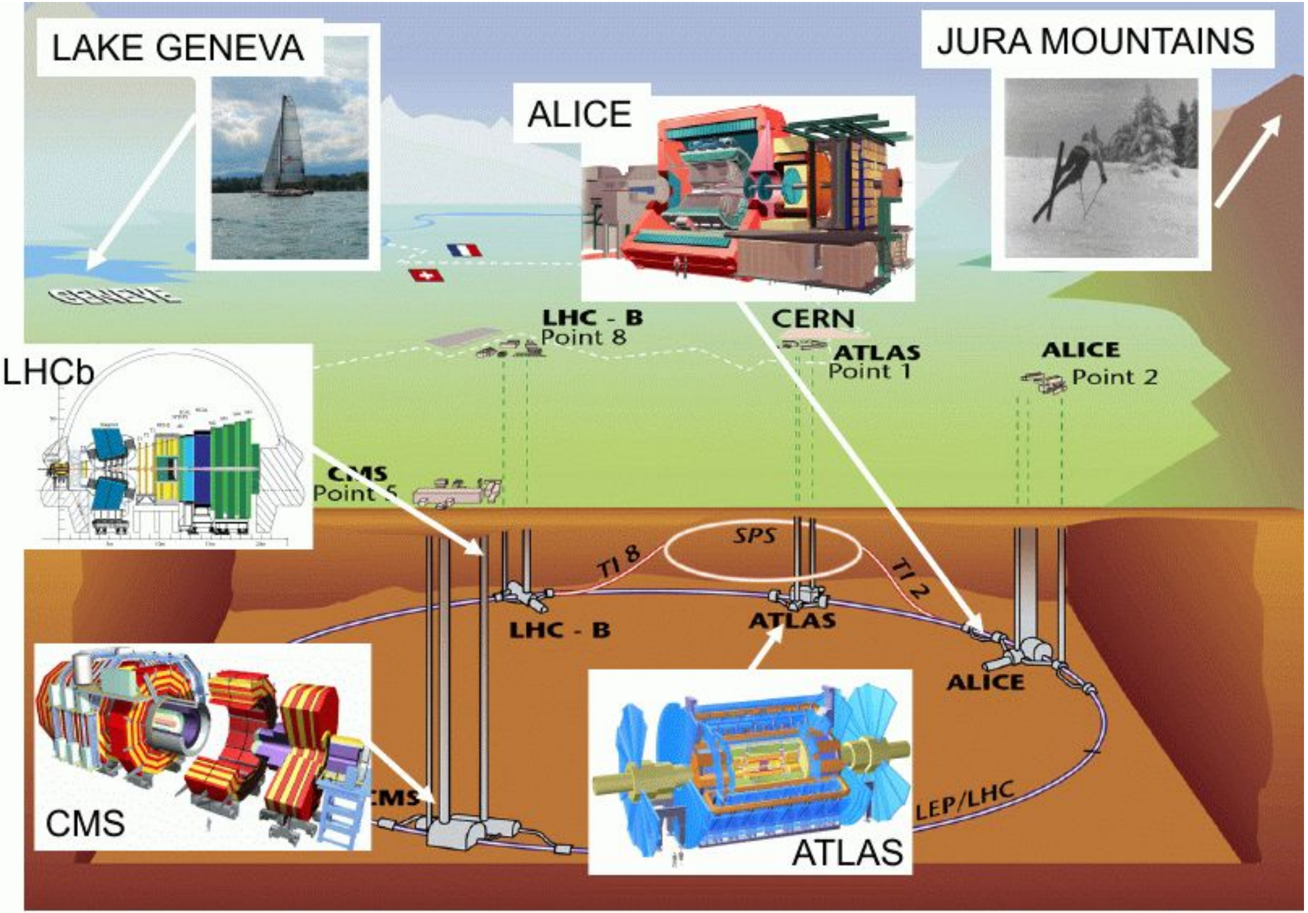
# The fastest Time Projection Chamber of the world

