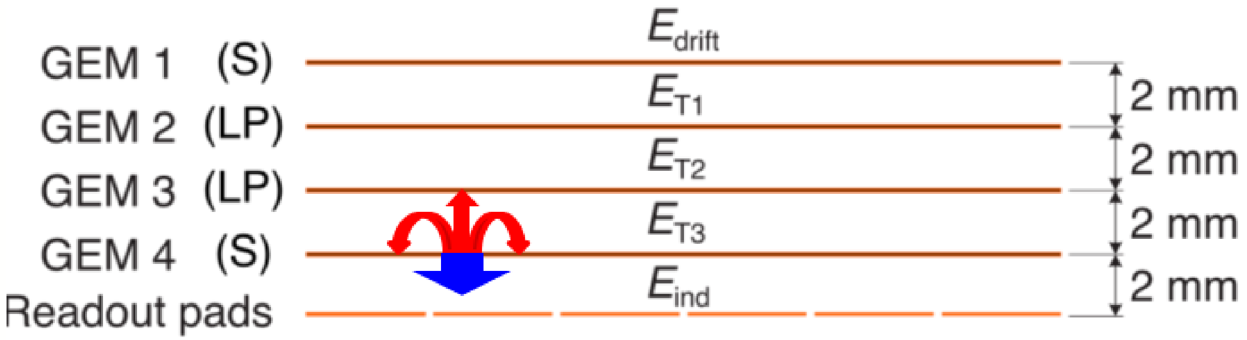
IBF SUPPRESSION

- Three measures to suppress the ion back flow into drift region:
  - Low gain in GEM 1, highest in GEM 4
  - Two layers of large pitch (LP) foils (GEM2 and GEM 3) block ions from GEM 4
  - Very low transfer filed E_{T3} (100 V/cm) between GEM3 and GEM4



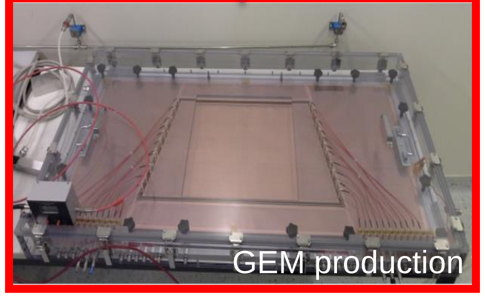
Performance with optimised HV configuration
IBF = Ion BackFlow
σ = energy resolution for ^{55}Fe

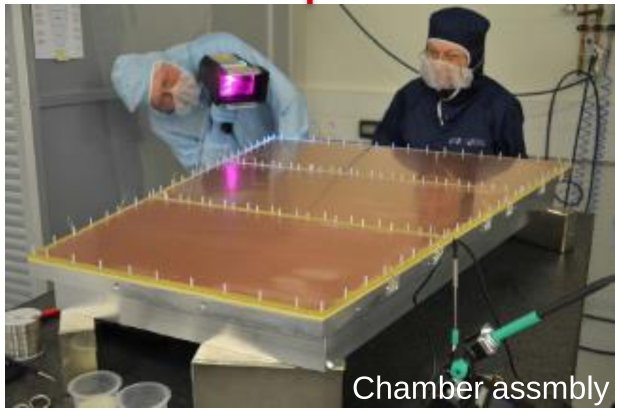


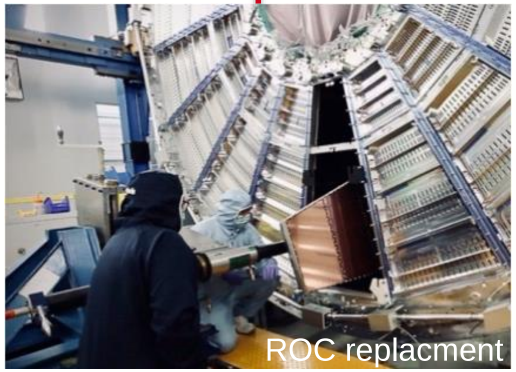


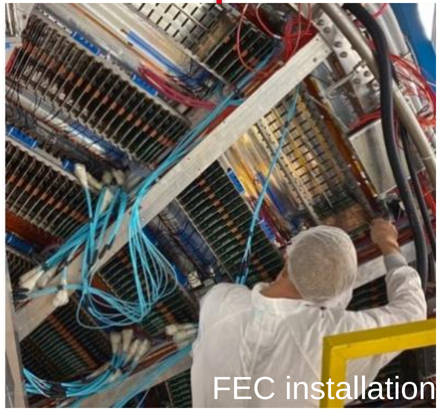
UPGRADE TIMELINE

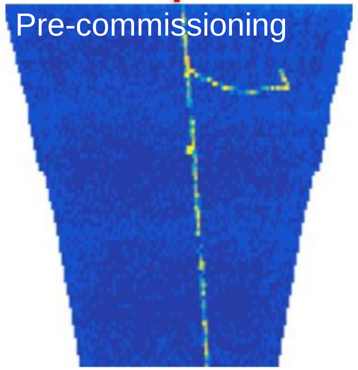
Aug 2016 — March 2017 — May 2019 — Sep 2019 — Nov 2019 — Aug 2020 — Dec 2020 — Oct 2021

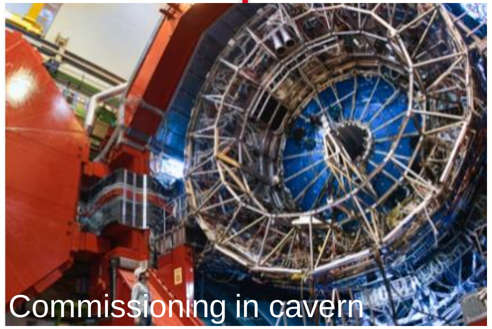


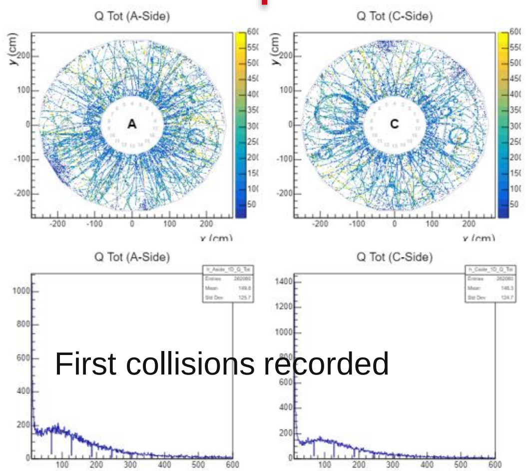








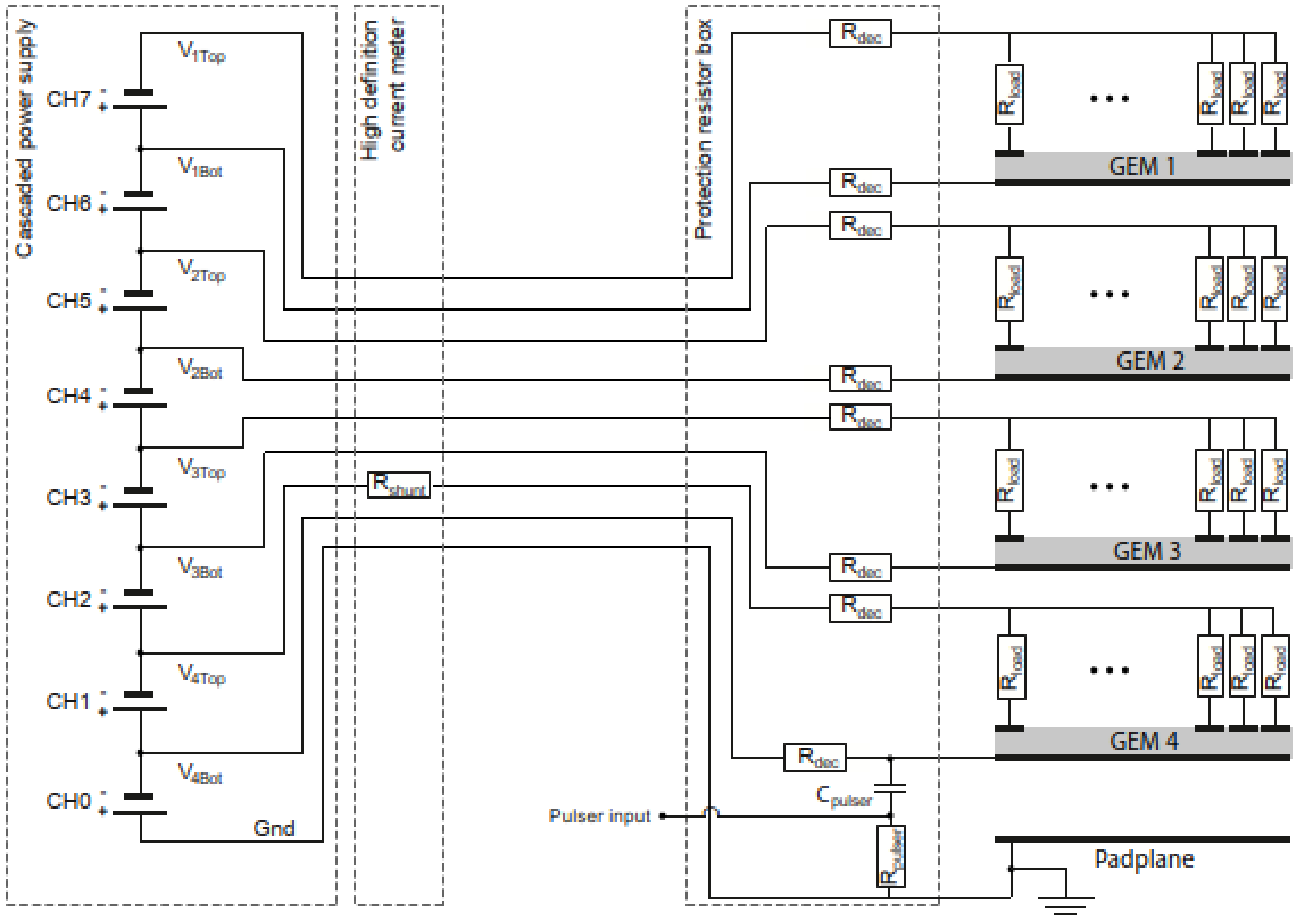




HV SYSTEM

HV SYSTEM

GEM powering schema



Requirement for HV system:

- Protection of GEM: Each HV line has a resitor (R_{dec} = 500 kΩ) - installed close to the chamber – to protect against secondary discharges

- Flexibility:
  - Allow operation also with shorts in single GEM segements (seperatly powered area on each GEM top side)
  - Loading resistor (R_{load} =5 MΩ) allow for up to 15 shorts

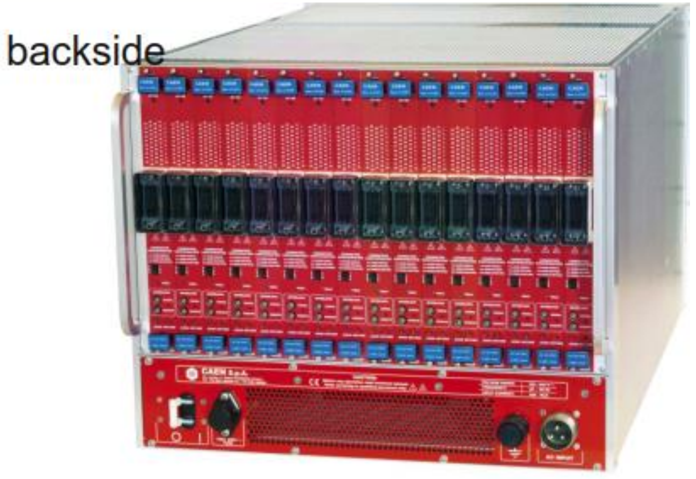
- Monitoring
  - Measure current for each GEM stack via R_{shunt} with resolution <1nA.

HV SYSTEM – HIGH VOLTAGE POWER SUPPLIES

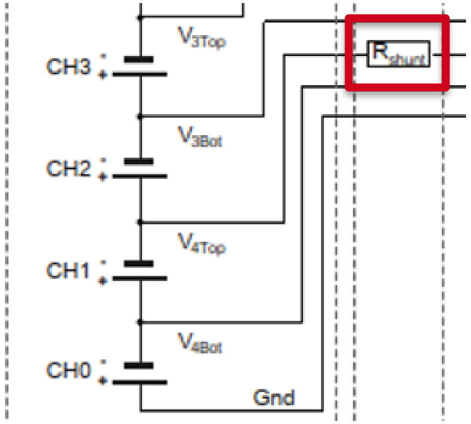
- CAEN A1515QGA
  - 8 channel cascaded floating HV PS, dedicated for GEM operation
  - Output: 1kV
  - Current Resolution: 100pA (High Resolution Mode) / 1nA (High Power mode)
  - Current limitation and trip delay (steps of 0.1 s)

- GEM operation at ALICE
  - Great flexibility: Each voltage can be adjust separately
  - Trip behavior provides good protection for GEMs

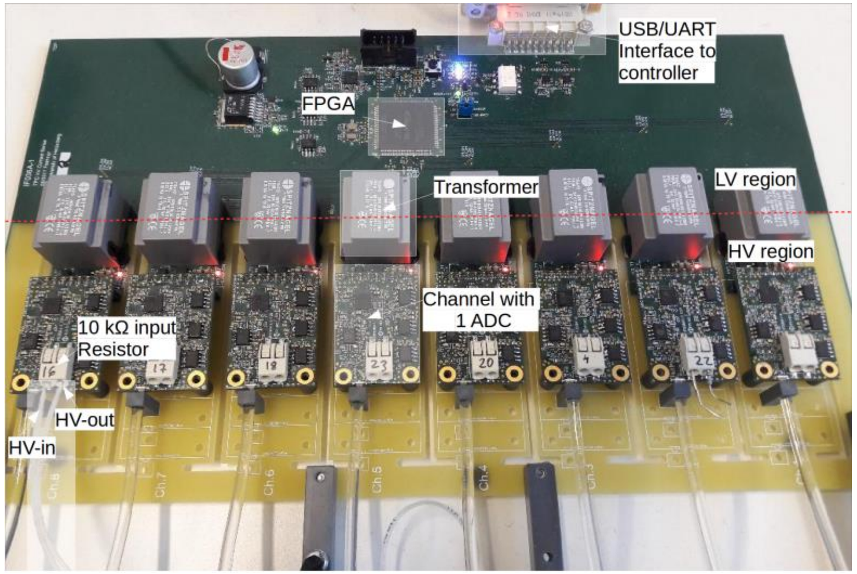
  - Additional software protection to detect missing and/or swapped cables



HV SYSTEM - CURRENT MONITOR



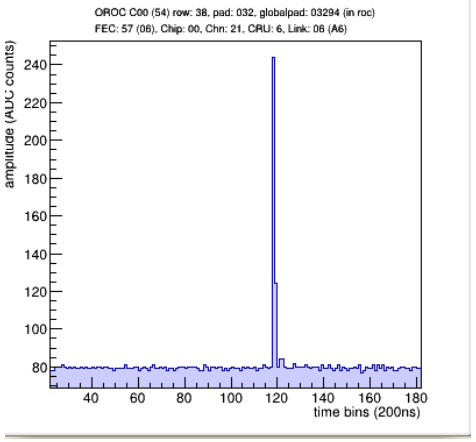
- Correction of space charge distortions require monitoring of local fluctuation
- Additional current measurement of GEM4 for each individual stack
  - High frequency (1kHz)
  - high precision current reading (24bit / 128uA)
  - Data inserted in raw data stream for online calibration and reconstruction
  - Additional monitoring in detector control software

