The ALICE Time Projection Chamber and its upgrade

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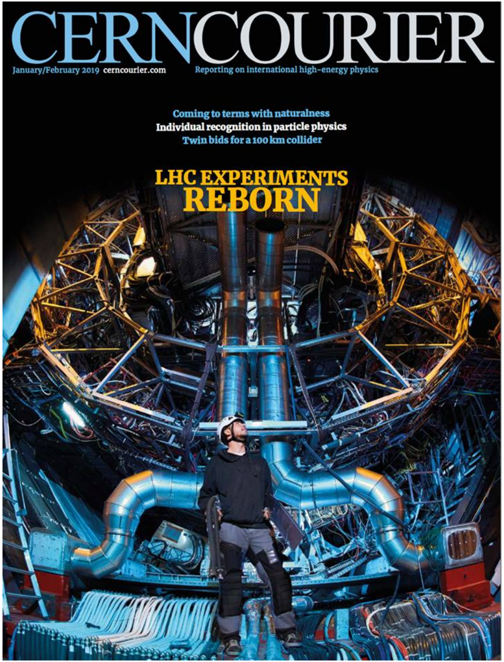
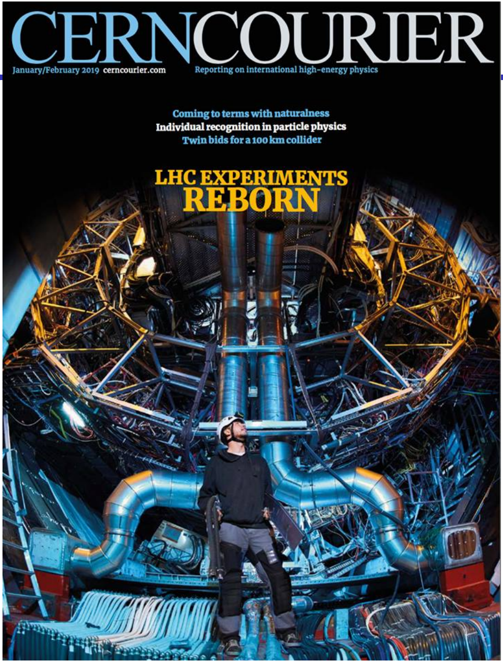
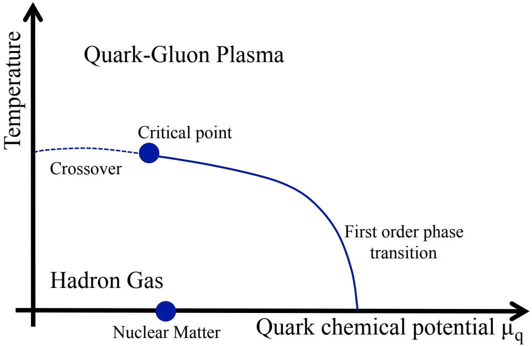


Outline

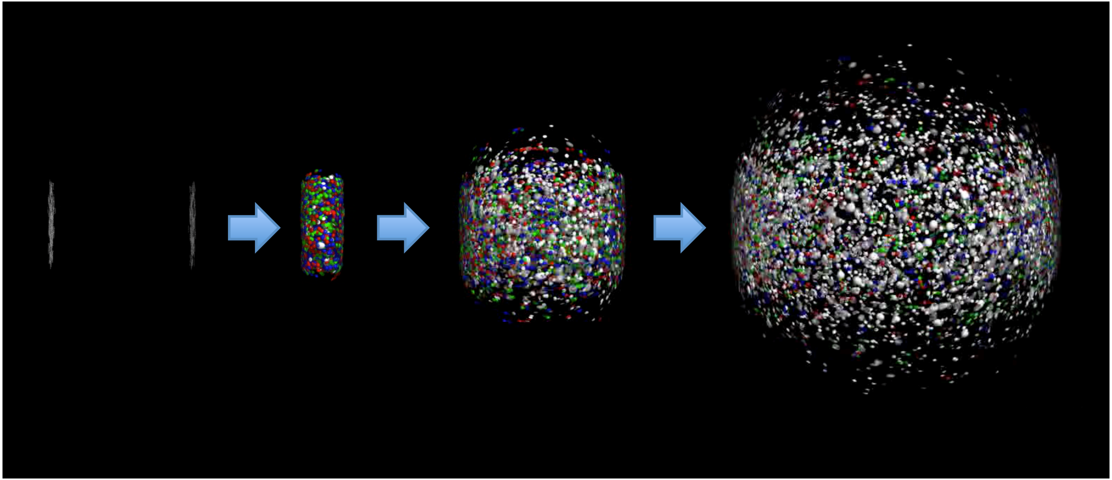
- A short introduction to heavy ion-collisions
- The ALICE detector at LHC
- A TPC at LHC: The ALICE Time Projection Chamber
- Upgrade of the ALICE Time Projection Chamber
- Summary

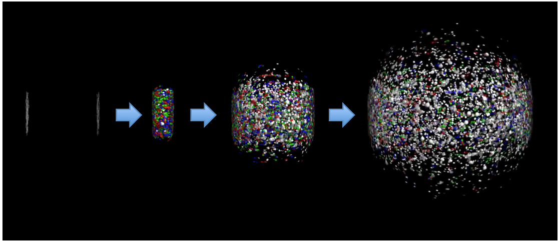


Phase diagram of strongly interacting matter



- There are different phases of matter governed by the strong interaction at different temperature T and chemical potential μ
- Quark-Gluon Plasma (QGP) phase:
  - Quarks and gluons are no longer confined into hadrons
  - Only the bare quark masses remain
- Nucleus-nucleus collisions are tool to study different regions of the phase diagram



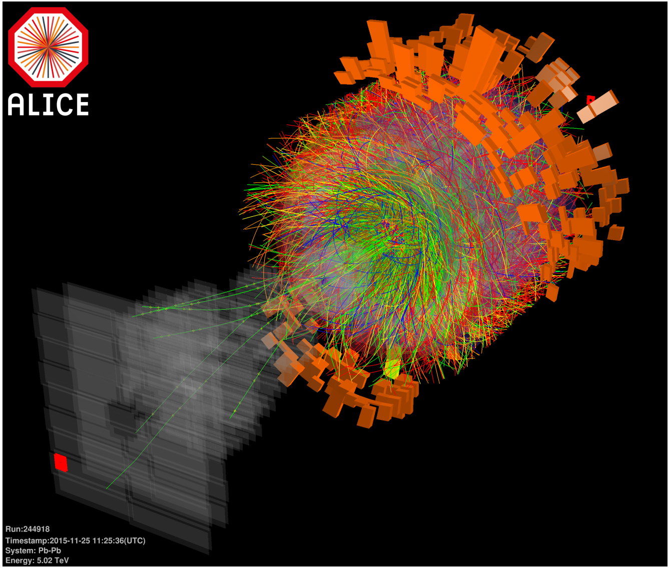


- Nuclei collide and after $\tau \sim 1\,\mathrm{fm}/c$ the QGP is formed
- (Light) quarks and gluons reach thermal equilibrium
- The QGP expands and cools down
- At $T \sim 155\,\mathrm{MeV}$ quarks and gluons are again confined into hadrons $\rightarrow$ phase transition to a hadron gas
- Non stable hadrons decay and with further expansion (elastic) collisions seize