# or

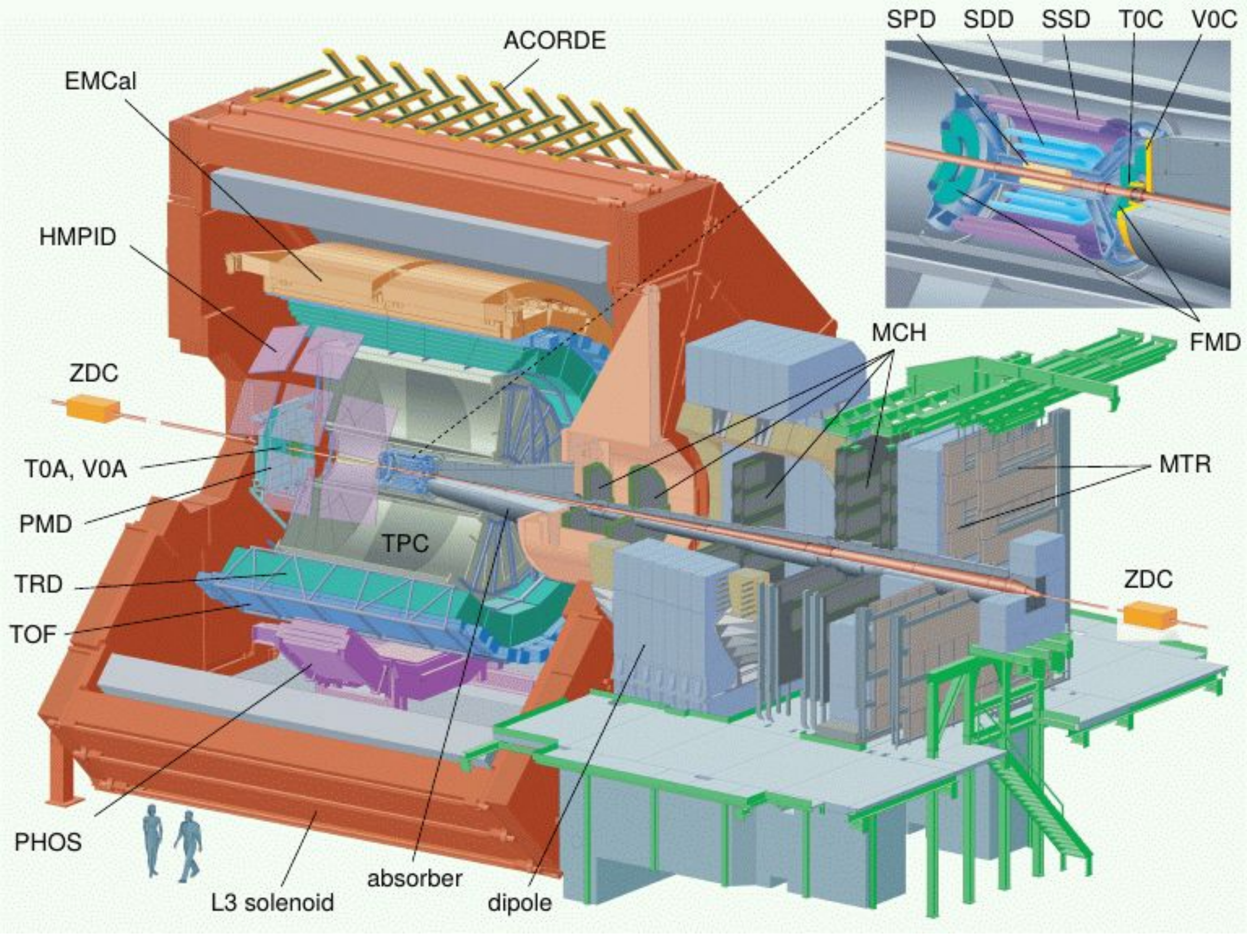
# the upgrade of the ALICE TPC

Dariusz Miskowiec, GSI Darmstadt
for the ALICE Collaboration

# Large Hadron Collider at CERN

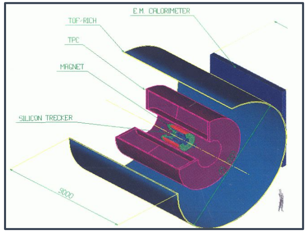


# A Large Ion Collider Experiment at CERN

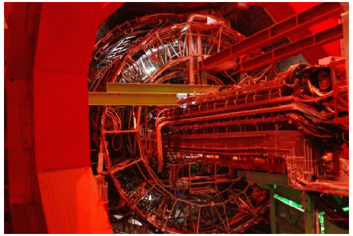


# ALICE timeline

~1990 inception

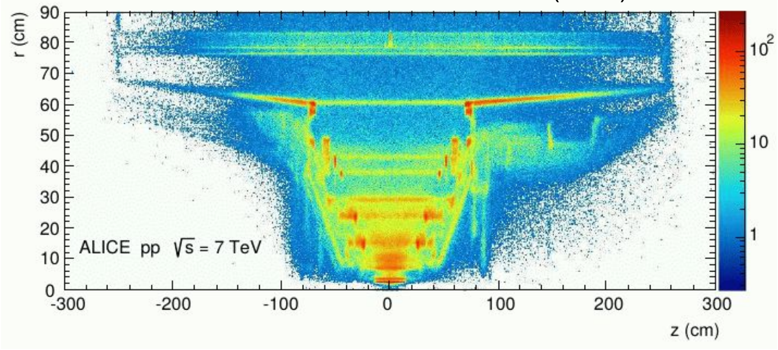



1995-2008 construction



2009-2013 LHC Run 1: Pb-Pb, p-Pb, pp at 50% energy

IJMPA 29 (2014) 1430044




2015-2018 LHC Run 2: Pb-Pb, Xe-Xe, p-Pb, pp at 93% energy