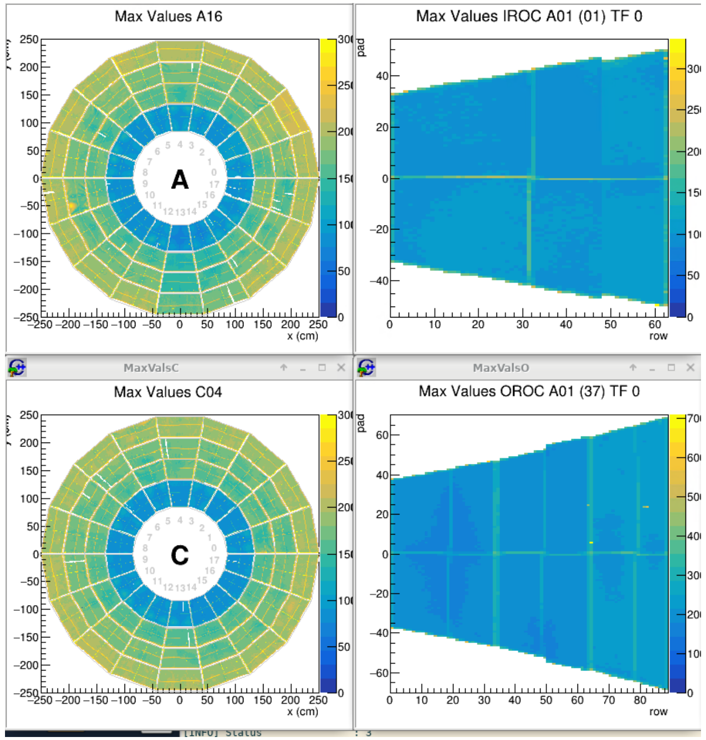


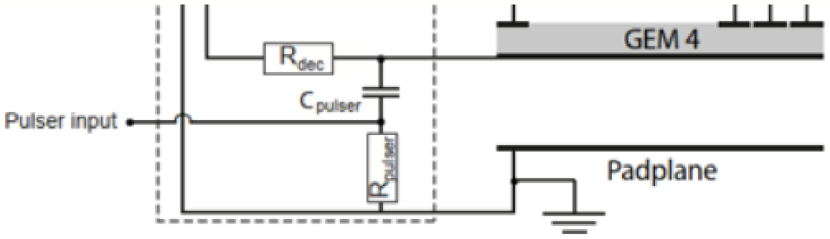
CALIBRATION SYSTEM SETUP (LASER/PULSER)

CALIBRATION PULSER SYSTEM

- Goal:
  - Pad response measurement
  - Common Mode calibration
- Signal induced via coupling capacitor of 10nF to GEM4B
- Signal amplitude: 7V
- Trigger rate: 90 Hz
- Syncronized with readout system

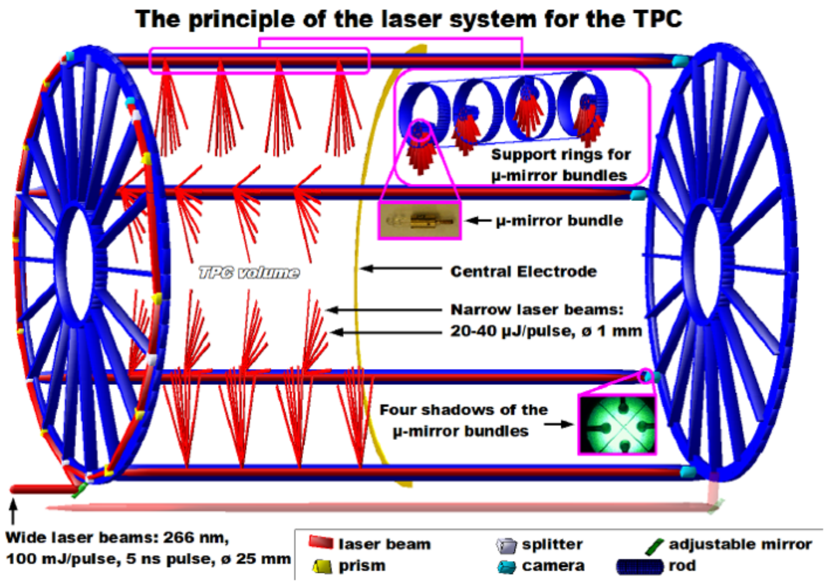


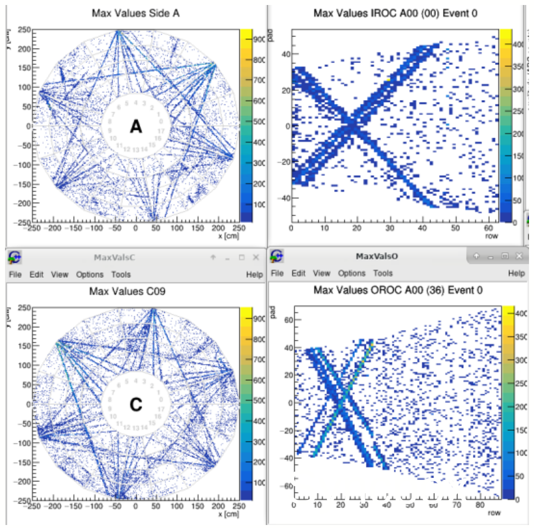




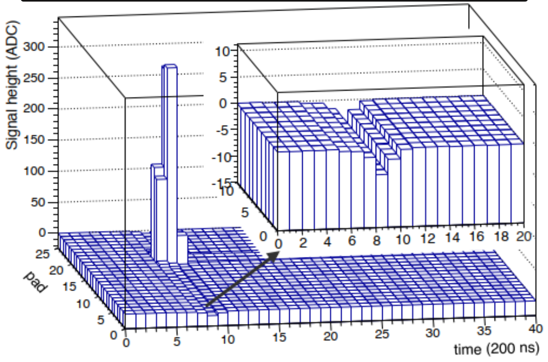
LASER SYSTEM

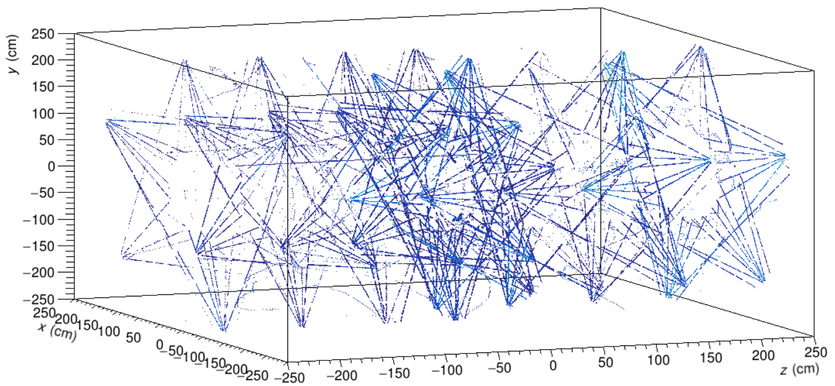
- Function
  - Alignment
  - Drift velocity measurement
  - Drift field distortions
  - Common Mode calibration
- Laser calibration system from Run1 & Run2
  - Two redundant lasers
  - 100mJ/pulser, 5 ns pulser, λ=266 nm
  - 10 Hz trigger rate





Common mode in adjecent pads



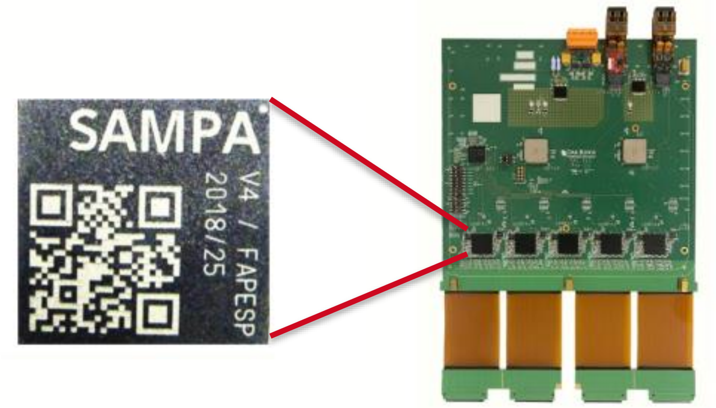


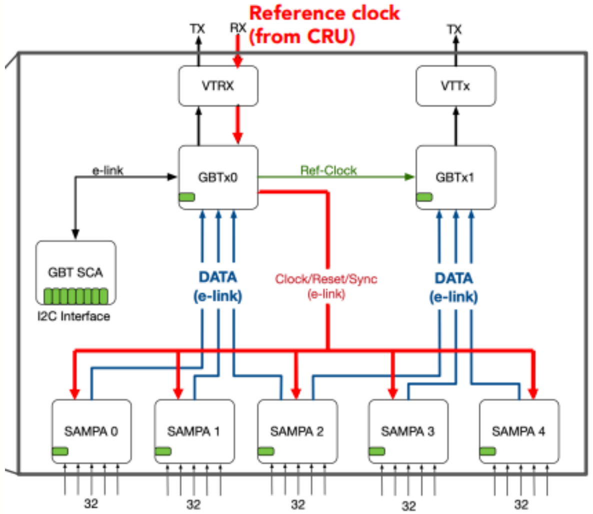
READOUT ELECTRONICS

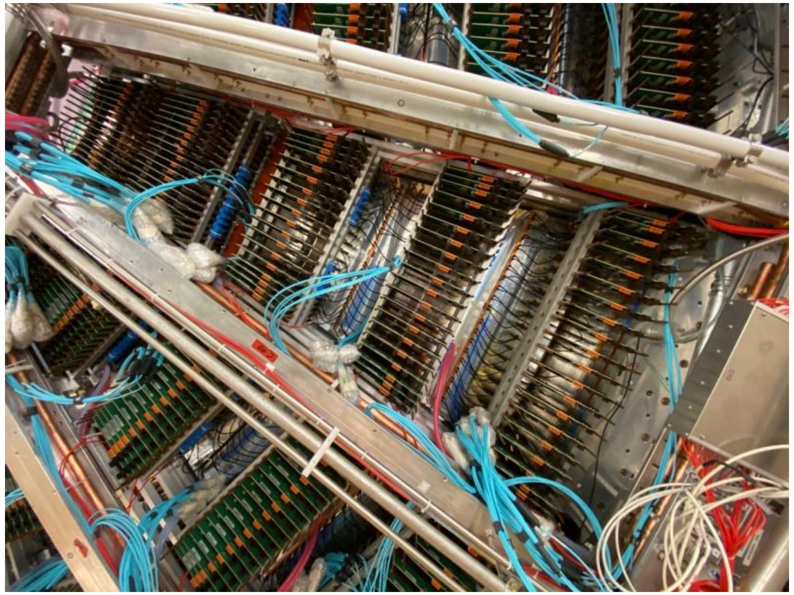
READOUT SYSTEM – FRONT END CARDS

- Newly developed FE ASIC SAMPA (120nm TSMC CMOS)
  - 32 channels with pre-amplifiers, shaper and 10 bit ADC
  - Readout mode: continous or triggered
  - Also used in the ALICE Muon spectrometer

- Front-End Cards (FECs)
  - 5 SAMPA chips per FEC (3276 FECs in total)
  - Continious sampling at 5 MHz
  - Total data rate: 3.3 TB/s
  - Readout link CERN GBT/ Versatile link system

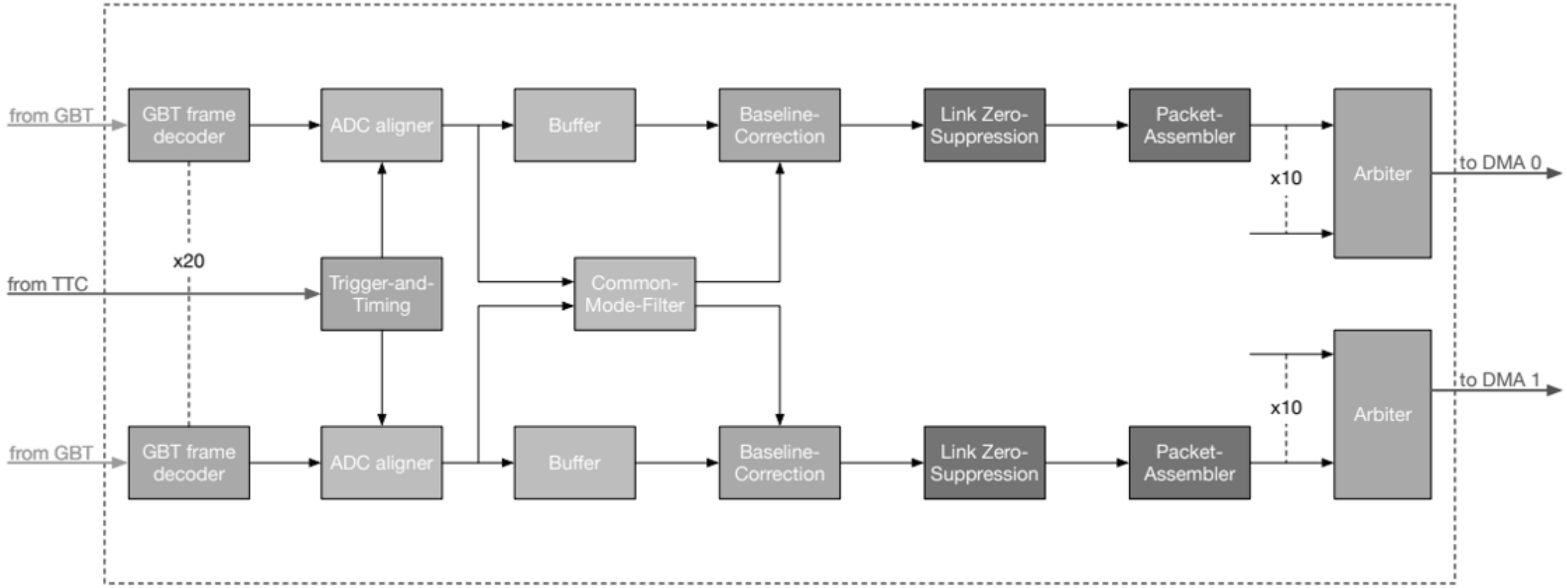




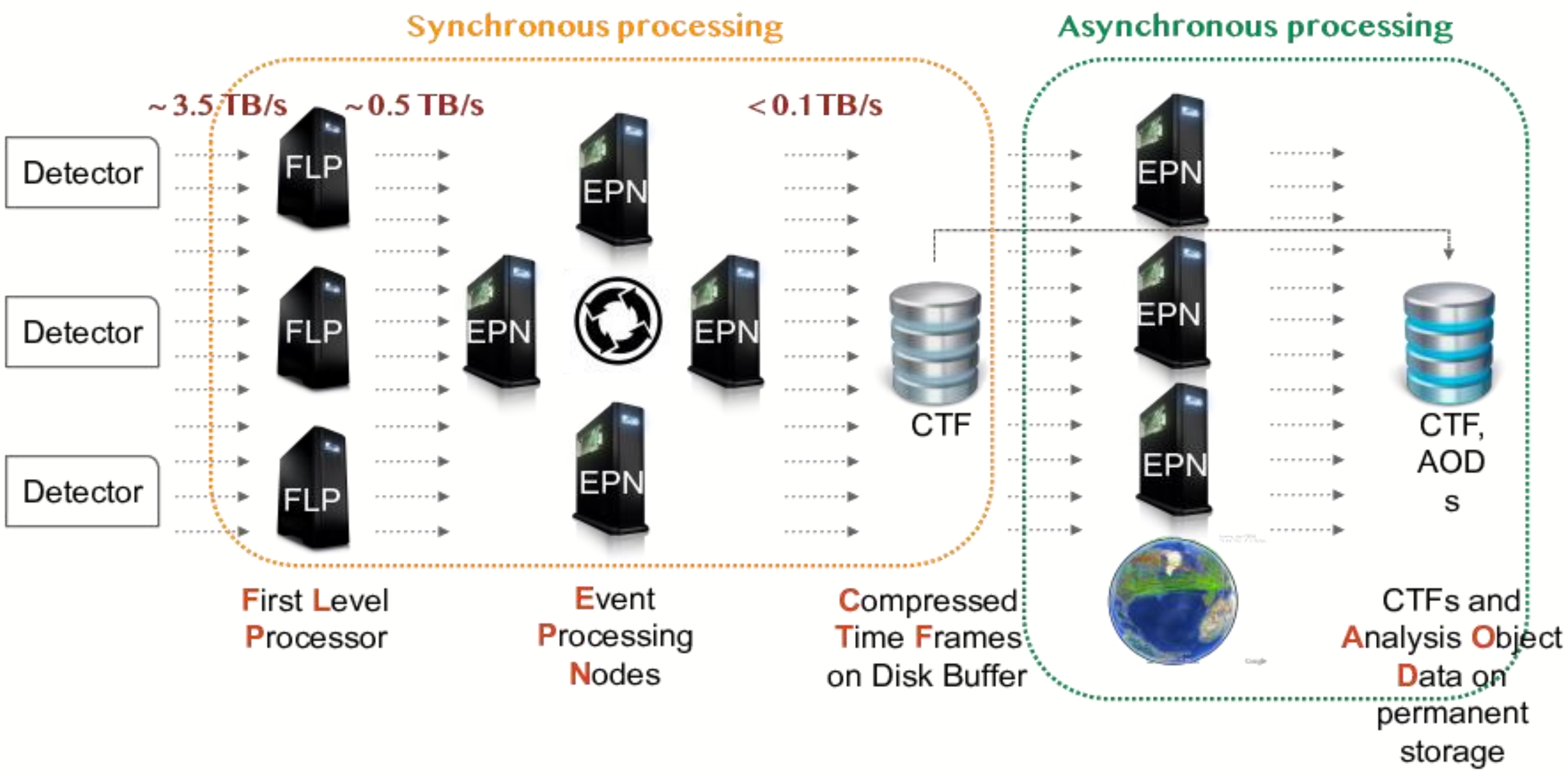


READOUT SYSTEM – CENTRAL READOUT CARDS (CRU)