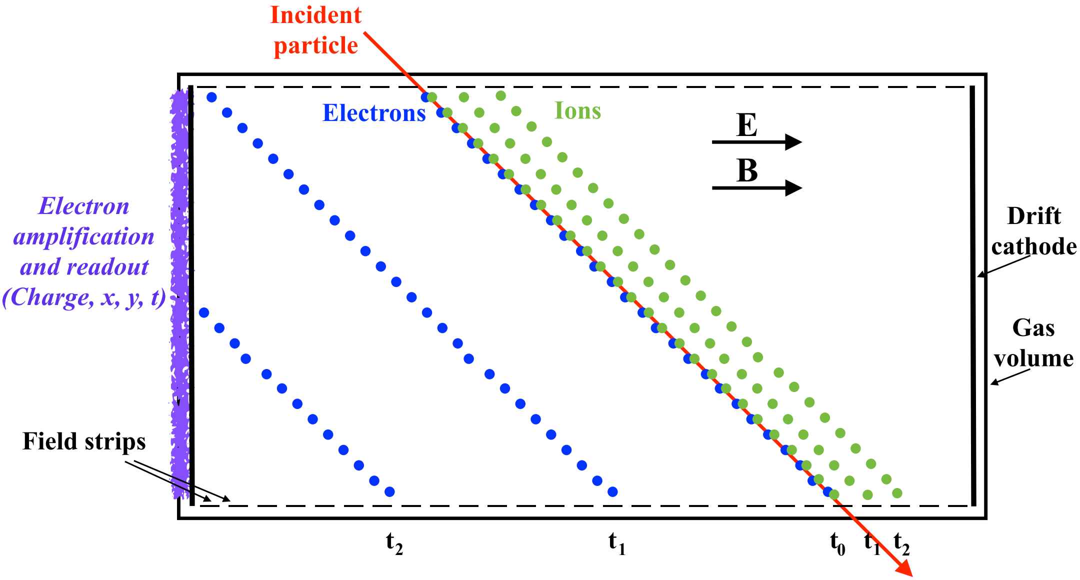
$\Rightarrow$ The remaining hadrons stream freely into the detector

Requirements on detectors for heavy ion collisions

- Able to record events with high particle multiplicities
- Capable of recording particles down to low momentum
- Good tracking capability and momentum resolution
- Ability to identify the tracked particles

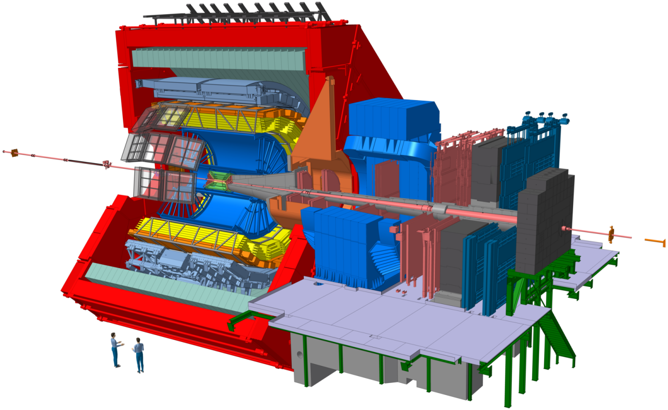


ALICE Time Projection Chamber



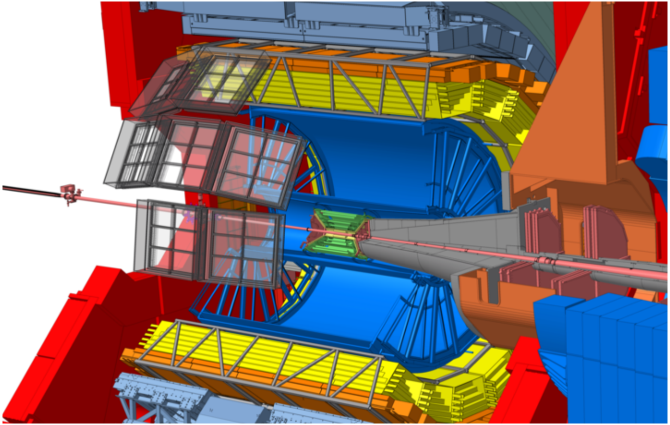
Incident particle
Electrons
Ions
E
B
Electron amplification and readout (Charge, x, y, t)
Drift cathode
Gas volume
Field strips
t2
t1
t0
t1
t2

ALICE – A Large Ion Collider Experiment



- Dedicated heavy ion experiment at the LHC
- Designed to cope with high particle multiplicities and to track and identify low momentum particles ($\sim 200\,\mathrm{MeV}/c$)
- Employs a Time Projection Chamber (TPC) as main tracking and particle identification detector in the central barrel

ALICE – A Large Ion Collider Experiment



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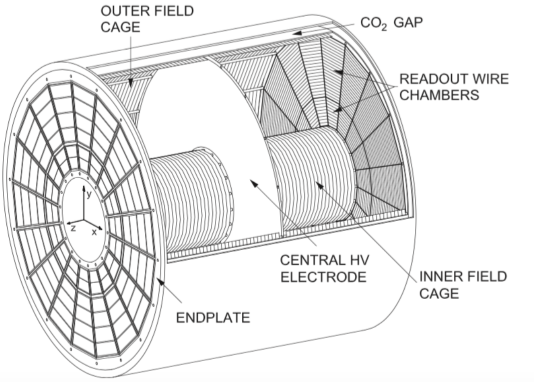
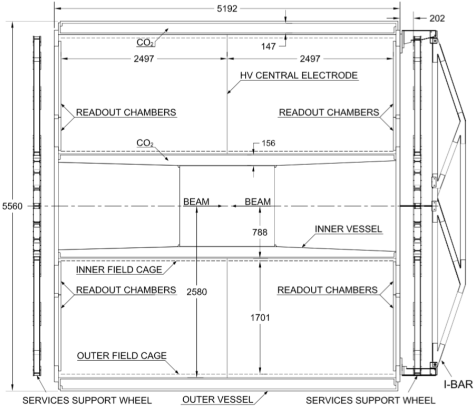
ALICE time projection chamber



- About $90\,\mathrm{m}^3$ gas volume filled with Ar-CO_2 (88-12) at atmospheric pressure
- Ne-CO_2-N_2 (90-10-5) and Ne-CO_2 (90-10) have been used as well
- Drift field of $400\,\mathrm{V\,cm^{-1}}$ ($\rightarrow$ central cathode at 100 kV)
- Maximal electron drift time: $\leq 100\,\mu\mathrm{s}$
- Multi Wire Proportional Chambers (MWPCs) with gated read-out
- Operated successfully in LHC Run 1 and Run 2

ALICE time projection chamber



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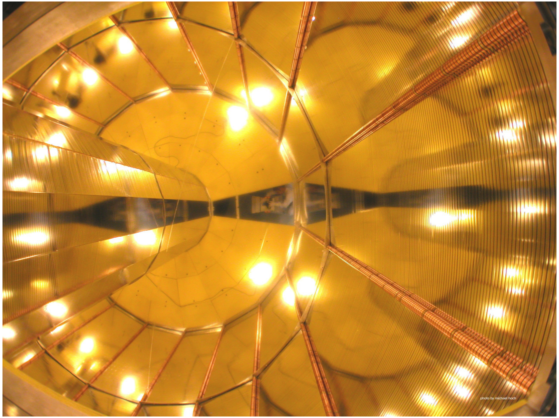

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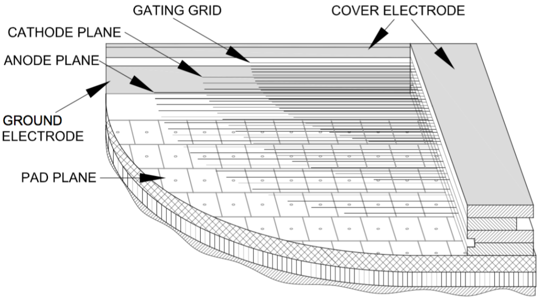
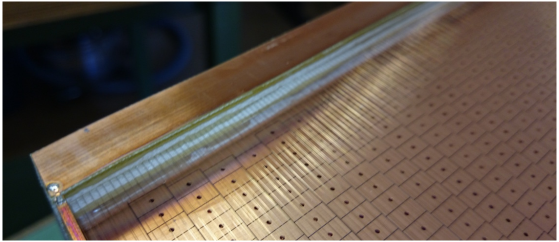
ALICE TPC multi wire proportional chambers