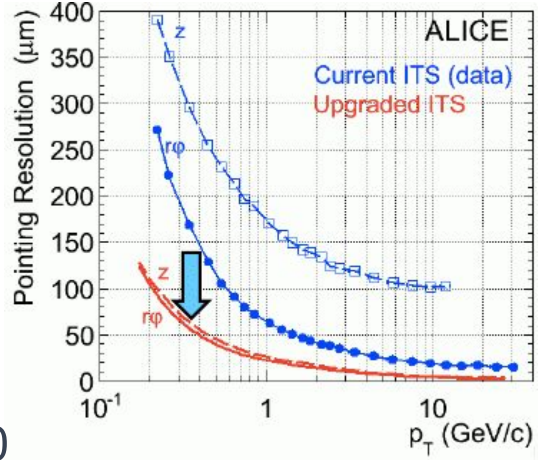
2021-2023 LHC Run 3 (increased luminosity and 100% energy)

# plan for Run 3

- improve statistics of minimum-bias Pb-Pb collisions by a factor of 100 by speeding up the Time Projection Chamber

**triggered operation with maximum Pb-Pb readout rate of 500 Hz** → **continuous readout of minimum-bias Pb-Pb interactions at 50 kHz**

- improve tracking resolution at low $p_T$ by a factor of 3 by reducing the radius and amount of material in the Inner Tracker System