- Contiuous data are read out in Time Frames (TF) of typical length ~11 ms (~100 drift times)
- Data processing on CRU:
  - GBT frame decoding
  - Base line correction (Zero suppression)
  - Common mode correction
  - Data formatting/packing (Optimized form for online reconstruction)
  - Calculation of integrated digital currents



ALICE DATA PROCESSING



First Level Processor (FLP):

- 200 nodes

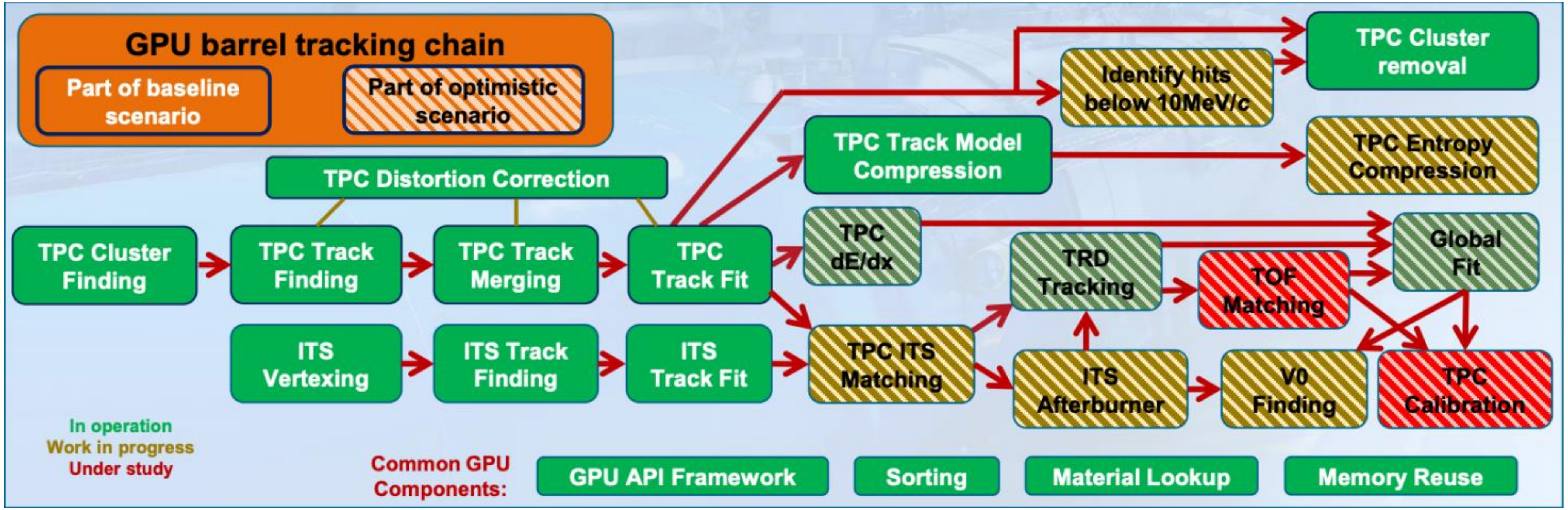
Event processong Nodes (EPN):

- 250 dual core AMD Rome
- 8 AMD MI 50 GPUs
- Event building
- Online reconstruction
  - Clusterization
  - Tracking
  - Track matching
- Calibration

Compression factor: ~7x ~100x

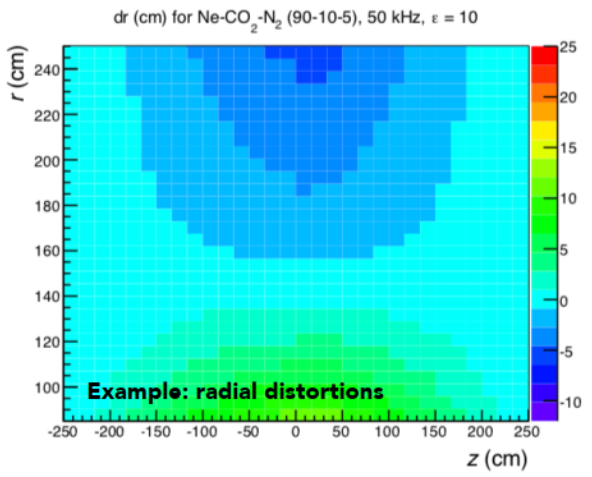
O2: ONLINE RECONSTRUCTION / GPU PROCESSING

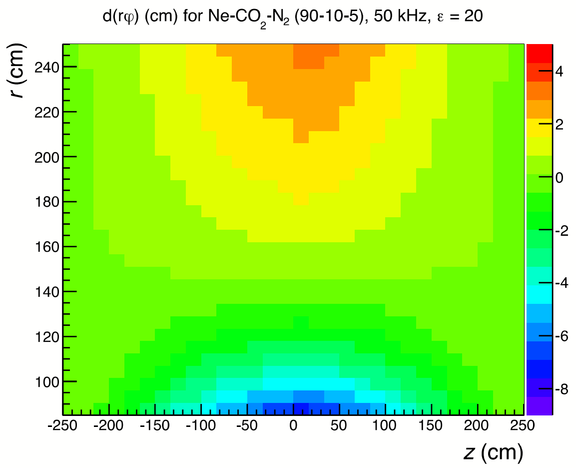
- Framework: Cross-platform; can be run on both GPUs and CPUs
- Goal: Use GPU for as many tasks as possible
- Basic components implemented and operated during pilot beams, including synchronous reconstruction
- Further tasks are being completed and consolidated

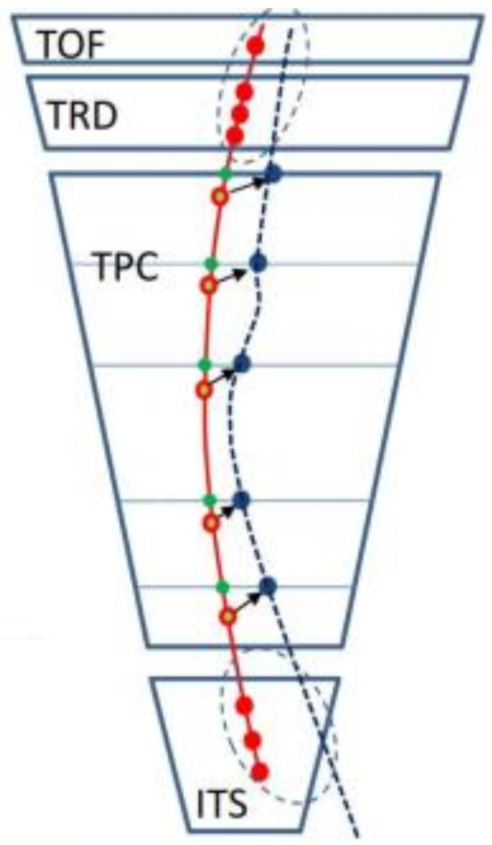


SPACE CHARGE DISTORTIONS

- Ion back flow reduced by GEM stacks
- Remaining distortions require space-point corrections
- Correction using track interpolation (experience from Run 1 and Run 2)
  Calculate average distortion map which is slowly changing with collision rate
- In addition: fluctuations around average distortions
- Fluctuations can be extracted by:
  - Integrated ADC values over one ion drift time (Integrated digital currents)
  - Reading of analog current of GEM4T with 1kHz (Sampled analog currents)







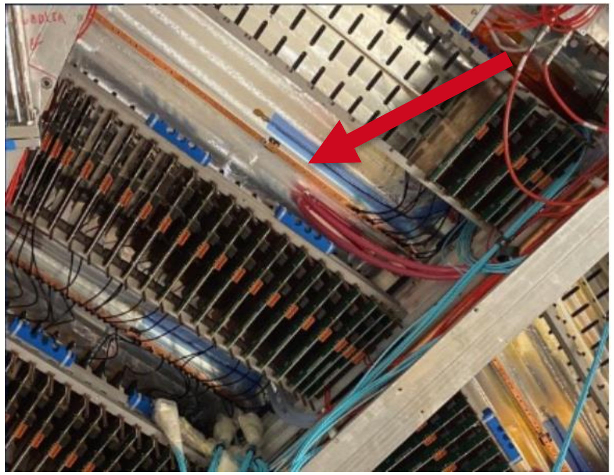
GLOBAL COMMISSIONING

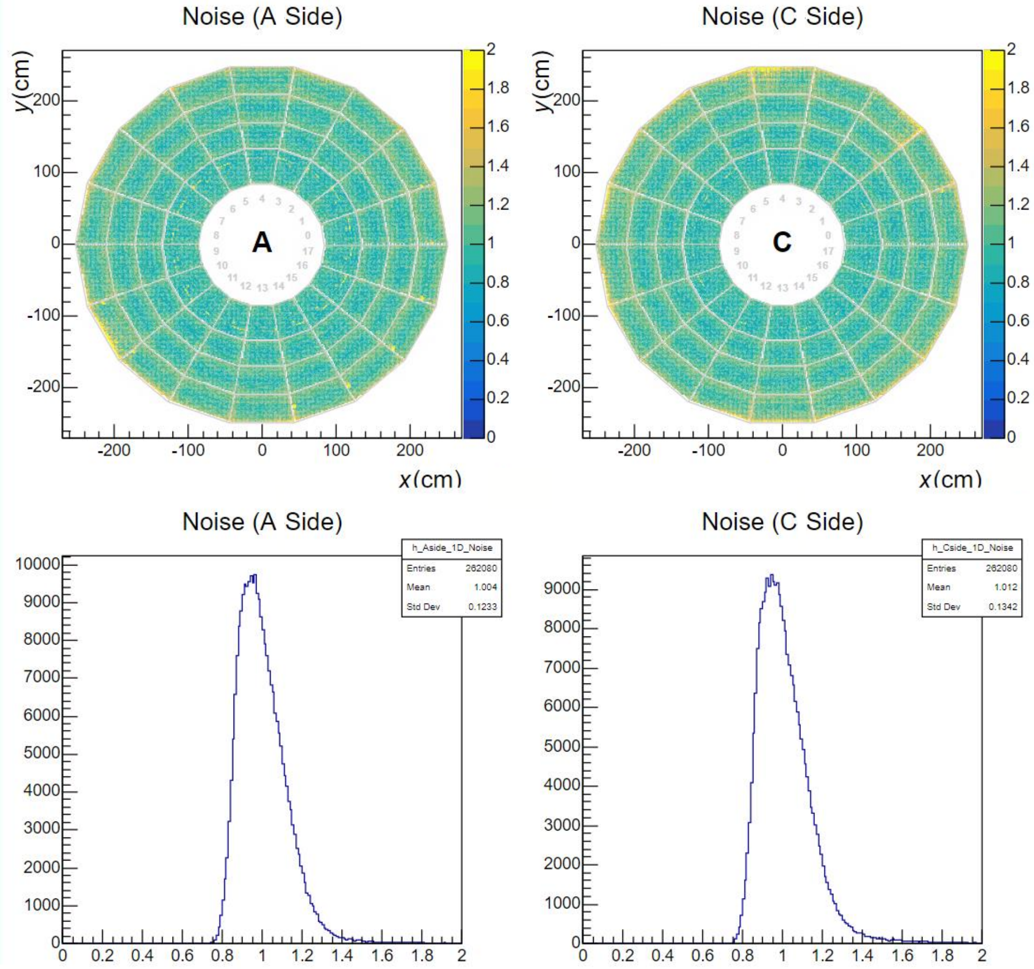
TPC NOISE

Noise Situation

- Noise distribution
  - Mean: 1.004 (A Side) / 1.012 (C Side)
  - Equal to design value of 1 ADC channel (ENC of 678 e^-)

- Distribution biased by auxiliary components
  - IROC: Noise induced by temperature sensors mounted on chambers close to FECs
  - OROC: readout of Field Cage currents near chamber edges
  - Both are read out via ELMB *
  - Noise could be reduced significantly by optimized grounding/shielding + ferrites

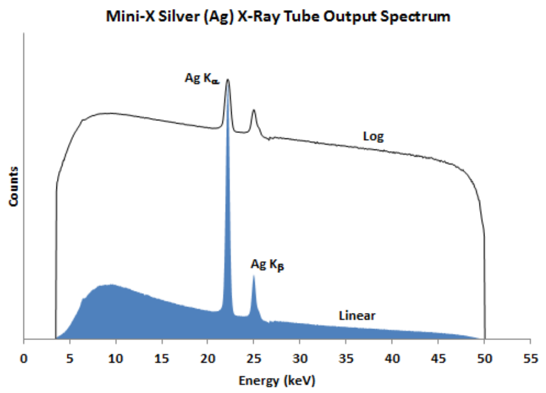


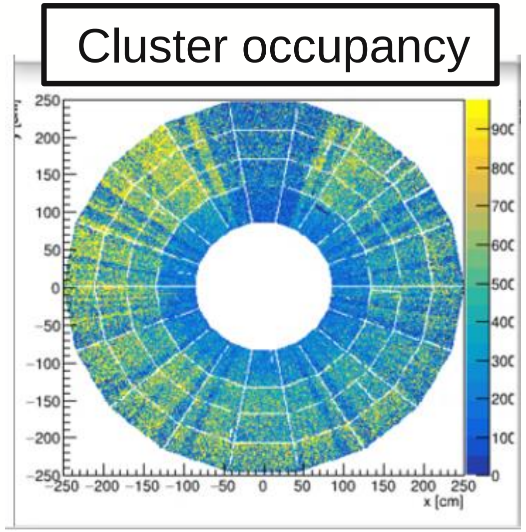


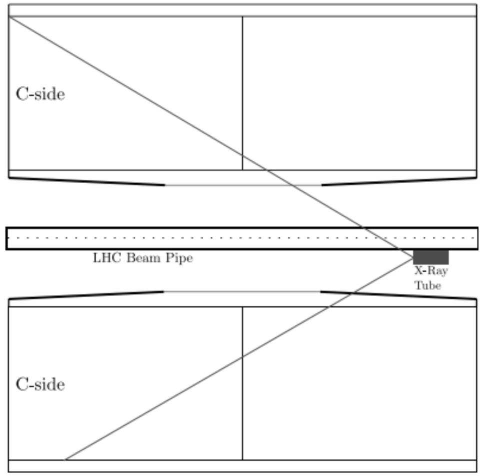
*ELMB: Embedeed Local Monitor Board

X-RAY CALIBRATION

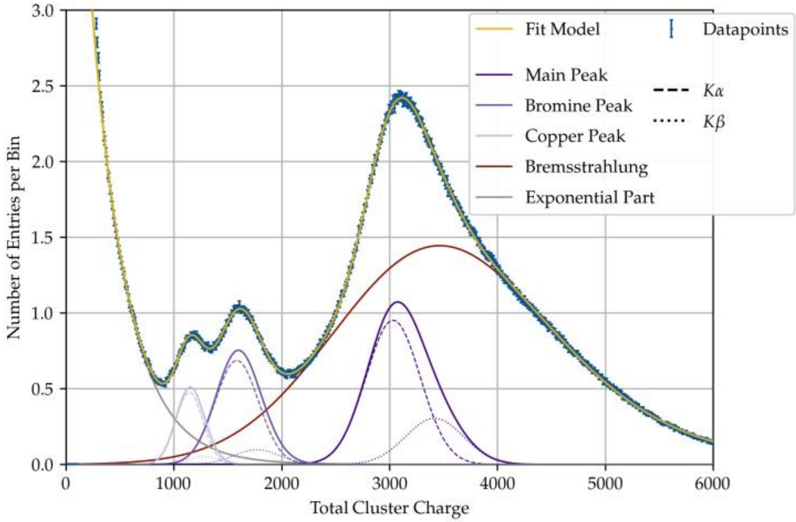
- Amptek mini-X :
  - Ag target: U_{max}= 50 kV / I_{max} = 80 uA
  - Current on GEMs similar to expected currents in Run3
- Pre-commissioning in clean room
  - Study chamber stability
  - Two sectors read out at a time; development of calibration routine
- Commissioning in cavern
  - Readout of Full TPC; extraction of full gain map
  - Stability studies
  - Bias due to material installed inside TPC (beam pipe, services for trackers)
- Sufficient statistics for gain map