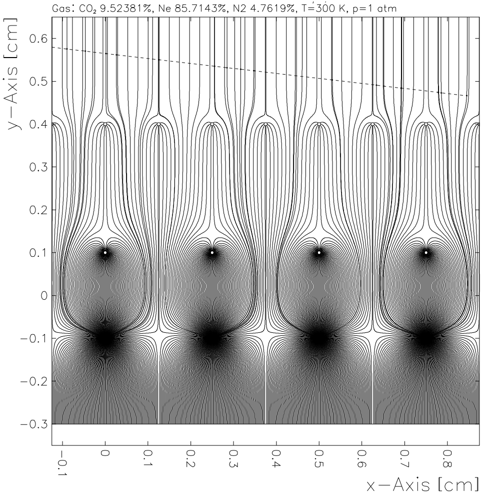




- 18 Inner and Outer ReadOut Chambers (IROCs/OROCs) per side
- Each has three wire planes: Anode wires, cathode wires and gating grid wires
- Pad sizes: $4 \times 7.5\,\mathrm{mm}^2$, $6 \times 10\,\mathrm{mm}^2$ and $6 \times 15\,\mathrm{mm}^2$, in total 160 pad rows

ALICE TPC Multi wire proportional chambers

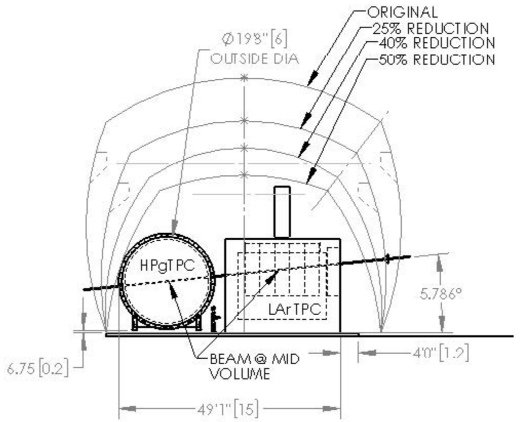
Ion drift lines with open gating grid



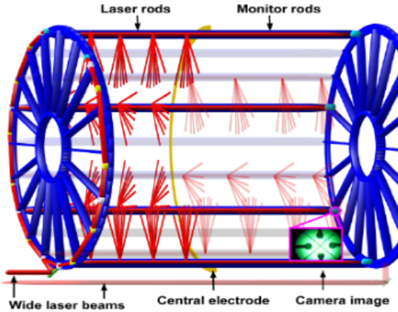
- An alternating potential is applied to switch the gating grid closed, *i.e.* $U_{\mathrm{GG}} = U_0 \pm \Delta U$
- In the closed configuration the gating grid is neither transparent to charge carriers from the drift volume nor from the readout chamber
- The grid is kept closed for 200 µs to efficiently block the ions from the gas amplification
- Together with the maximum drift time of $\sim$ 100 µs, the closing time of the grids limits the readout rate to $\sim$ 3 kHz

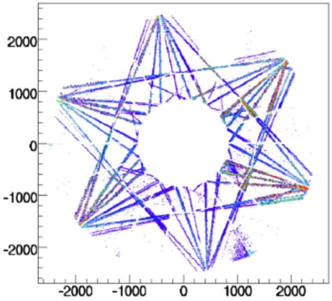
DUNE HPgTPC

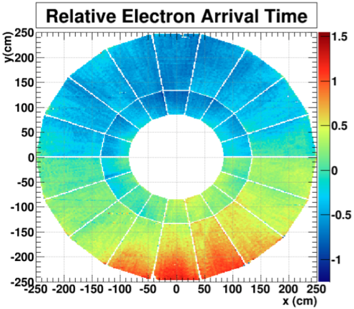
- Deep Underground Neutrino Experiment (DUNE) decided to have a High Pressure gaseous TPC as part of their near detector
- The particular cylindrical shape is driven by the fact that they intend to buy the ALICE TPC readout chambers
- Therefore some of you may see the old ALICE chambers again



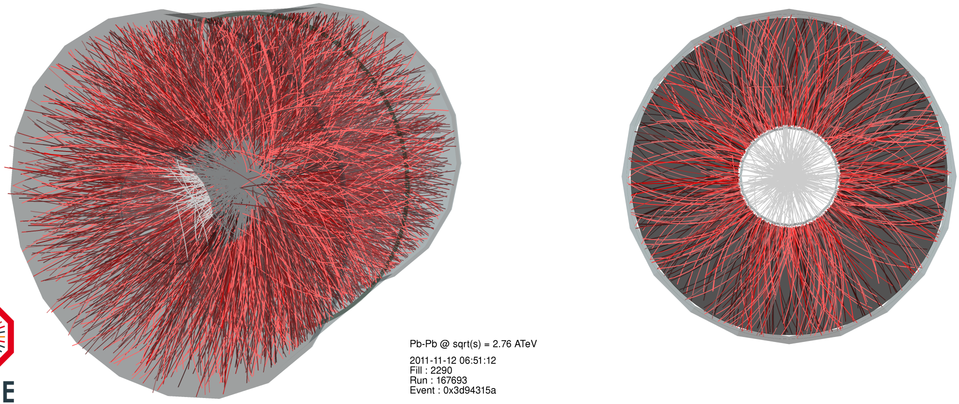
Laser calibration system



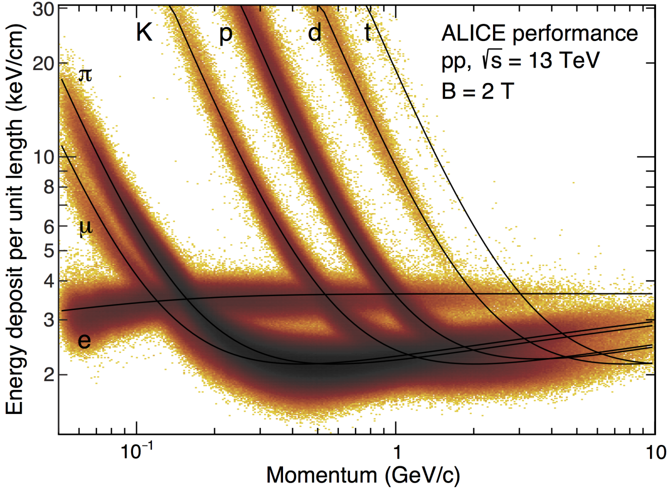




- An ultra-violet laser is guided into the TPC, split and produces tracks at defined positions
- Stray-light hits the cathode and ejects photo electrons which drift the full drift distance


Pb-Pb @ sqrt(s) = 2.76 ATeV
2011-11-12 06:51:12
Fill : 2290
Run : 167693
Event : 0x3d94315a

Some performance figures



Material budget

- 4.1 % X_0 at the $\eta \sim 0$ region

$\mathrm{d}\varepsilon/\mathrm{d}x$:

- 5.2 % in pp collisions
- 6.5 % in PbPb collisions

Transverse momentum:

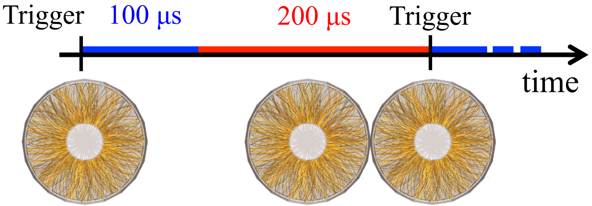
- $\sim 6\,\%$ for particles with $p \sim 10\,\mathrm{GeV/c}$
- $< 1\,\%$ for particles with $p \sim 1\,\mathrm{GeV/c}$

Upgrade of the ALICE Time Projection Chamber

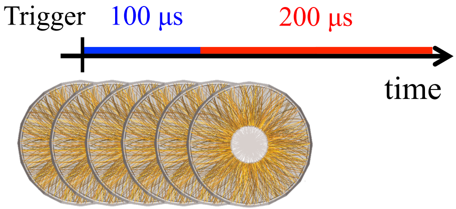
- LHC run 3: Increased rate of PbPb collisions of up to 50 kHz
- ALICE goal: Examining every event at this rate

ALICE TPC upgrade: Towards a continuously read-out TPC

Current read-out schema at low rate:



At 50 kHz:



- At 50 kHz there are on average 5 events piled up inside the drift volume
- The gated readout of the MWPCs is no longer feasible as is their un-gated operation
- New readout chambers are needed which allow for continuous read-out and preserve the current TPC's performance

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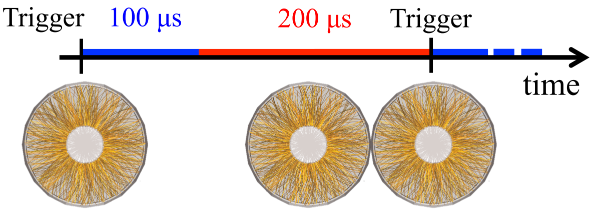
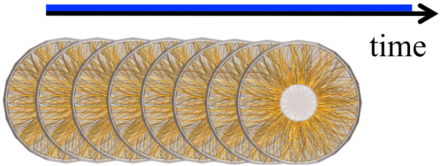


Continuous readout:



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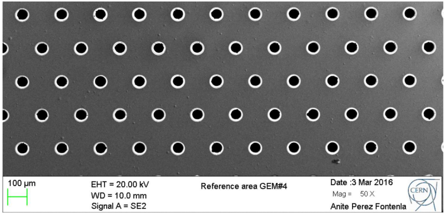
Gas Electron Multiplier foils

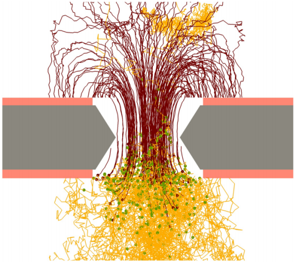
- 50 µm polyimide foils with a 5 µm copper cladding on both sides
- Hexagonal hole pattern with a standard pitch of 140 µm



Requirements on the ALICE TPC GEM stacks:

- Provide an Ion Back Flow (IBF) of less than 1 % in order to keep the space charges in the TPC at a tolerable level
- Preserve the momentum and $\mathrm{d}\varepsilon/\mathrm{d}x$ resolution of the old chambers ($\frac{\sigma_\varepsilon}{\varepsilon_{^{55}\mathrm{Fe}}} \leq 12\%$)
- Stable operation at LHC Run 3 conditions

GEM cross section with simulation:



Measuring IBF and local energy resolution

IBF & effective gain measurement

- Irradiate a detector with a source (all voltages in the GEM stack at zero)
- Measure the current on the cathode (I_{Primary}) and on the top side of GEM1

→ Primary ionisation

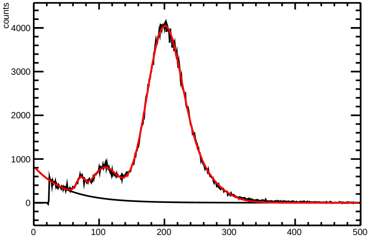
- Apply desired voltage to the stack
- Current measurement on cathode (I_{C}) and anode (I_{A})

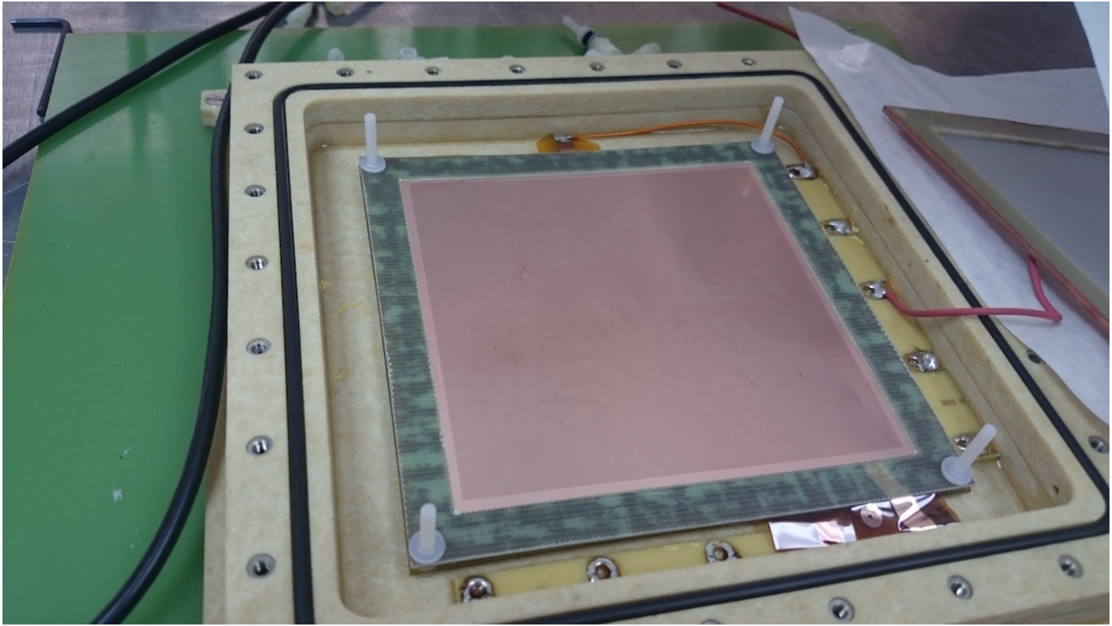
→ $G_{\mathrm{Eff}} = I_{\mathrm{A}}/I_{\mathrm{Primary}}$, $\mathrm{IBF} = I_{\mathrm{C}}/I_{\mathrm{Primary}}$

If e.g. a $^{55}\mathrm{Fe}$ is used, the I_{Primary} can be compared to the expected primary ionisations

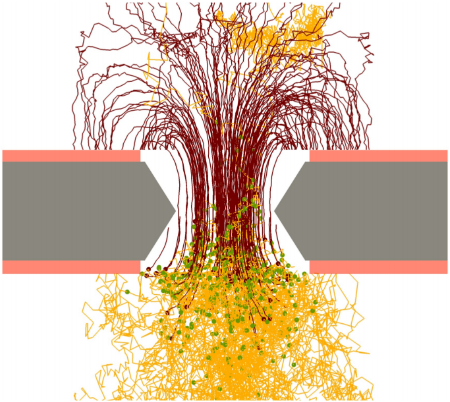
Energy resolution

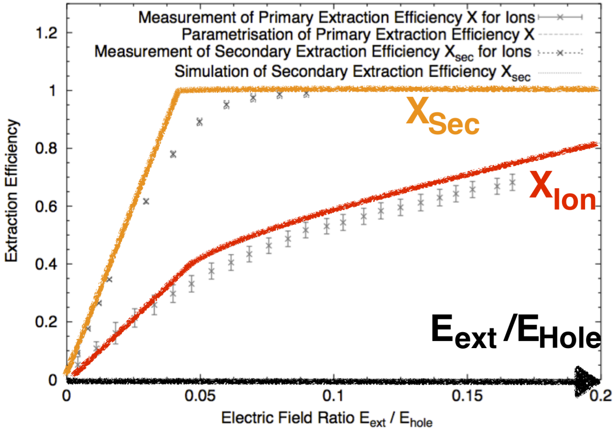
- Set desired voltage settings
- Record a pulse-height spectrum from the signals on the anode plane