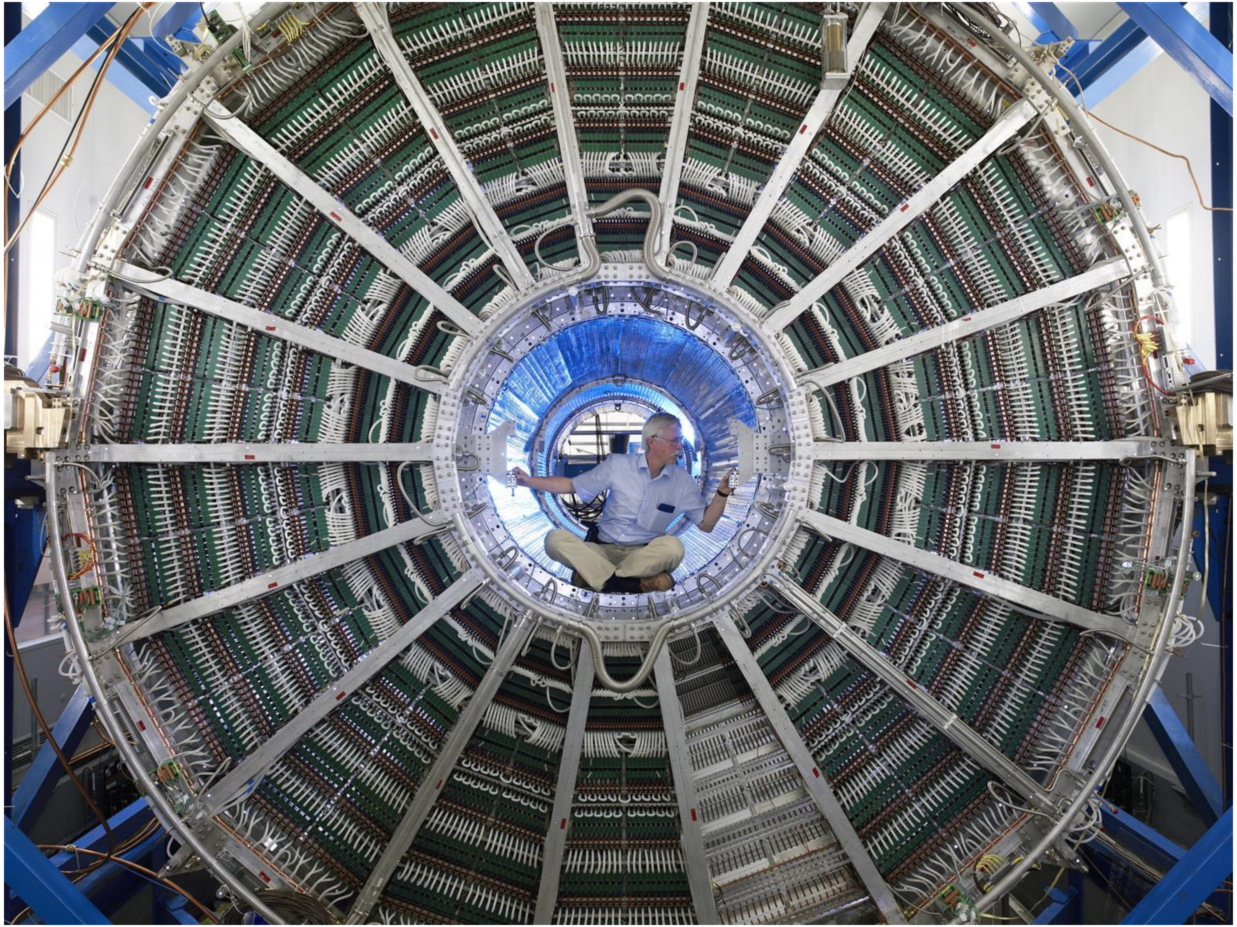

With higher statistics and better resolution, study

- open charm and beauty at low $p_T$, J/ψ down to $p_T$=0
- photons, thermal dileptons, vector mesons
- light nuclei and exotica