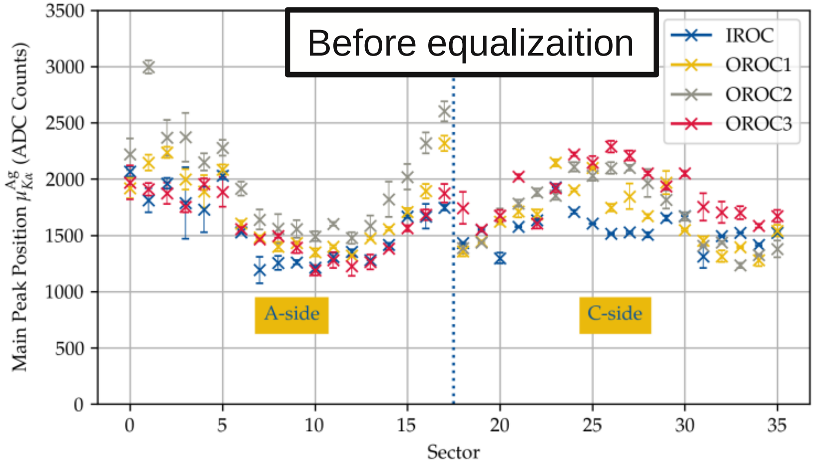


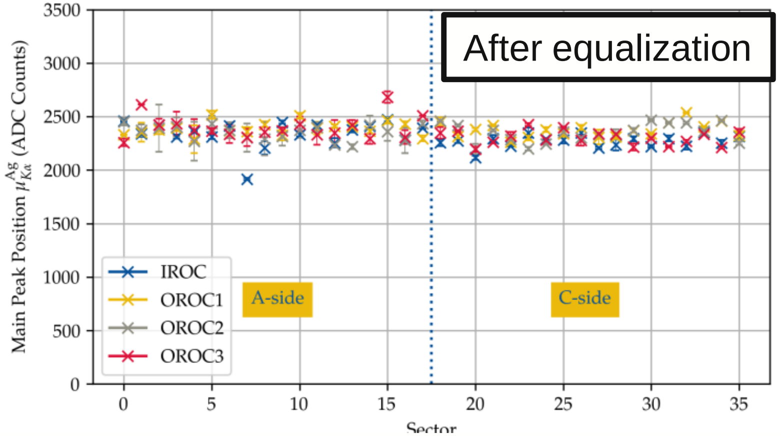
GAIN EQUALIZATION WITH X-RAYS



- Fit model to described full disribution
  - K_α and K_β from Ag X-ray tube
  - Copper flurescence from GEMs
  - Bromine flurescence from vessel material
  - Continuous x-ray emmision

- Pad-wise correction applied
- Spectrum for individual stacks. Interative process to equalize gain
- Tuning of gain by adjusting GEM3/GEM4 potential to minimize effect on IBF
- N.B. total potential on GEM 1T has to be equal among all stacks to match drift field

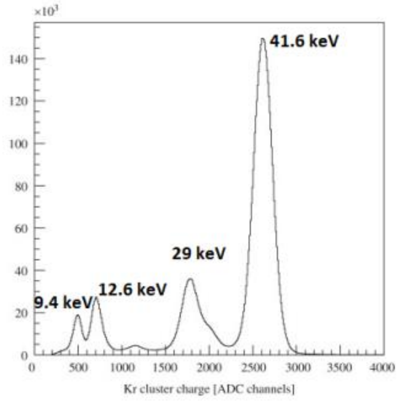




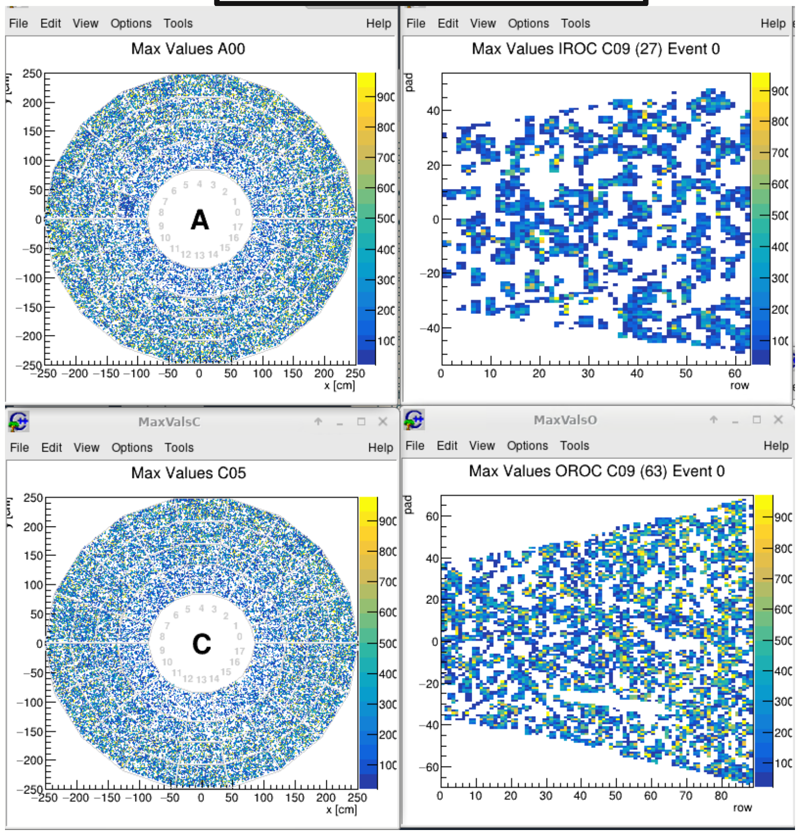
GAIN EQUALISATION WITH ^{83}KR DECAYS

- Common method to calibrate TPCs
  - Well know spectrum
  - Already used in Run 1 and Run 2 for calibration of TPC with MWPC
- ^{83}Rb decays to ^{83m}Kr
  - Rb lifetime : 86 days
  - Implanted into polyimide foil, produced at ISOLDE

[Alme et al. – NIMA 622 – 2010]



Online screenshot



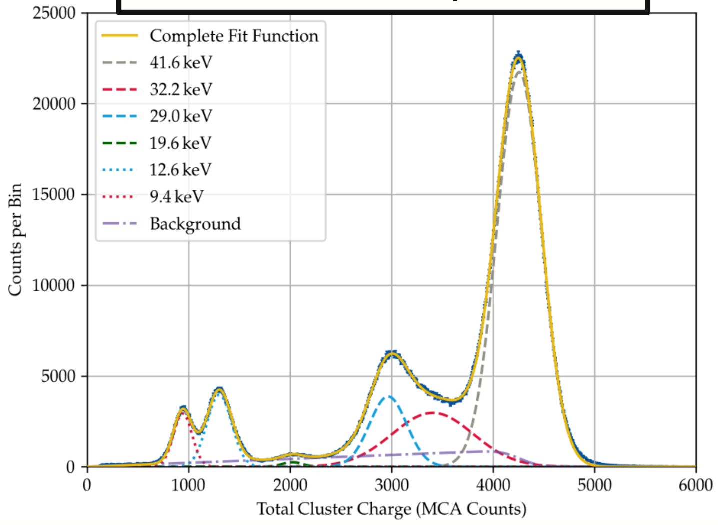
KRYPTON CALIBRATION

- Common method to calibrate TPCs
  - Well know spectrum
  - Already used in Run 1 and Run 2 for calibration of TPC with MWPC
- ^{83}Rb decays to ^{83m}Kr
  - Rb lifetime : 86 days
  - Implanted into polyimide foil, produced at ISOLDE
- Further tuning of HV of stack
- Pad-by-pad calibration

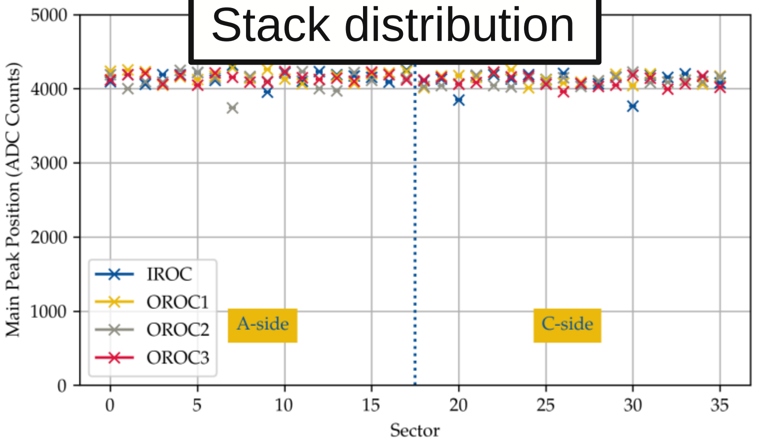
- Goal:
  - Energy resolution: σ_E/E = 12% @ K(α) of ^{55}Fe
  - Corresponds to: σ_E/E = 4.5% @ 41.6 keV (Krypton main peak)

- Energy resolution:
  - Measured value: σ_E/E = 5.8%
  - Iterative calibration procedure. Gain correction before clusterization
  - Effect due to electron attachment: ~11% of charge loss (few ppm of O2)

Measured Kr spectrum

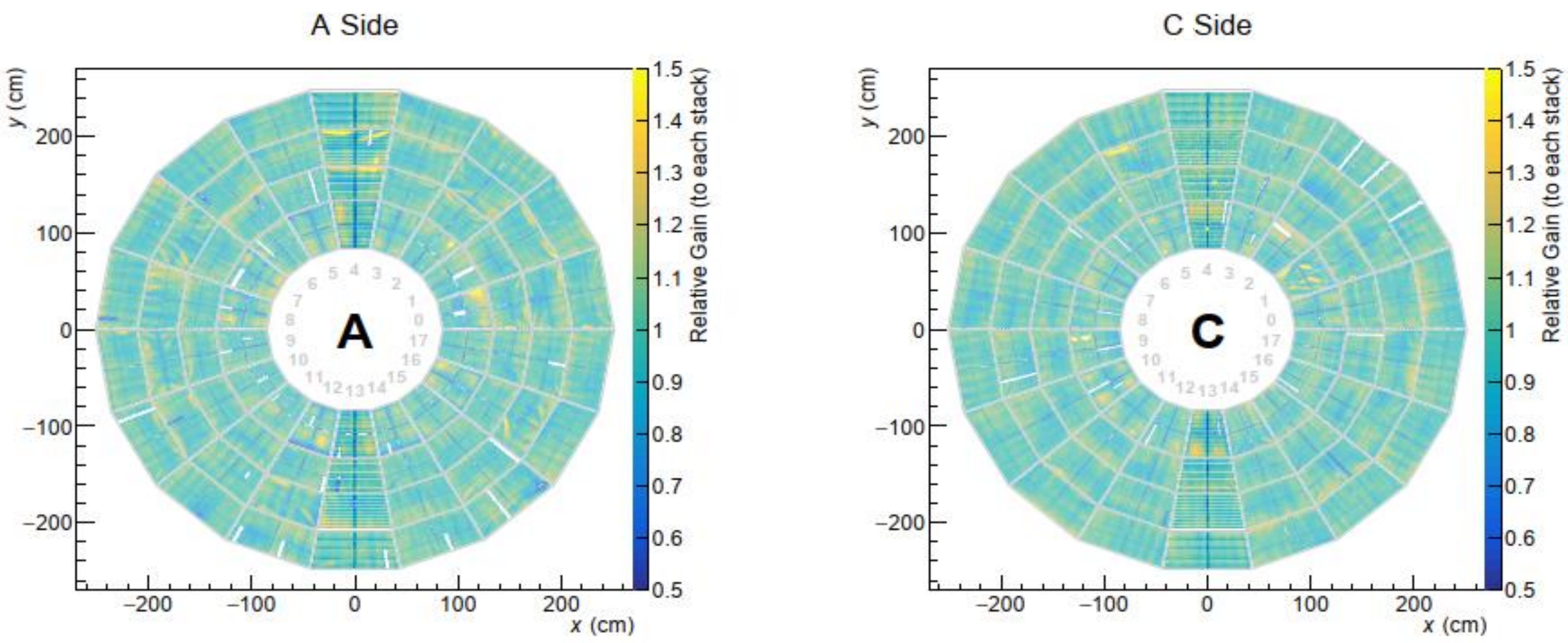


Stack distribution



KRYPTON CALIBRATION

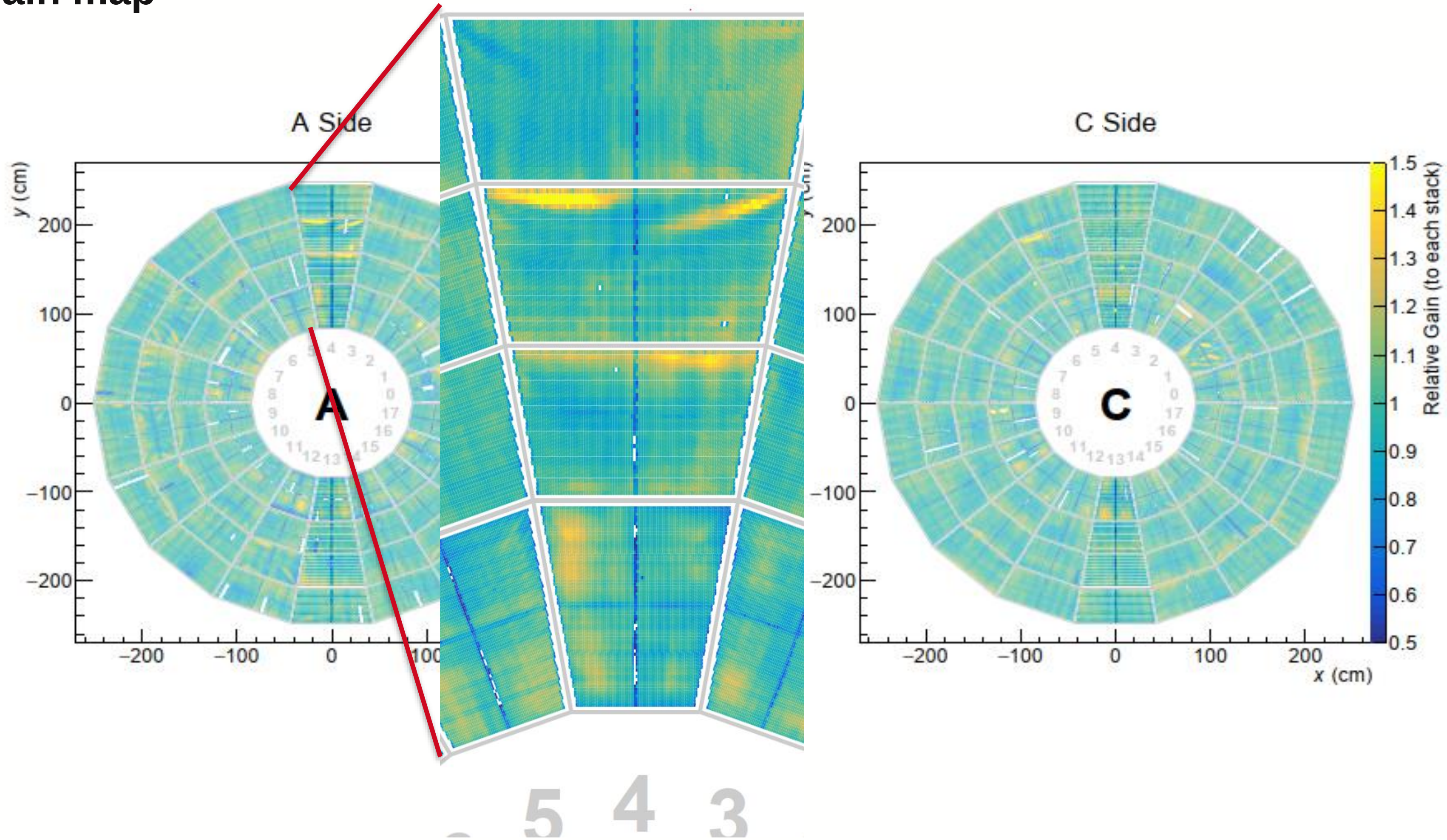
Gain map



- Structures:
  - Sagging
  - Wrinkles
  - Hole-size dist.