Intrinsic ion back flow suppression in a GEM





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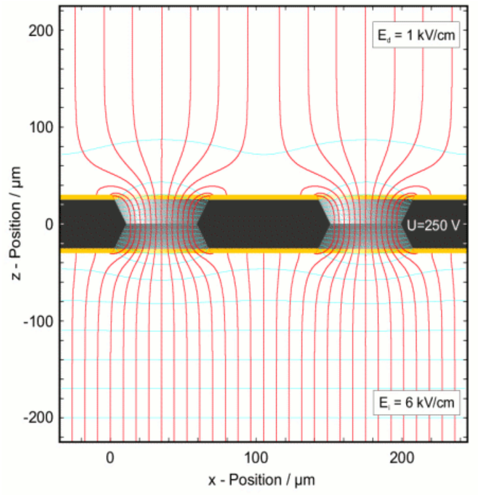
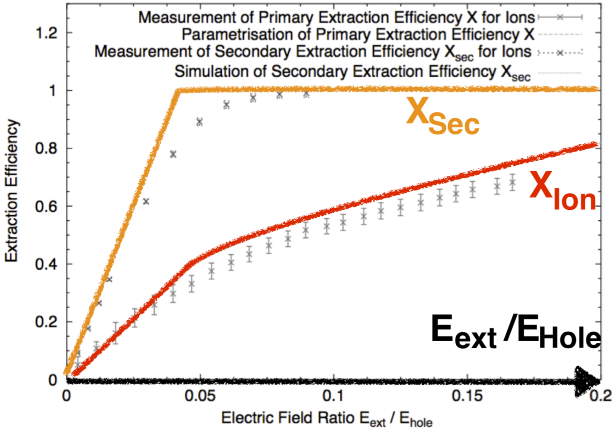


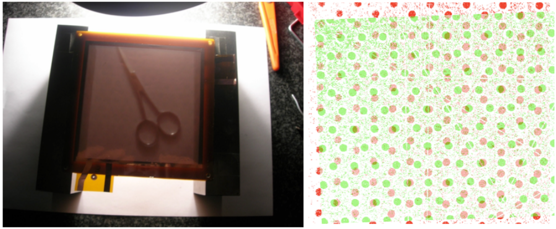


Optimising the ion back flow

- Low gain in GEM1
- Trap ions from GEM foils with high gain in the transfer regions

→ Maximal misalignment between GEM foils

→ Specially tuned voltage settings

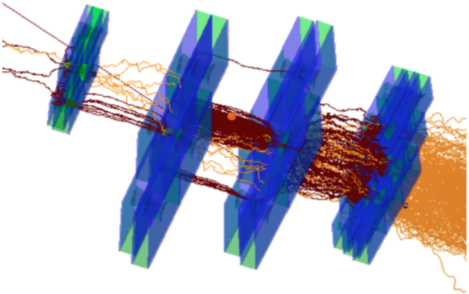


90° relative to the other foil

No rotation of the two foils

ALICE TPC GEM stack settings

ΔU_{GEM1}	ΔU_{GEM2}	ΔU_{GEM3}	ΔU_{GEM4}	E_{D}	E_{T1}	E_{T2}	E_{T3}	E_{Ind}
270 V	230 V	288 V	359 V	$0.4\,\frac{\mathrm{kV}}{\mathrm{cm}}$	$4\,\frac{\mathrm{kV}}{\mathrm{cm}}$	$4\,\frac{\mathrm{kV}}{\mathrm{cm}}$	$0.1\,\frac{\mathrm{kV}}{\mathrm{cm}}$	$4\,\frac{\mathrm{kV}}{\mathrm{cm}}$



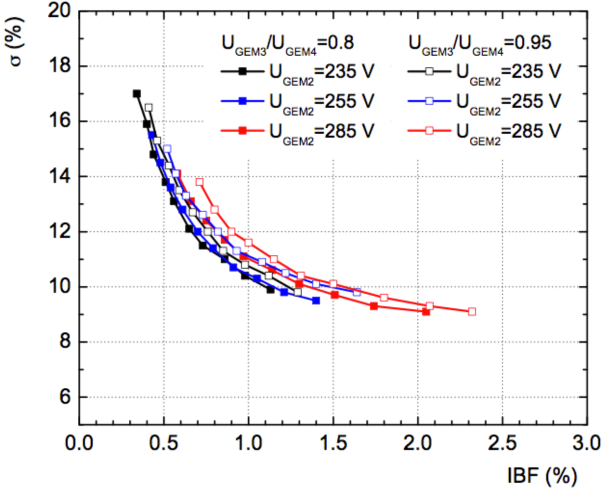
ALICE TPC GEM stacks:

- Quadruple GEM stacks
- Position 1 & 4: Standard GEMs
- Position 2 & 3: Large pitch (280 µm) GEMs
- Each GEM mask rotated by 90 °
- Gain 2000
- Gas mixture: $\mathrm{Ne\text{-}CO_2\text{-}N_2}$

Performance: Energy resolution vs IBF

- Quadruple GEM stacks (S-LP-LP-S)
- Done with small prototypes ($10\,\mathrm{cm} \times 10\,\mathrm{cm}$ GEMs)
- $225\,\mathrm{V} \leq \Delta U_{\mathrm{GEM1}} \leq 315\,\mathrm{V}$, keeping the gain at 2000
- E_{T1} & $E_{\mathrm{Ind}} = 4\,\mathrm{kV\,cm^{-1}}$, $E_{\mathrm{T2}} = 2\,\mathrm{kV\,cm^{-1}}$, $E_{\mathrm{T3}} = 0.1\,\mathrm{kV\,cm^{-1}}$

$\Rightarrow$ **Optimisation of energy resolution and IBF are competing effects**

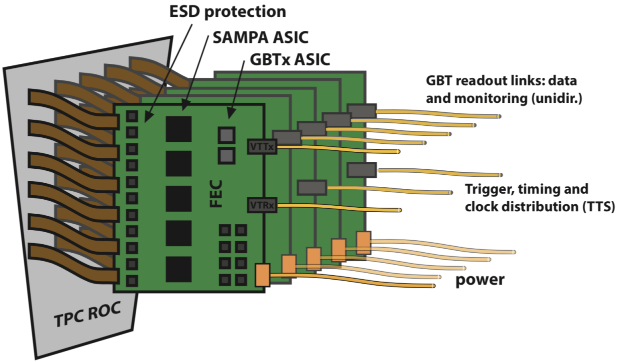


Readout electronics

New readout electronics necessary to accommodate for:

- Different signal polarity
- Sample data continuously and ship if of detector
- Higher readout rate