KRYPTON CALIBRATION

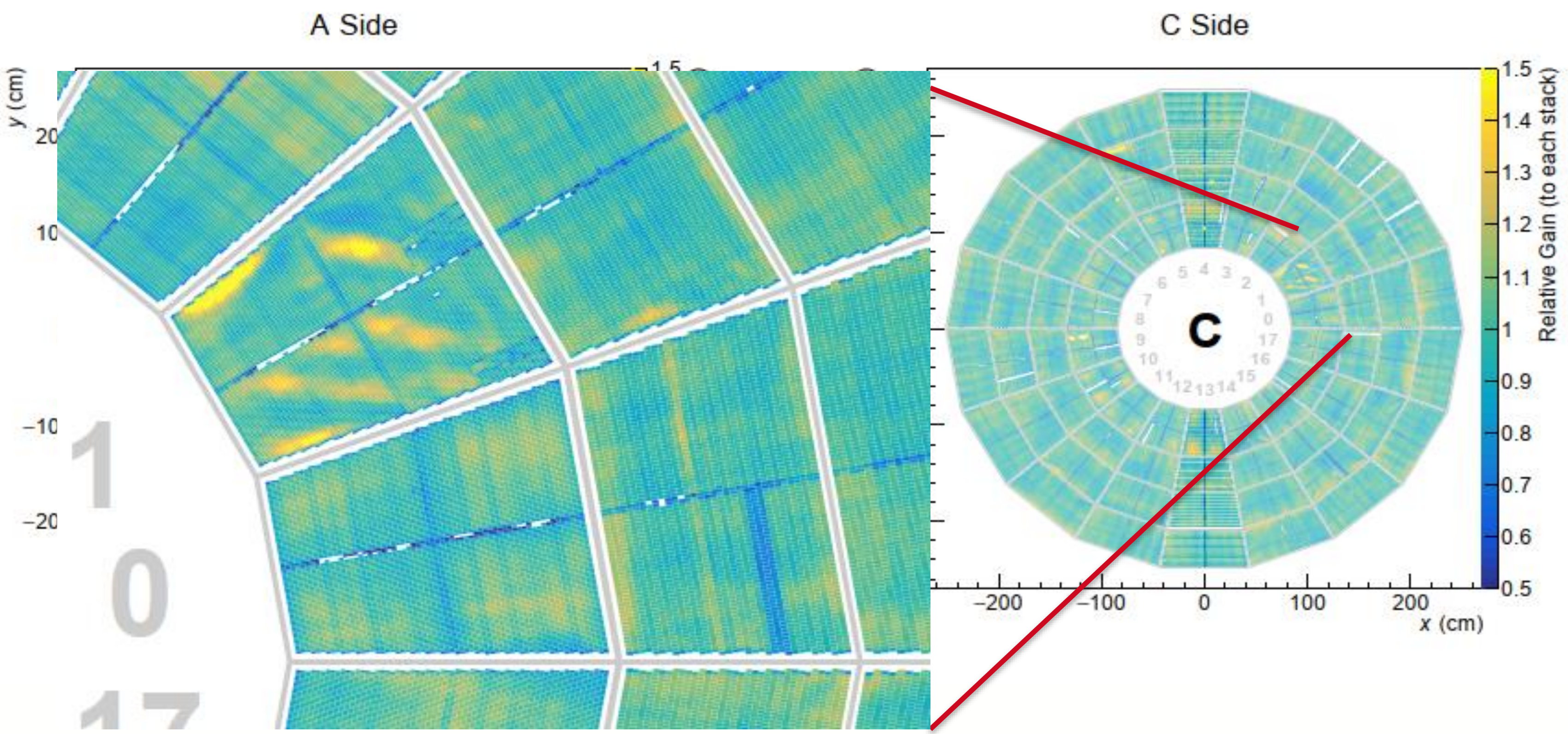
Gain map



- Structures:
  - Sagging
  - Wrinkles
  - Hole-size dist.

KRYPTON CALIBRATION

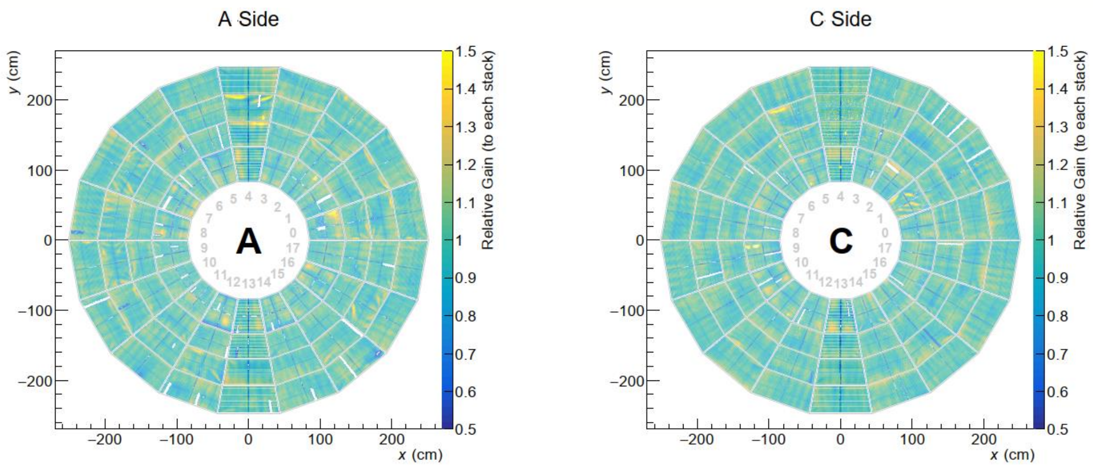
Gain map

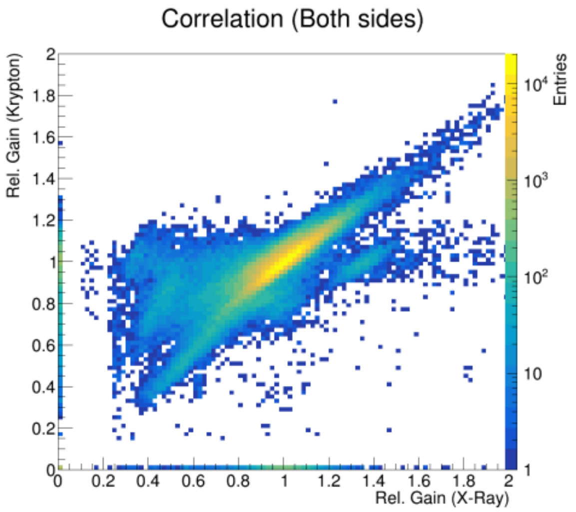


- Structures:
  - Sagging
  - Wrinkles
  - Hole-size dist.

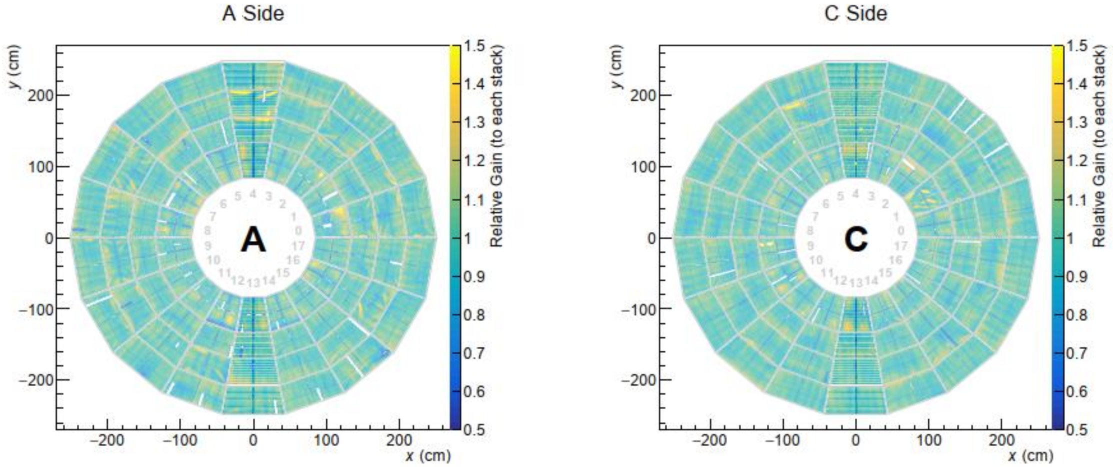
KRYPTON VERSUS X-RAY CALIBRATION

X-Ray





Krypton



Good agreement of gain measured by x-ray and Kr clusters

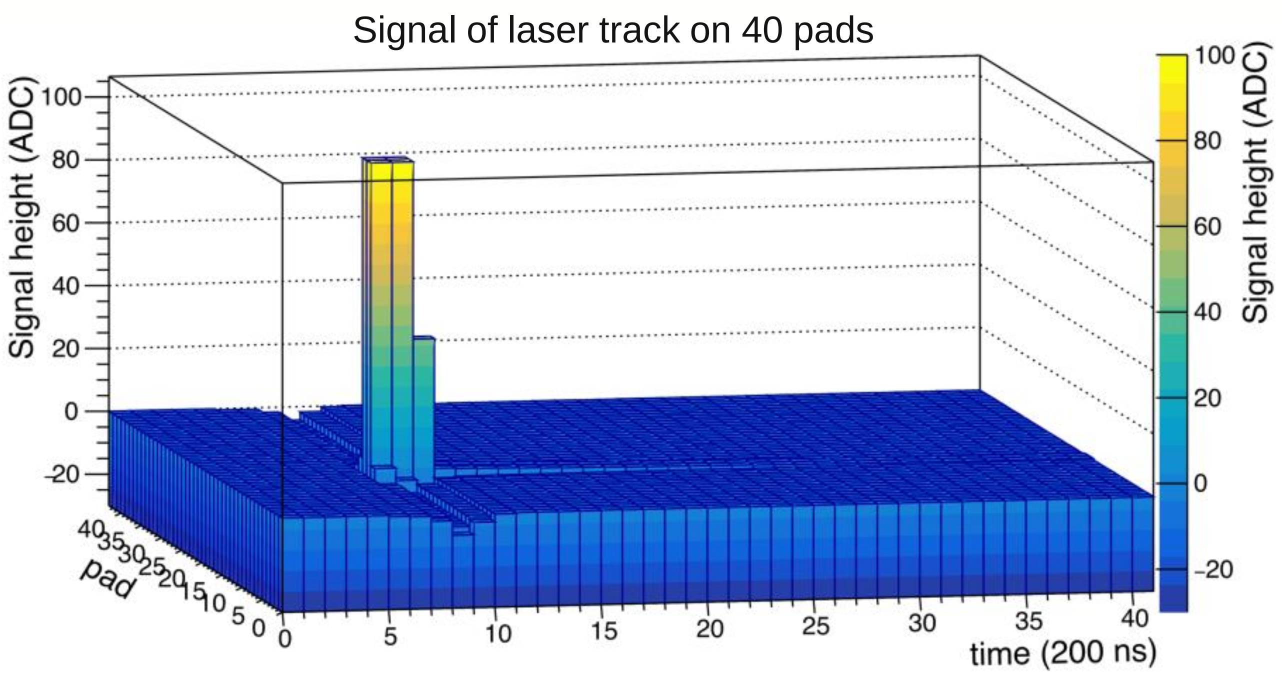
Difference can be explained:

- Changes in readout system (e.g. active FECs)
- Changes in HV settings

COMMON MODE / ION TAIL

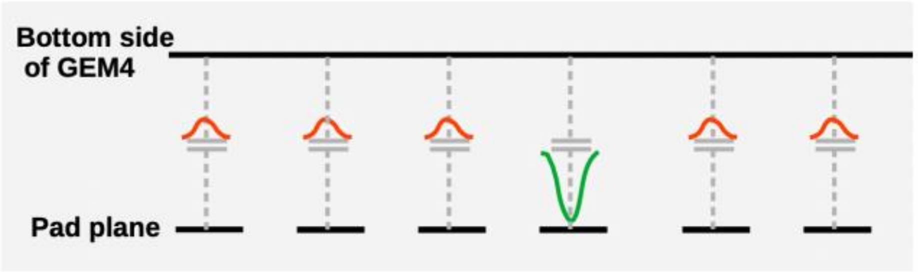
COMMON MODE/ ION TAIL

- Signal shapes averaged over 1000 events from laser track in TPC
- Zoom-in to low amplitudes shows (negative) signals on all pads from common mode effect and (positive) ion tail

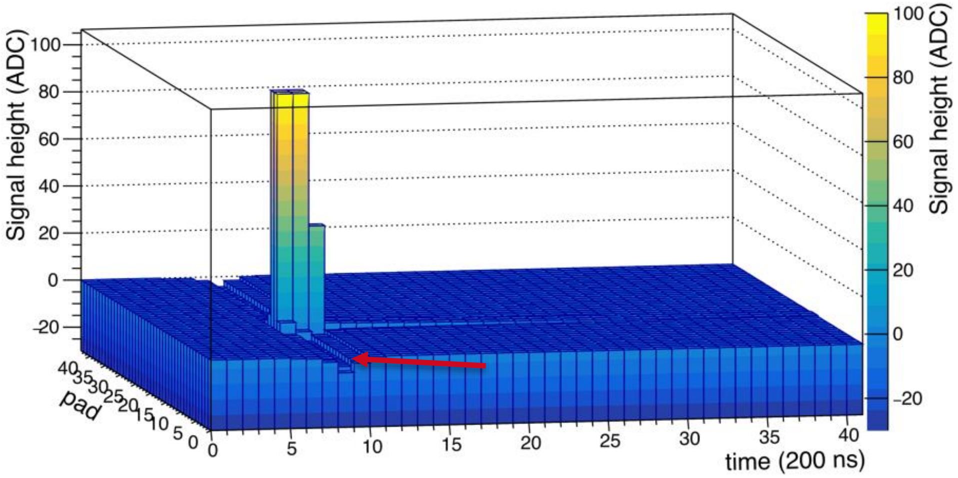


COMMON MODE/ ION TAIL

- Common mode effect present, as capacitors in HV distribution would lead to potential problems with discharges
- At high occupancy the common mode signals from many tracks will superimpose and lead to a baseline shift
- This baseline shift is measured in the readout system (CRU FPGA) and removed online



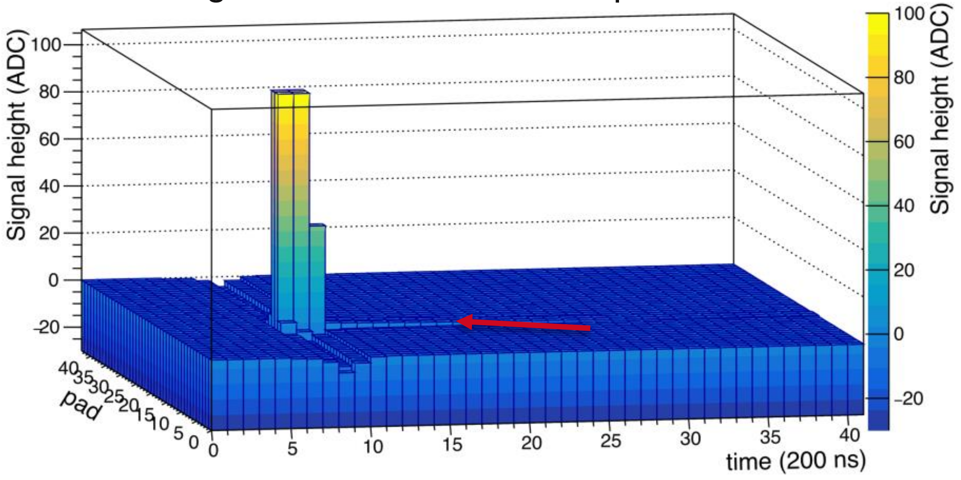
Signal of laser track on 40 pads



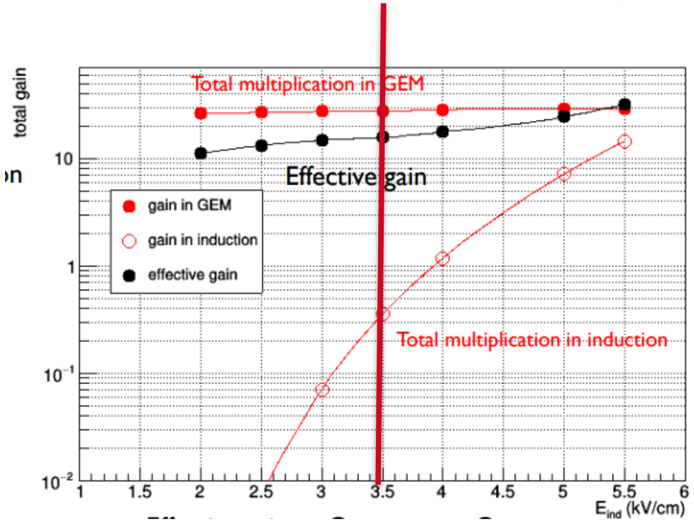
COMMON MODE/ ION TAIL

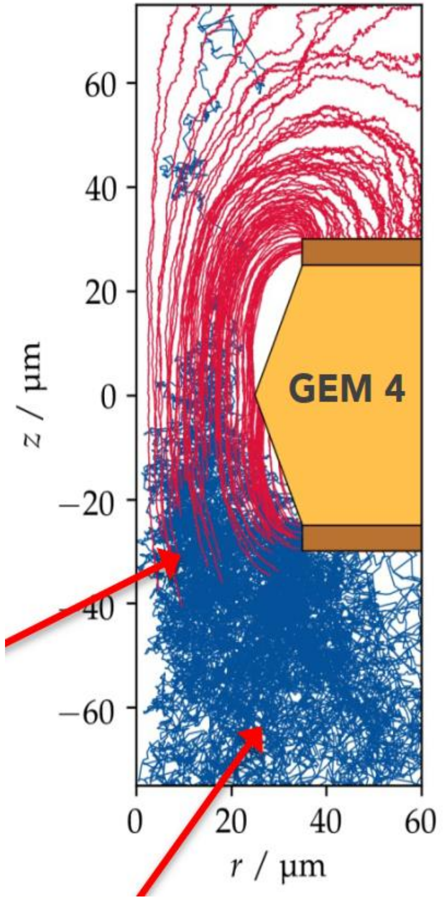
- Ion tail visible with two different contributions:
  - Exponential contribution from ions created in GEM4
  - Linear component from ions produced in induction gap (particular TPC HV setting)
- Online ion tail correction also in CRU FPGA