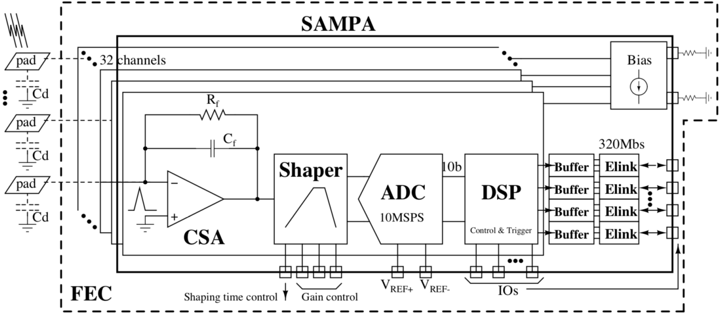
SAMPA ASIC has been developed in a combined effort by the TPC and muon chamber groups



$$\textbf{FECs} \xrightarrow{3.3\,\mathrm{TB/s}} \textbf{CRU} \xrightarrow{500\,\mathrm{GB/s}} \textbf{Online farm} \xrightarrow{10\,\mathrm{GB/s}} \textbf{Tape}$$

The SAMPA ASIC

- 32 channels, 10 bit
  5 MHz sampling frequency
- Positive or negative input charge
- Programmable conversion gains and peaking times
- Readout modes: triggered or continuous
- Optional digital signal processing



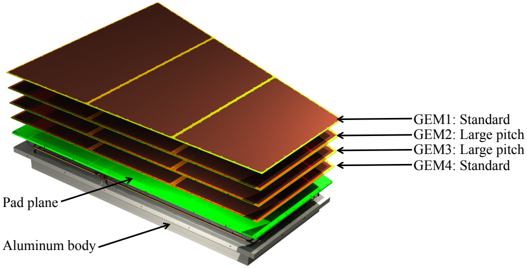
The ALICE O2 – Online-Offline – project

- Merge the data acquisition with the offline part: Calibration and reconstruction.
  In case of the TPC the following steps happen synchronously with the data taking:
  1. Preliminary calibration, online cluster finding
  2. Tracking
- Decoupled from the data taking the full calibration will be applied and then the data permanently stored
- This will allow un-triggered readout of the experiment and the latter selection of interesting events

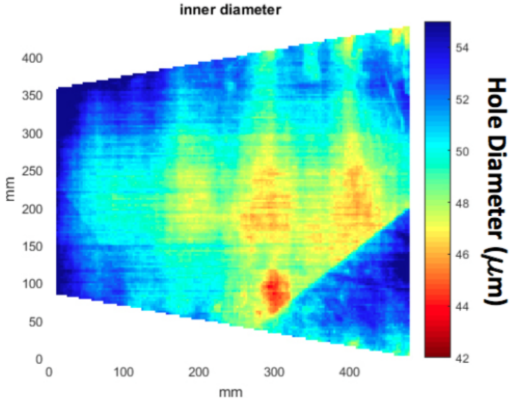
Towards the commissioning of the upgraded ALICE Time Projection Chamber

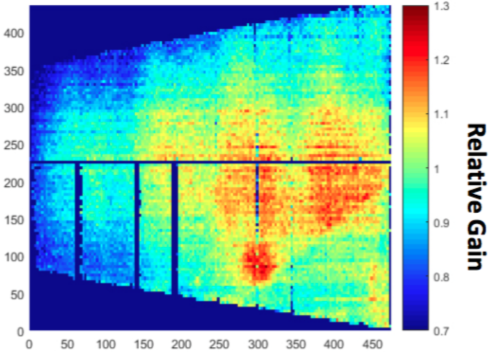
Mass production of readout chambers

- Several institutes in the US and in Europe are participating
- There is a dedicated quality assurance for the different items, *e.g*
  - Leakage current tests for the GEM foils
  - Gas tightness tests for the chamber bodies
  - Connectivity tests for the pad-planes
- The assembled readout chambers undergo again dedicated tests



GEM foil mapping for the ALICE TPC upgrade

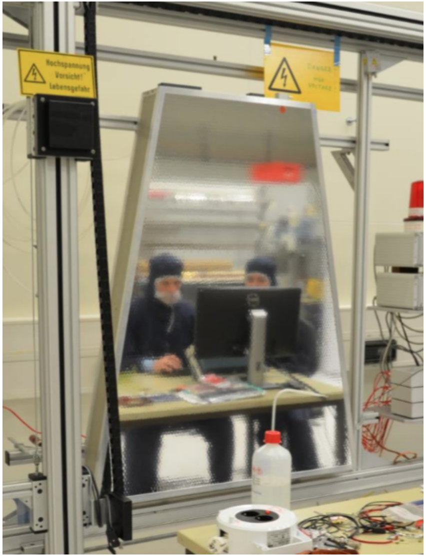




Scan of the *inner hole diameter* of a GEM foil and a gain scan of the very same foil.

Readout chamber acceptance tests

- Gas tightness test (Required leak rate: $< 0.5\,\mathrm{mL\,h^{-1}}$)
- GEM capacitance and conductance measurement
- Leakage current measurement at 250 V between the GEM electrodes (Required leakage current: $< 1\,\mathrm{nA}$)
- Gain curve measurement and gain uniformity scan (Uniformity better than 20 % required)
- Ion backflow measurement (IBF $< 1\,\%$, Uniformity $< 20\,\%$)
- Energy resolution test ($\frac{\sigma_\varepsilon}{\varepsilon_{^{55}\mathrm{Fe}}} \leq 12\%$)
- Stability measurement with full X-ray irradiation ($10\,\mathrm{nA\,cm^{-2}}$ current at the pad-plane)



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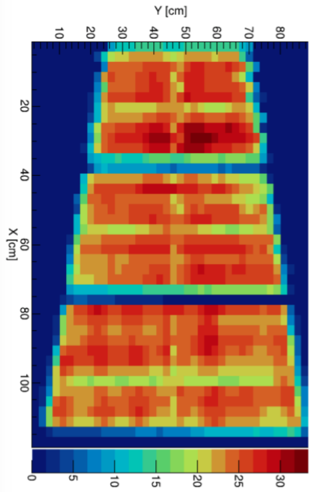
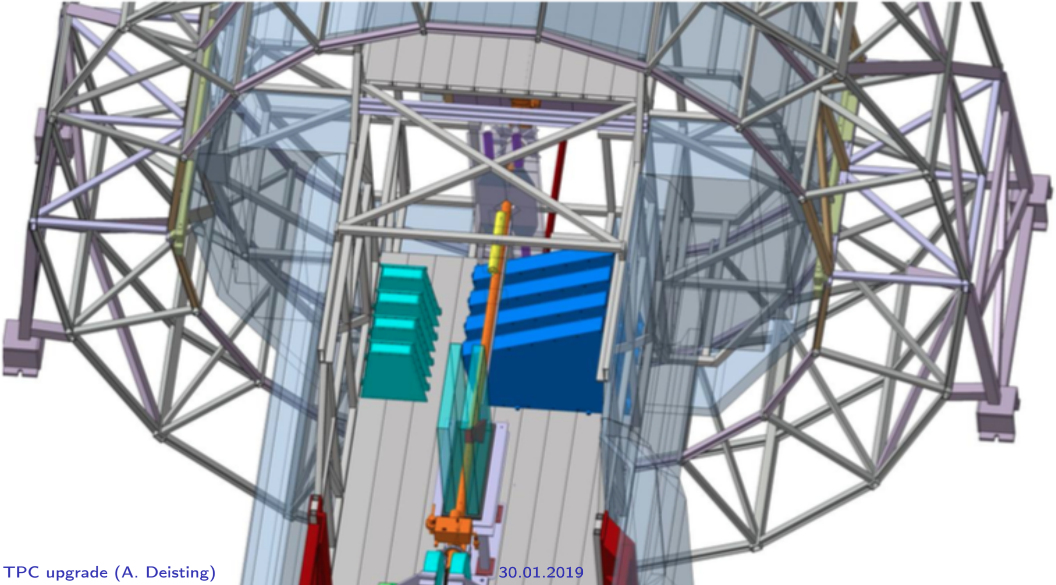
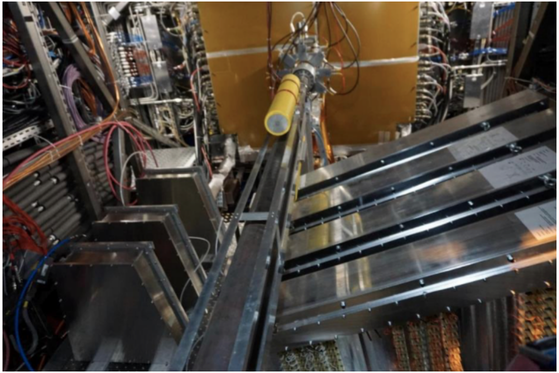