Signal of laser track on 40 pads



TPC setting

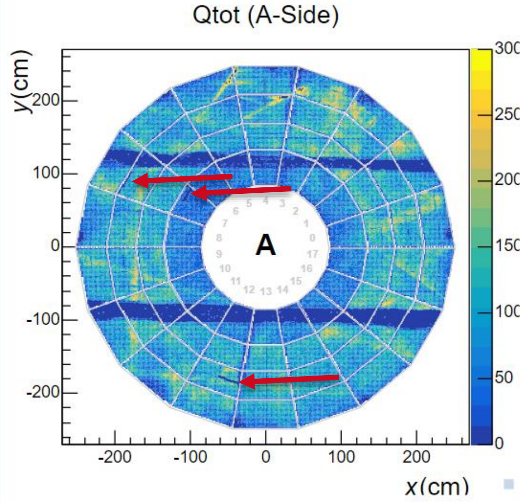


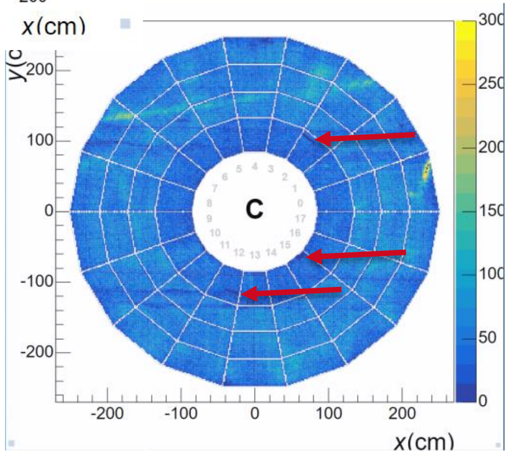


READOUT CHAMBERS

GEM OPERATION

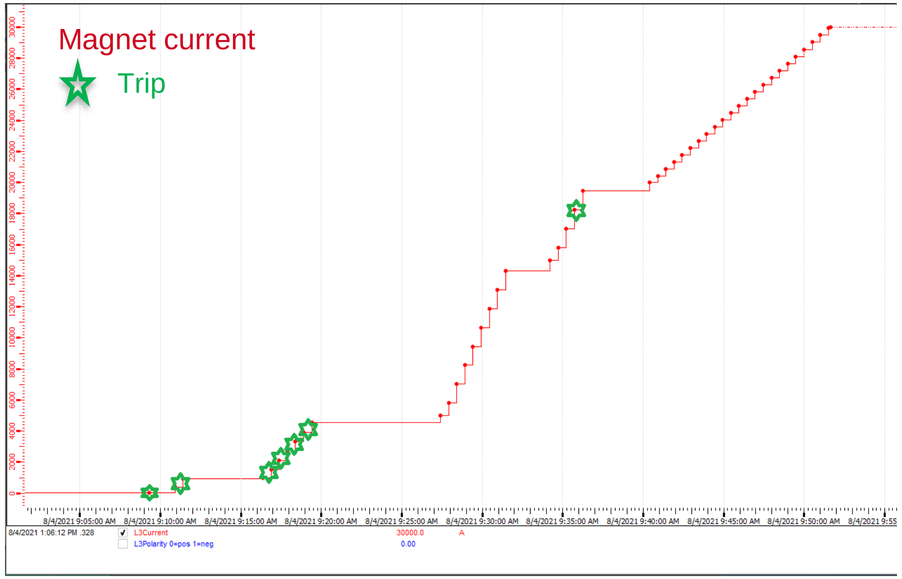
- Extensive testing of ROCs during (pre-) commissioning
  - Long-term operation after installation
  - X-ray irradiation produces realistic load on GEMs at 50 kHz Pb-Pb
  - Operation of GEMs in general very smooth
  - During tests few shorts appeared in GEM due to several reasons:
    - Dust related
    - Damaged HV cable
    - Discharge under load
    - Magnetic field transition
  - Stacks were replaced as long TPC was in cleanroom
  - N.B. GEMs were designed to allow for shorts in segments
  - One segment correspond to ~5% of the active area of a stack
  - Total acceptance loss: 0.21 %





OPERATION WITH MAGNETIC FIELD

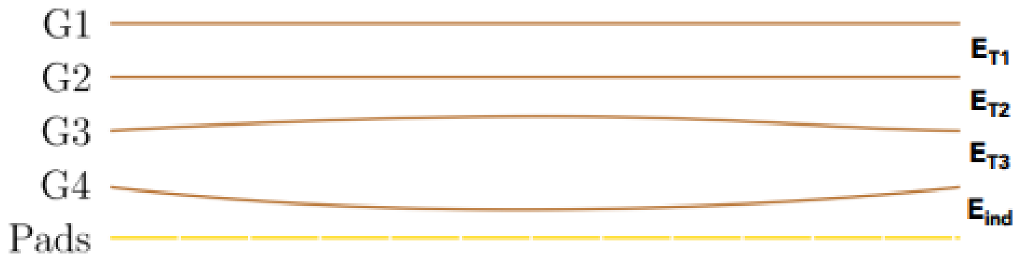
- TPC sits inside a 0.5 T solenoid magnet
- April 2021: First ramp up of magnetic field
- Observations:
  - No change of stability observed with magnets field on
  - Trip of GEMs at full voltage mainly at low magnet currents during ramping
  - 3 shorts occurred during ramping, when GEMs were not at full voltage
- Hypothesis:
  - Ramping up or down of E and B fields may cause dust particles to move, if they carry charge
  - Dust particles on electrodes, moving inside GEM holes, either melts (short + trip) or evaporates (only trip)



- Solution:
  - Keep GEMs at full voltage while magnet is ramping
  - Well established procedure
  - Trip rate during magnet ramp reduced over time; not much dust on GEMs
  - No further issue observed with this procedure

TRIP RATE

- At nominal setting a trip rate of 0.2 - 0.3 trips/h was observed.
- No significant difference to operation with load
- Trips happen mainly in GEM3
- Possible explanation:
  - Sagging of GEMs
  - Because of the asymmetric fields around GEM3, this foil experiences a larger electrostatic force
  - Effective field increased for ET_2 (Effect in induction field smaller due to stiff pad plane)
- Solution:
  - Significant increase of stability by reducing ET_2 from 3.5 -> 3.0 kV/cm
  - Lab measurement: Small effect on IBF and energy resolution
  - Effect on TPC will be studied during operation with beams



ALICE

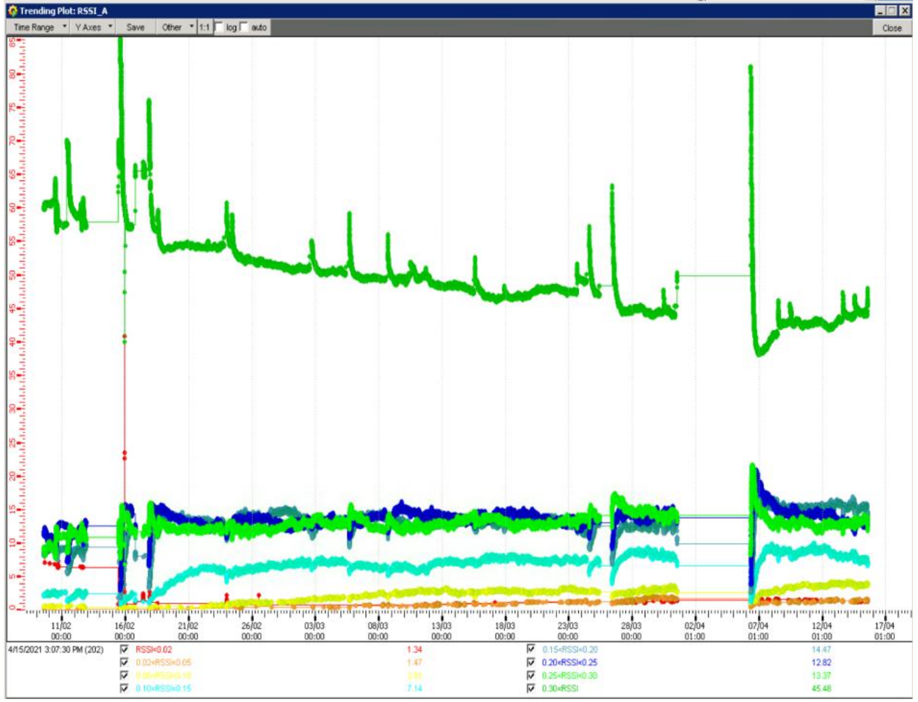
VTRX PERFORMANCE

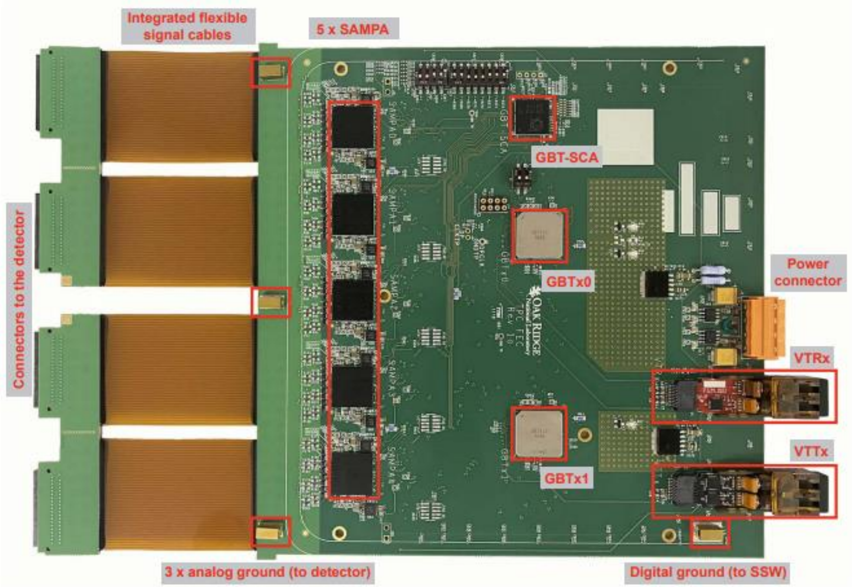
VTRX PERFORMANCE

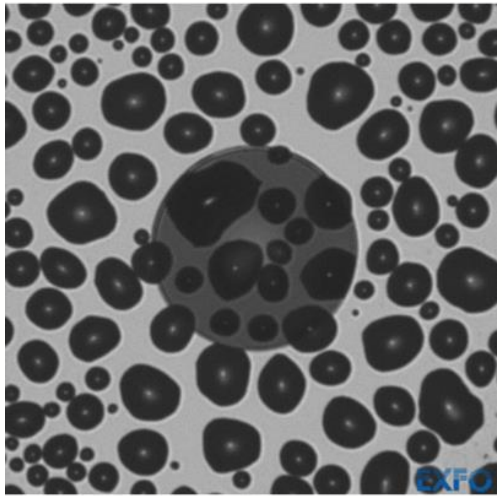
- Each FEC has two optical devices
  - Decreasing optical current spotted on recieving part due to outgasing

- Connection loss to FECs after certain time of operation
- Cleaning of fiber only helps temporarily

Fraction of FEC with good optical current





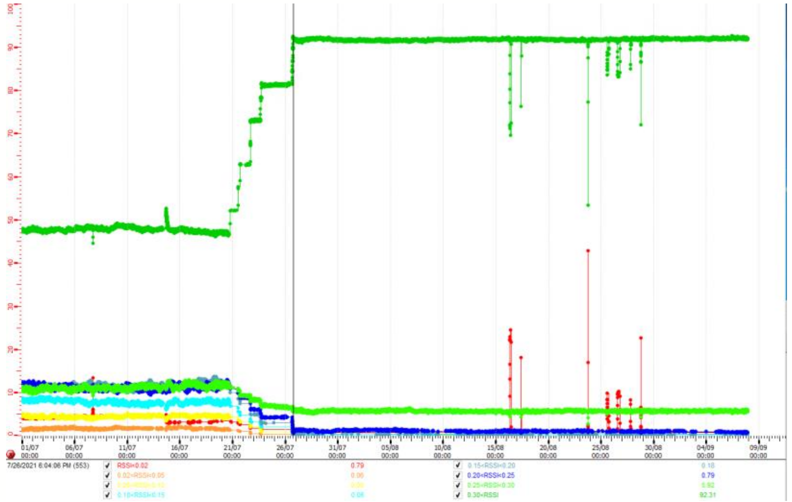


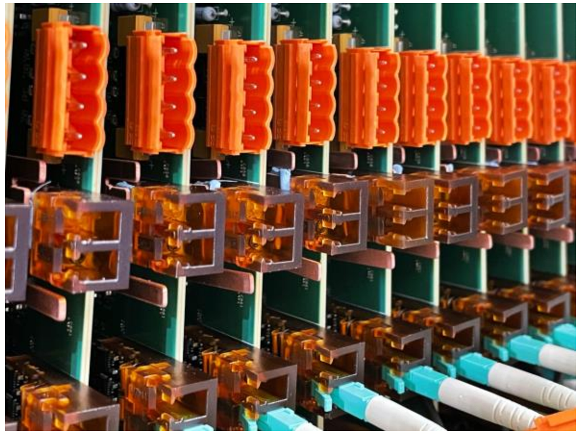
Microscope image from VTRx

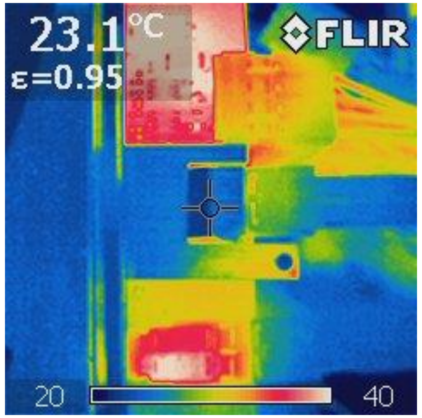
VTRX PERFORMANCE

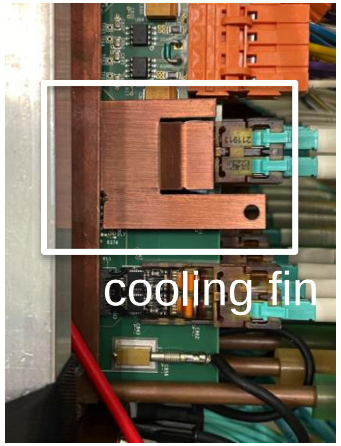
- Extensive investigation campaign was carried by central CERN group and by different detector groups

- Possible method to mitigate effect:
  - Baking of VTRx module (80°C for ~200h)
    Would require unmounting all FEC on TPC
  - Reducing temperture on VTRx moduel < 40°C
    - Installation of additional cooling fins as heat bridge between cooling plate and VTRx module in summer 2021
    - Achieved temperature on VTRx : ~ 33°C)
- Long term studies:
  - Only 2 out of 3276 FECs show degrading optical power after 10 months



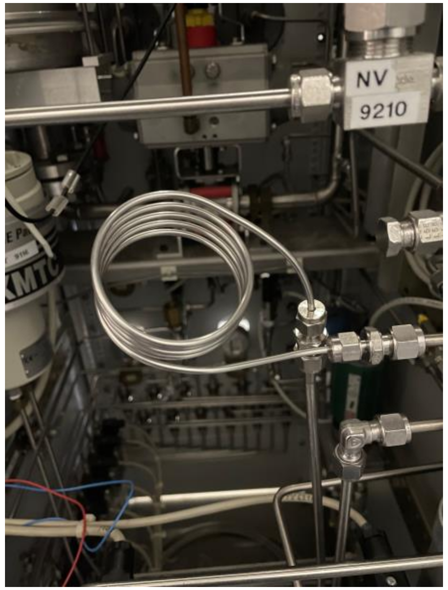






NEON CONSUMPTION

- TPC is operated with $Ne/CO_2/N_2$
- ~70% of the world's neon gas is (was) produced in three plants in Ukraine. Two of three companies are closed since the beginning of the war. Big amounts are bought by semi conductor industries
- CERN has currently no supplier of neon
- Actions to reduce neon consumption in the TPC gas system:
  - Fresh gas injection reduced from 30 l/h to 8 l/h (~ 7 l/h of neon)
  - Decrease gas exhausted through analyzers by reducing flow and sampling frequency
  - Running mode was changed:
    - Fresh gas is injected only on demand, no extra gas exhausted
    - Required changes and optimization in the gas control system
  - Existing neon supply at P2 should last for >3.4 years

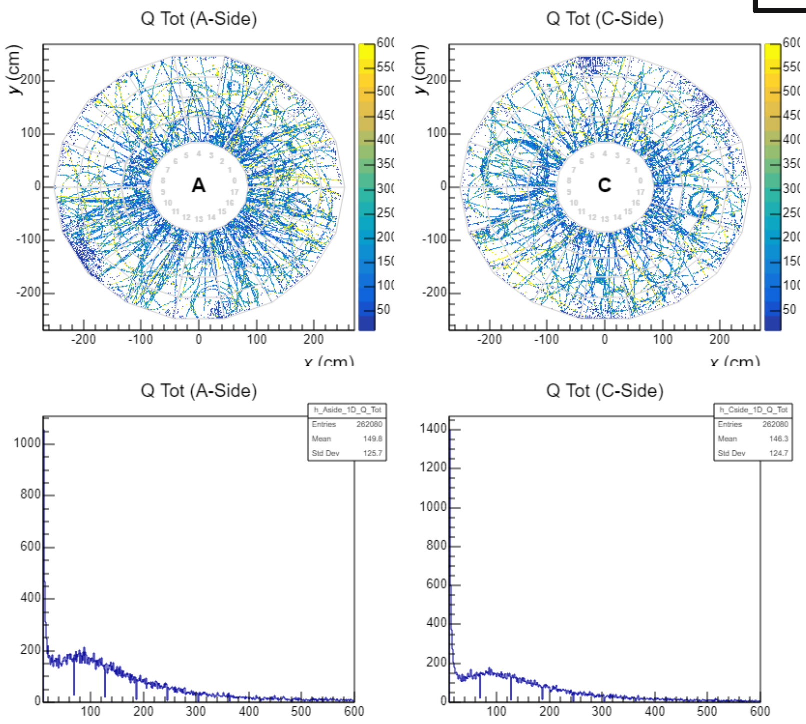


Pigtail installed at exhaust of analysis chain in order to be able to reduce the flow

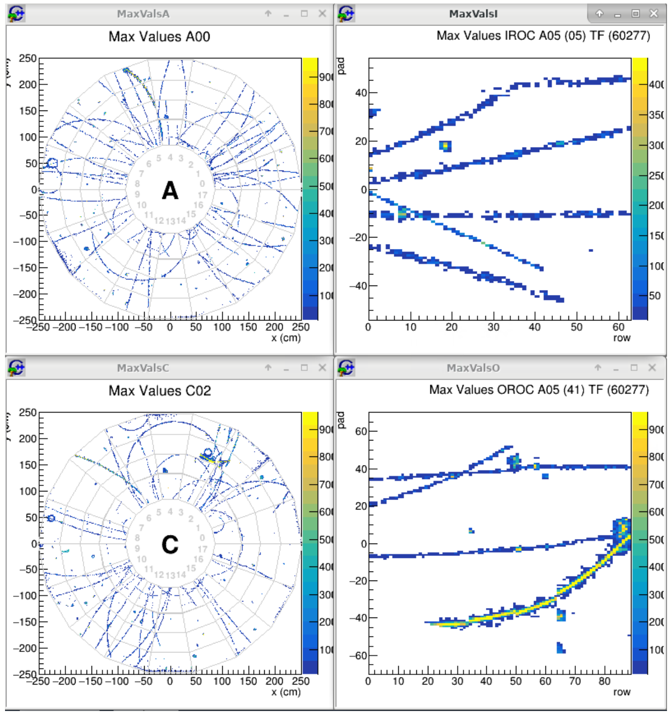
PILOT BEAM DATA

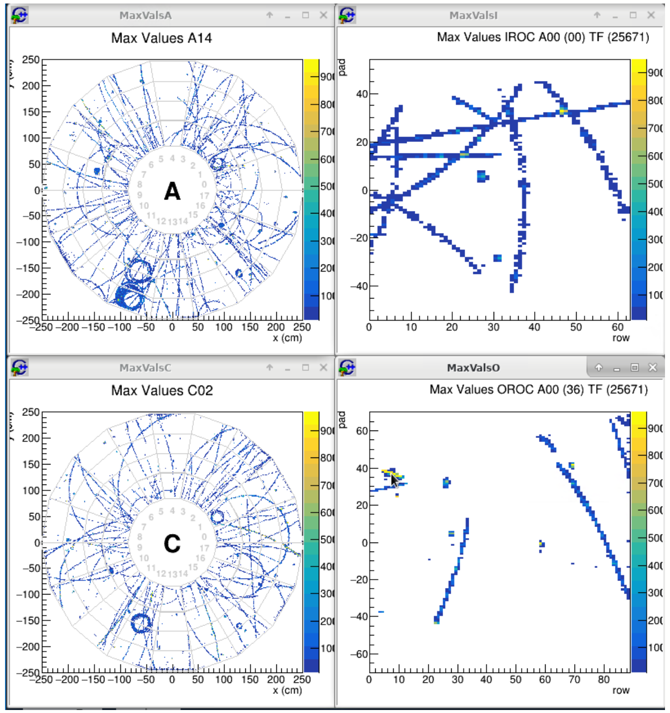
TPC DATA TAKING WITH STABLE BEAMS

- First stable beam in 2021 and in 2022 (last weeks)
  - Injection energy (900 GeV/c)
  - Low interaction rate (~800 Hz + ~10% beam background)
- Mostly smooth data taking.
- Tracks visible in Online Monitor and QC during first data taking



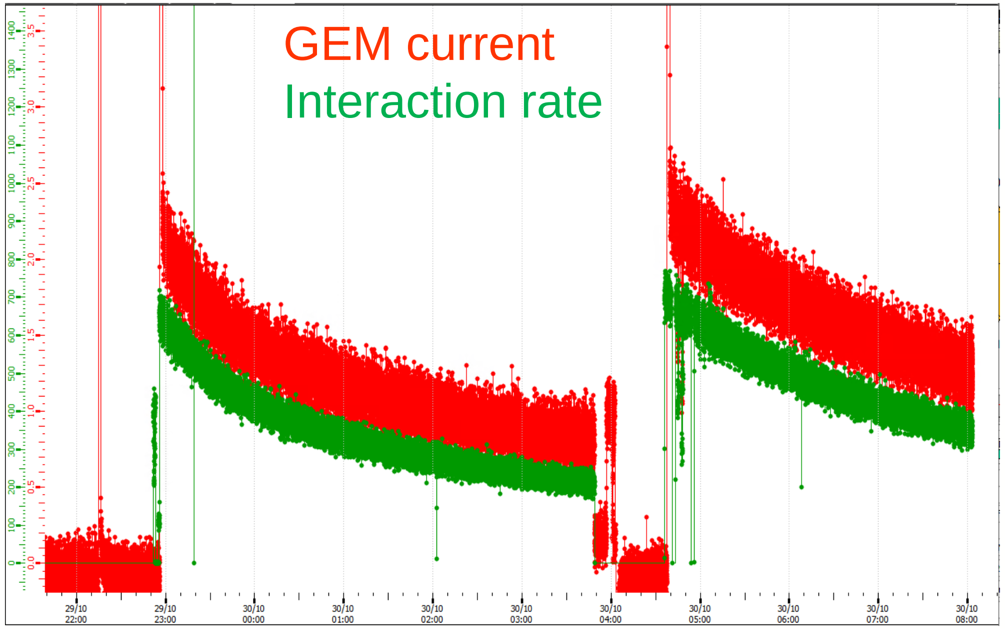
Online monitor for single TF (~100 drift times)



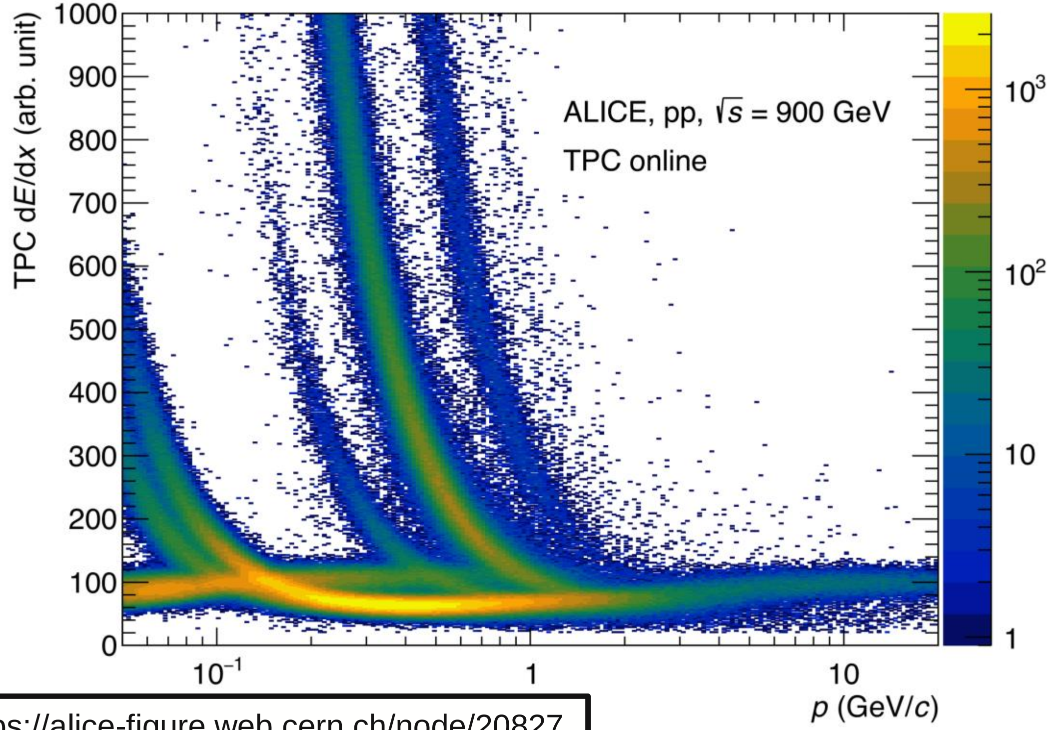


TPC DATA TAKING WITH STABLE BEAMS

- Stable GEM operation
  - No HV trip
  - Still low interaction rate
- Average current in GEM follows nicely interaction rate