Readout chamber test at LHC



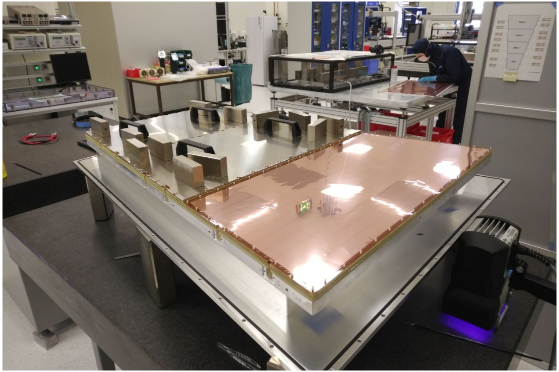
Readout chamber test at LHC

- Four inner and outer readout chambers are installed in the ALICE cavern
- The chambers are located at very forward rapidity, $\sim 5\,\mathrm{m}$ from the interaction point
- They are operated with the nominal gas-mixture and the future ALICE TPC high voltage supply schema
- The purpose of this test is to verify the electric stability of the chambers under beam conditions

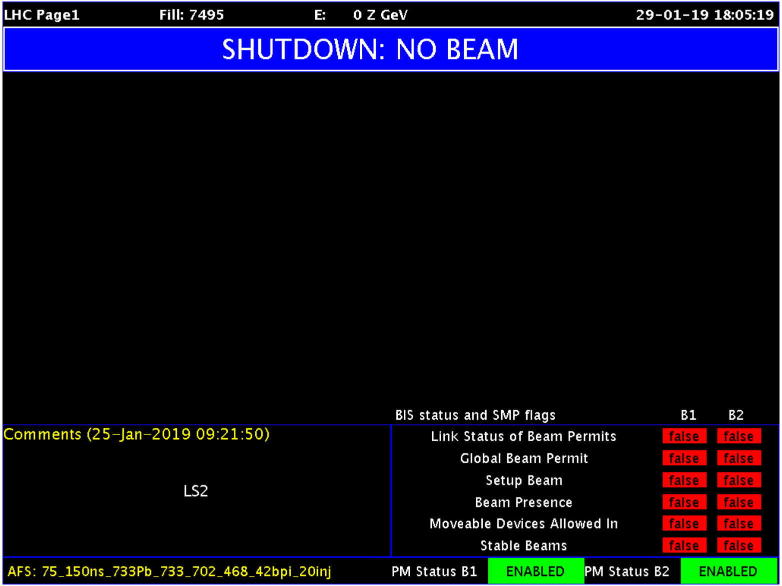


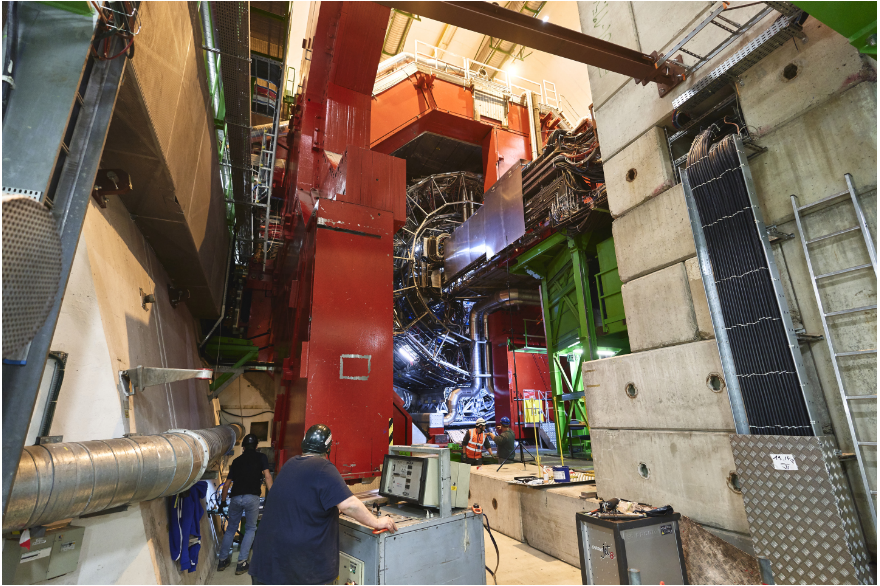
Project status – late 2018

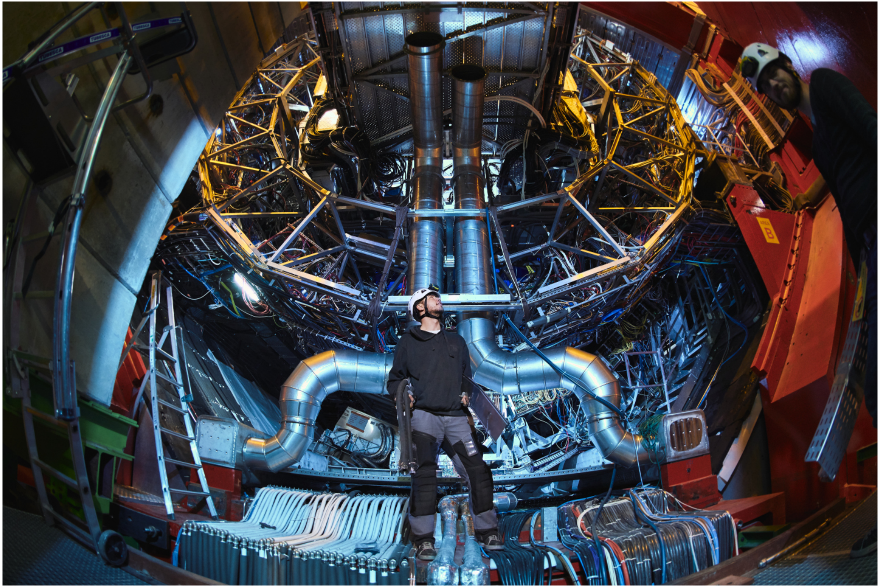
Mass production phase of readout chambers – GSI:

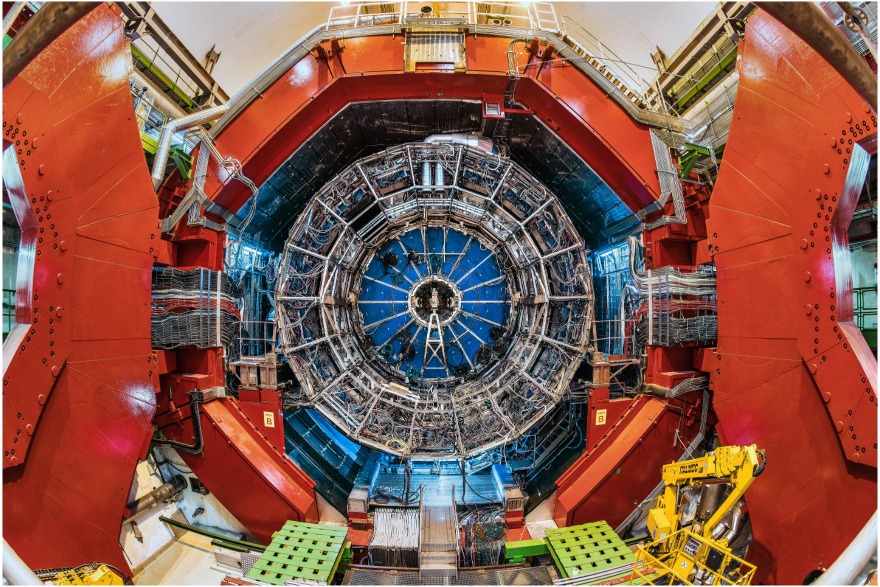


Chamber storage at CERN:


LHC Page1
Fill: 7495
E: 0 Z GeV
29-01-19 18:05:19
SHUTDOWN: NO BEAM
BIS status and SMP flags
B1
B2
Comments (25-Jan-2019 09:21:50)
LS2
Link Status of Beam Permits false false
Global Beam Permit false false
Setup Beam false false
Beam Presence false false
Moveable Devices Allowed In false false
Stable Beams false false
AFS: 75_150ns_733Pb_733_702_468_42bpi_20inj
PM Status B1 ENABLED
PM Status B2 ENABLED

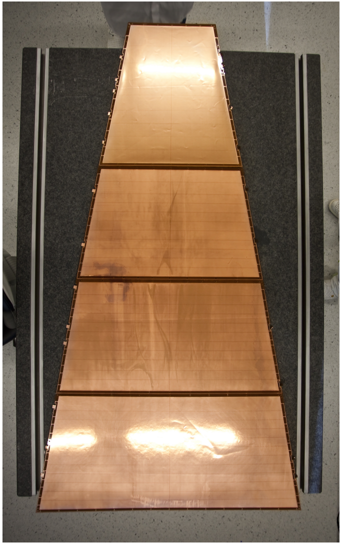






Summary

- ALICE at LHC employs a TPC as main tracking and PID detector
- The ALICE TPC has been successfully operated in LHC run 1 and 2
- The TPC will be upgraded in order to exploit the full PbPb interaction rate of 50 kHz during LHC run 3
- New readout chambers employing stacks of four GEMs have been developed, which:
  - Allow for continuous read-out
  - Preserve the performance of the current TPC
- The mass production of readout chambers done
- Commissioning of the upgraded TPC is approaching



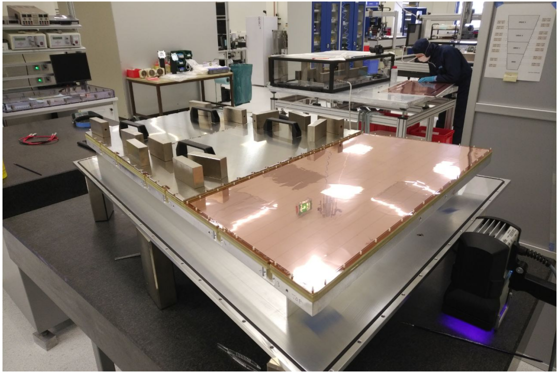
Backup

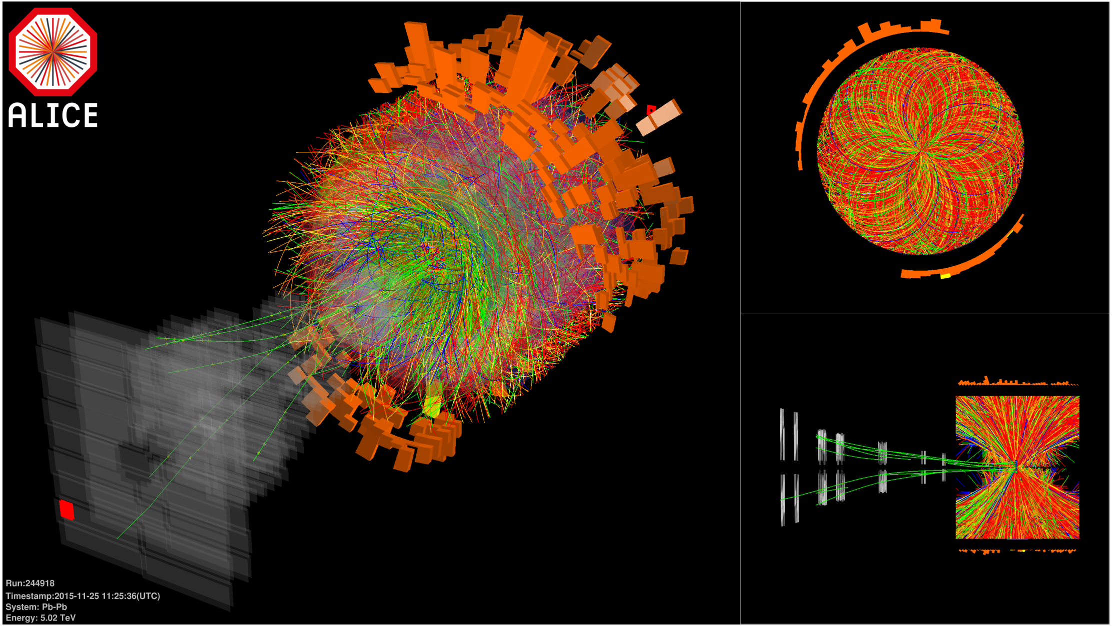
Performance goals for the new readout chambers

Tests with prototype and final design chambers show:

- ☑ Less than 1% IBF in order to keep the space charges in the TPC manageable
- ☑ Preserve the momentum and $\mathrm{d}\epsilon/\mathrm{d}x$ resolution of the old chambers
- ☑ Stable during operation at LHC Run 3:
  - SPS beam-time: $(6 \pm 4) \times 10^{-12}$ discharges per incoming hadrons
  - Comparing to 5×10^{-11} particles crossing a GEM stack (on average) during 1 month of lead-lead data taking at 50 kHz

Currently: mass production phase of readout chambers




ALICE
Run:244918
Timestamp:2015-11-25 11:25:36(UTC)
System: Pb-Pb
Energy: 5.02 TeV

SAMPA specifications

		RUN 1 (measured)	RUN 3 (requirement)	
Signal polarity		Pos	Neg	
Detector capacitance (range)	(pF)	12 – 33.5	12 – 33.5	
$S{:}N$ ratio for MIPs (IROC)		14:1	20:1	
(OROC $6\times10\,\mathrm{mm}^2$ pads)		20:1	30:1	
(OROC $6\times15\,\mathrm{mm}^2$ pads)		28:1	30:1	
MIP signal	(fC)	1.5 – 3[14]	2.4 – 3.2	
System noise (at 18.5 pF, incl. ADC)		670 e	670 e	
PASA conversion gain (at 18 pF)	(mV/fC)	12.74	20 (30)	
PASA return to baseline	(ns)	< 550	< 500	
PASA average baseline value	(mV)	100	100	
PASA channel-to-channel baseline variation (σ)	(mV)	18	18	
PASA shaping order		4	4	
PASA peaking time	(ns)	160	160 (80)	updated
PASA crosstalk		< 0.1 %[15]	< 0.2 %	
PASA integrated non-linearity		0.2 %	< 1 %	
ENC (PASA only, at 12 pF)		385 e	385 e	
ADC voltage range (differential)	(V)	2	2	SAMPA: 2.2 V
ADC linear range (differential)	(fC)	160	100 (67)	
ADC number of bits		10	10	
ADC sampling rate	(MHz)	10 (2.5, 5, 20)	10 (20)	TPC: 5 MHz
Power consumption (analog & digital)	(mW/ch)	35	< 35	