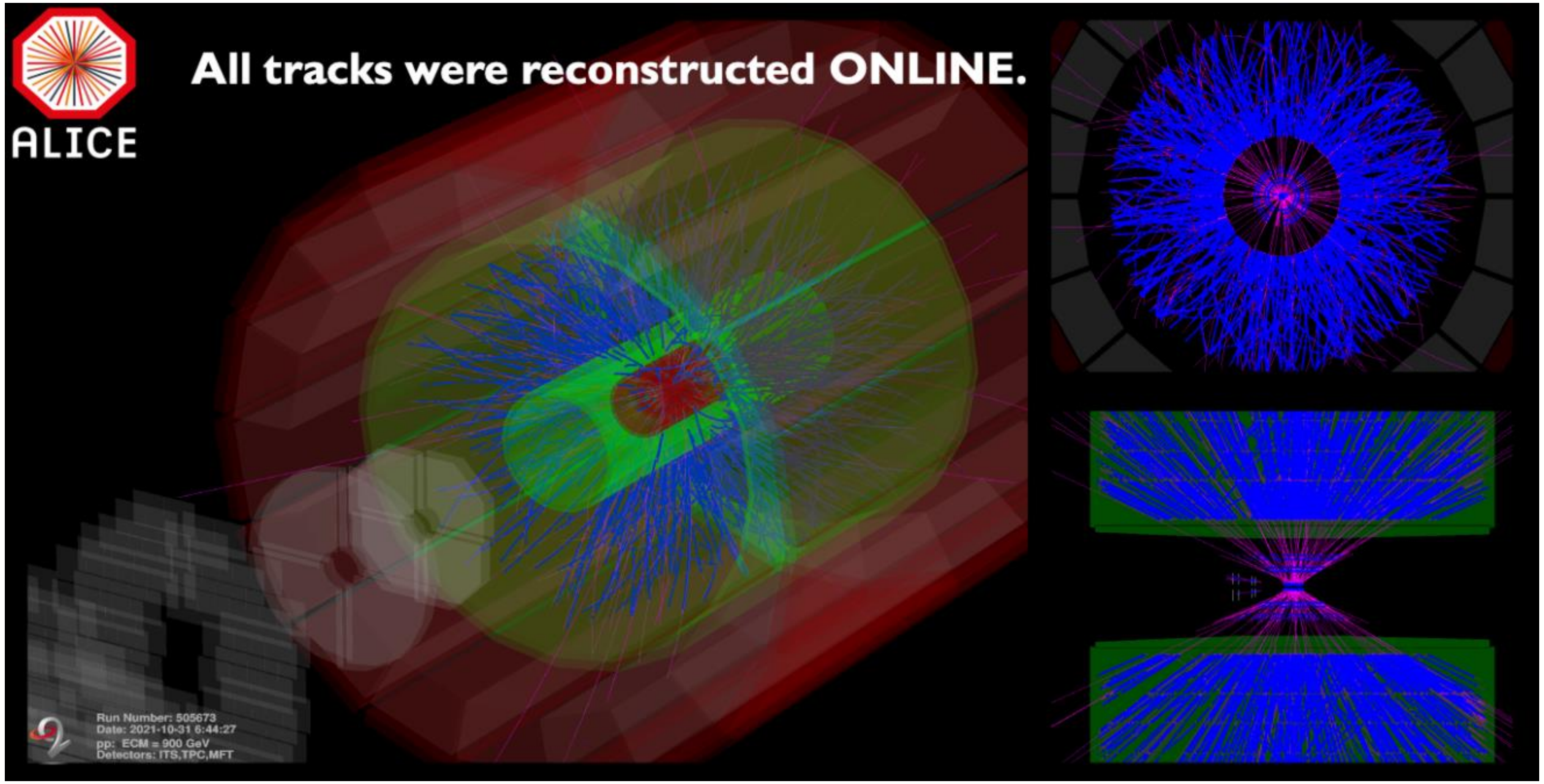


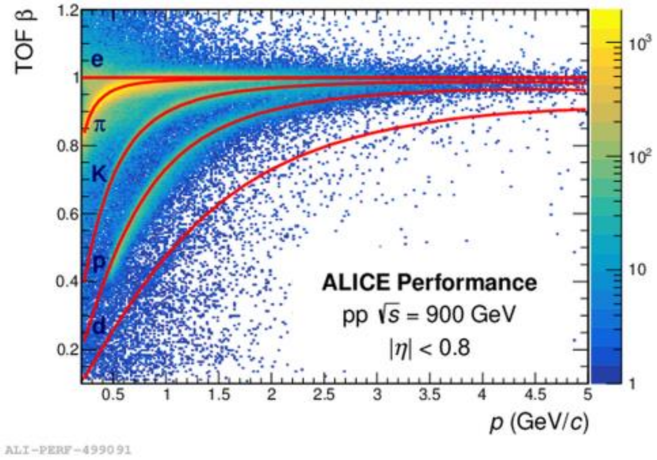
- Online tracks reconstruction with PID

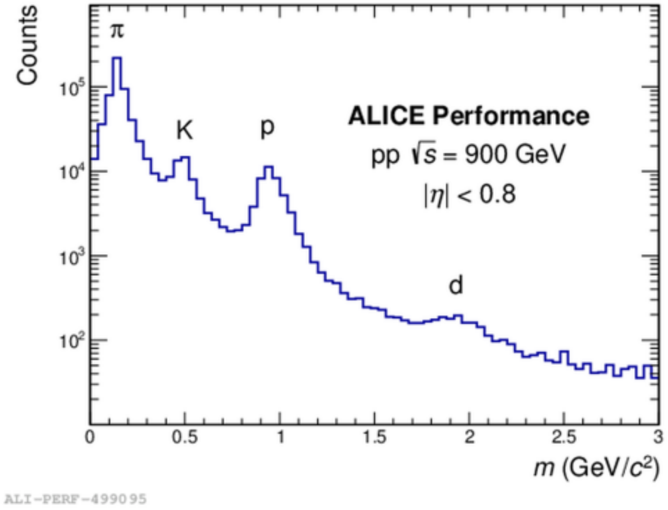


https://alice-figure.web.cern.ch/node/20827

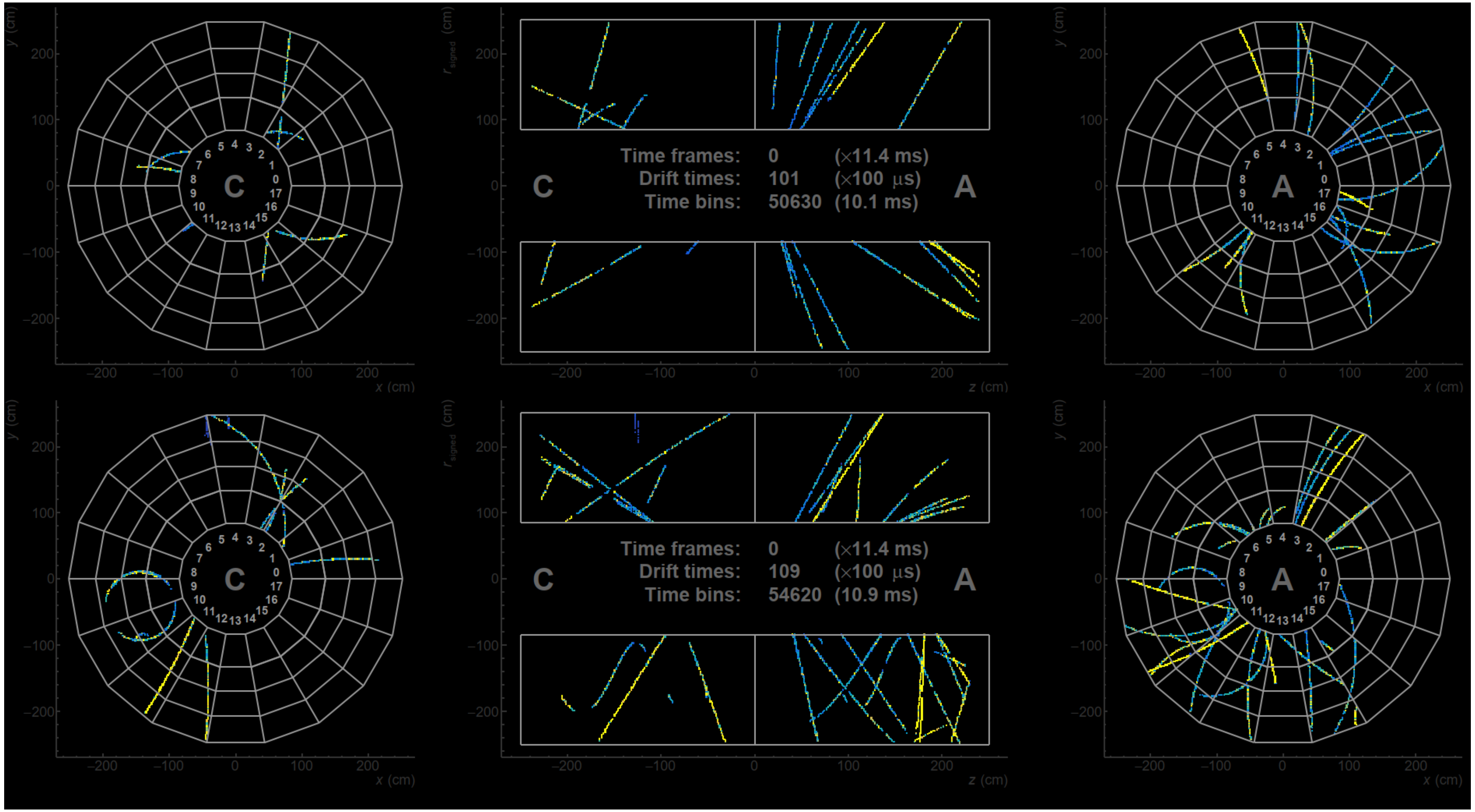
ALICE EVENT DISPLAY







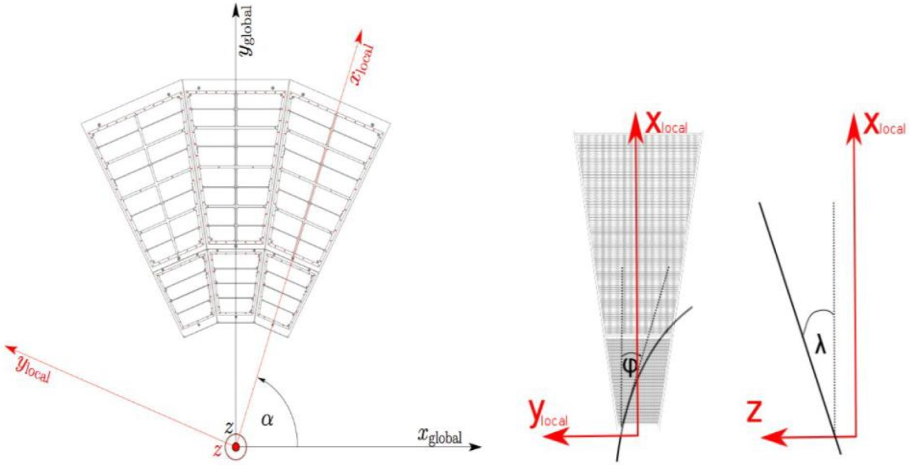
EVENT DISPLAY



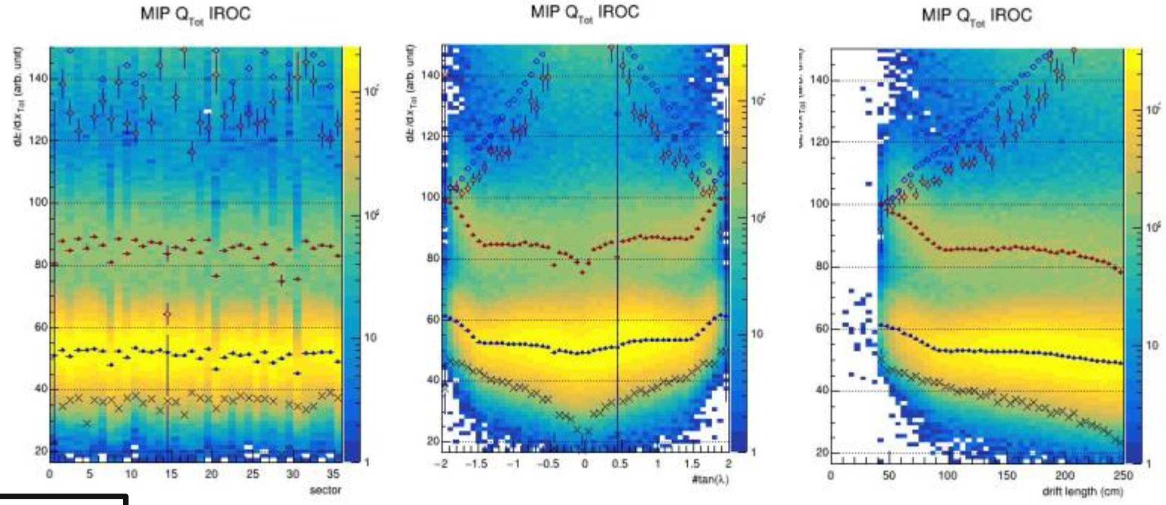
Movie: https://cernbox.cern.ch/index.php/s/xWLxU8N7SRAQqZ7

CORRECTIONS

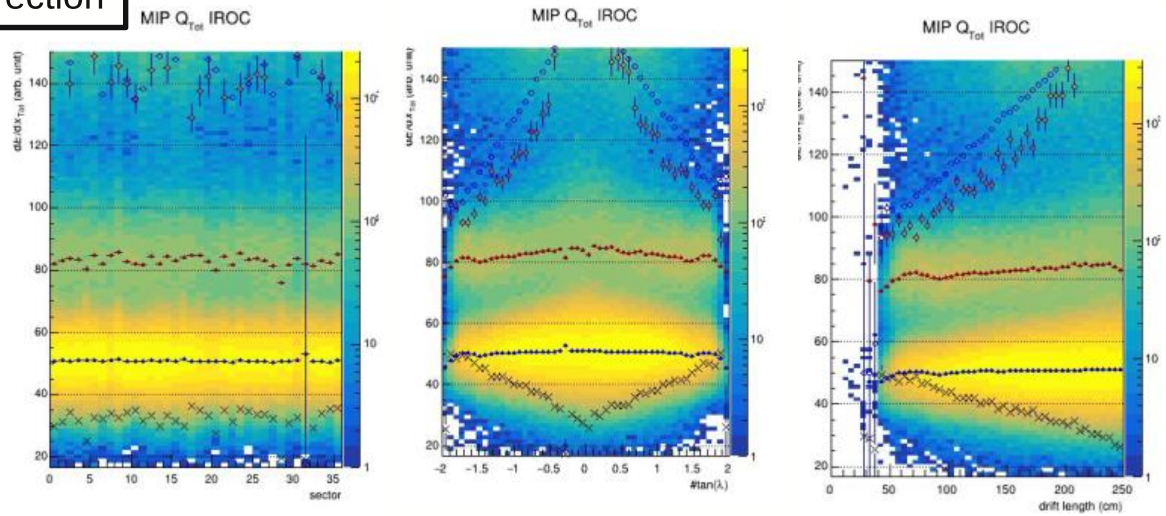
- dE/dx calculation required correction to achieve optimal resolution
  - Stack correction
  - Tracks topology correction (track inclination)
  - Drift length: Require track matching with further detectors



Before correction



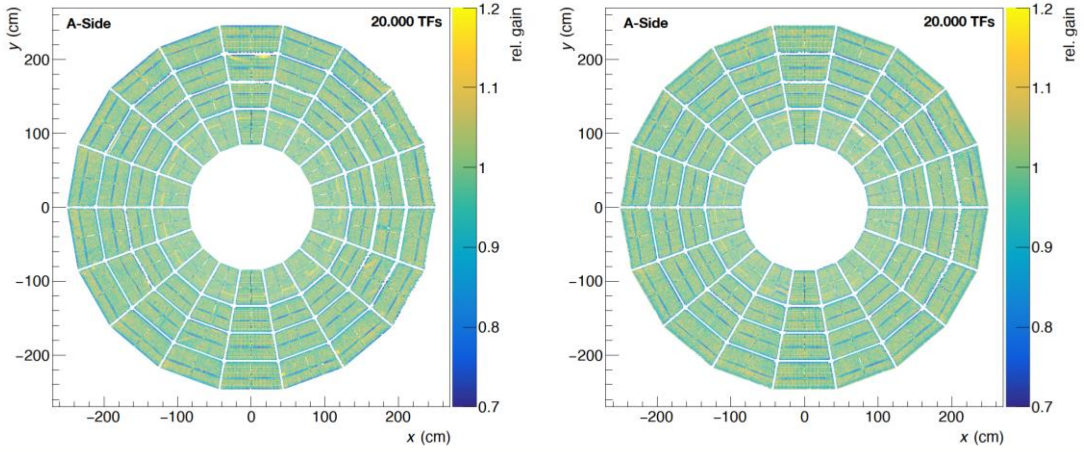
After correction



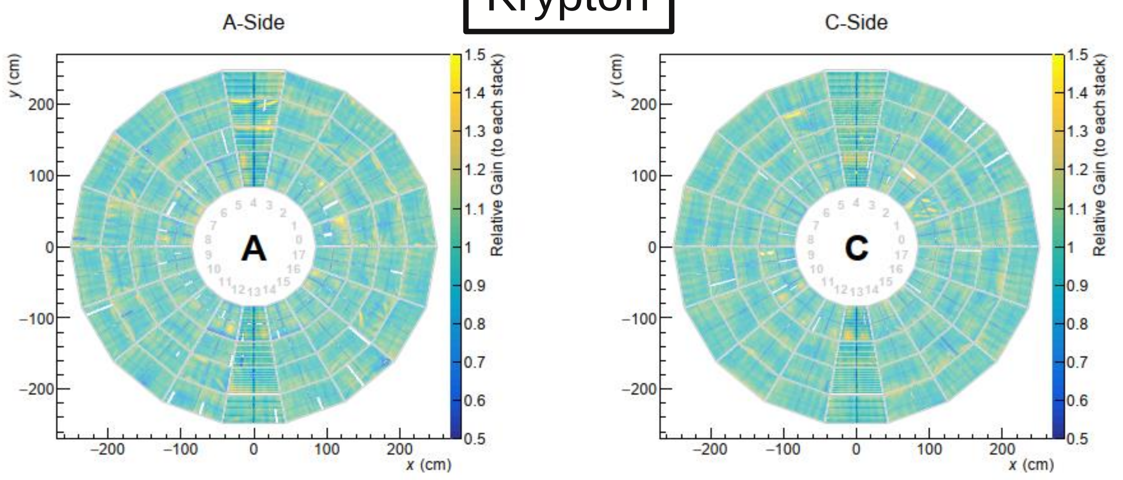
CALIBRATION FROM BEAM DATA

- Monitor gain distribution during beam operation
- Extract gain map from beam data
  - Extract cluster charge from reconstructed tracks
  - Gain map from truncated mean fit of pad-by-pad charge distribution

- Gain map in good agreement with Krypton calibration



Krypton



ALICE

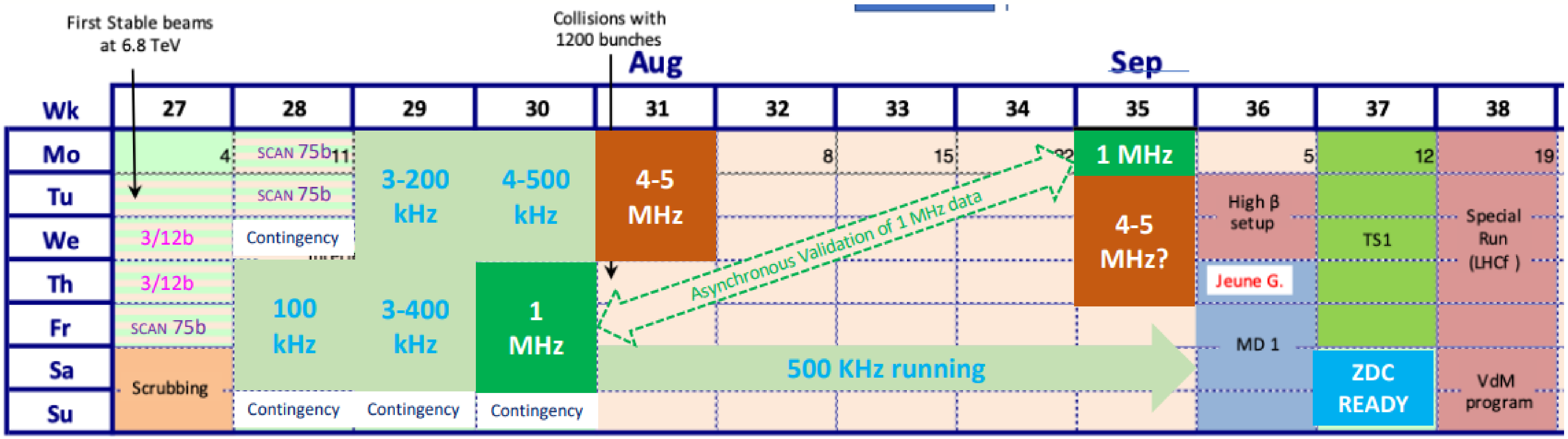
SUMMARY

- ALICE TPC upgraded to operate in Run 3 and Run 4 in Pb-Pb collision at 50 kHz
- Commissioning phase finished successfully
  - Minor issue with HV stability – Could be mitigated by optimizing HV setting and operation
  - Noise at designed value
  - Continuous readout of 3 TB/s raw-data with online reconstruction
  - X-ray irradiation used to check stability
  - Extraction of gain maps and equalization by using Krypton and X-ray source
- First collisions
  - Smooth operation of TPC during first LHC STABLE BEAM collisions
  - Online track reconstruction and PID
  - Calibration of data and correction procedure ongoing

TPC is READY (and looking forward) for Run 3

OUTLOOK

- Collisions at full energy expected beginning of July followed intensity ramp-up
- Goal: Increase interaction rate up to 5 MHz (equivalent to 50 kHz Pb-Pb)



OUTLOOK

- Collisions at full energy expected beginning of July followed intensity ramp-up
- Goal: Increase interaction rate up to 5 MHz (equivalent to 50 kHz Pb-Pb)
- Pb-Pb collisions at the end of the year