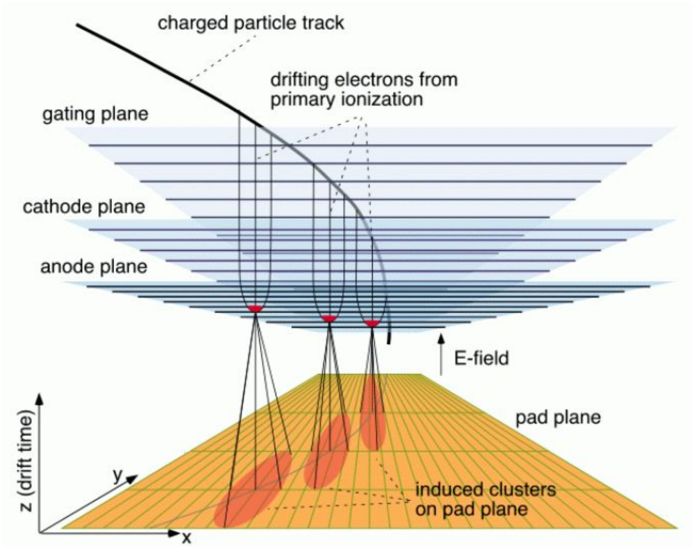
this talk is about

speeding up the ALICE TPC on the detector side
(involvement of the ALICE group at GSI Darmstadt)

# ALICE Time Projection Chamber in 2006



# Time Projection Chamber



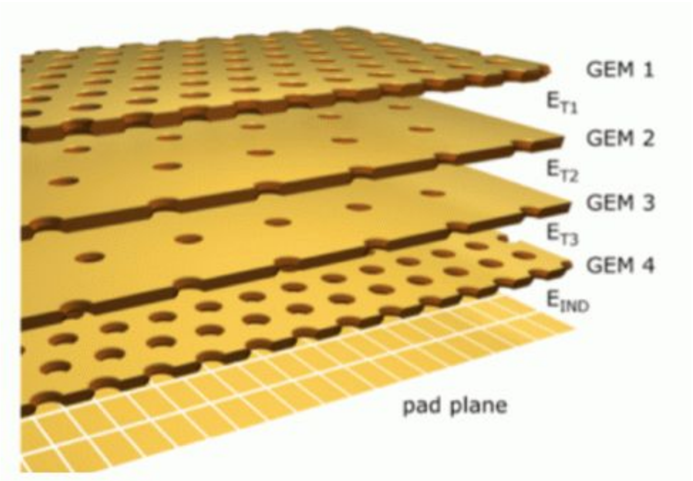

gating grid closes 100 μs after the trigger and stays closed for 180 μs to keep ions off the drift volume → maximum event-taking rate of 3.5 kHz

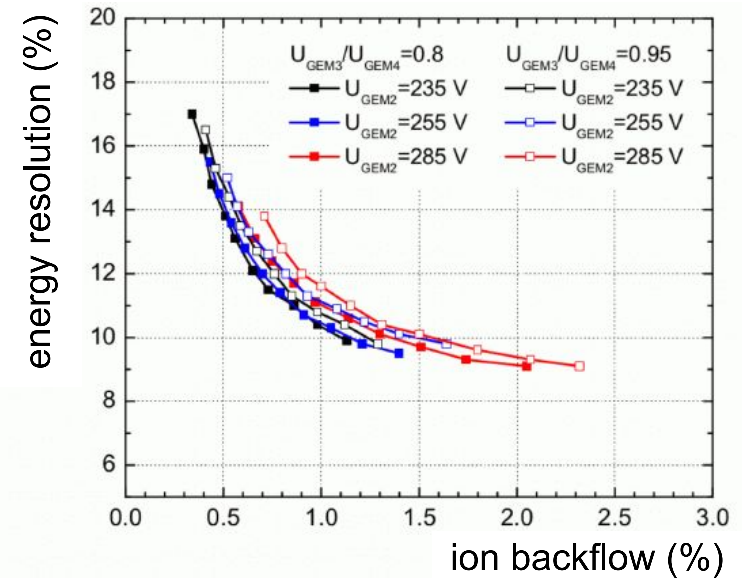
LHC Run 3 will offer 50 kHz of Pb-Pb

# solution for the rate limitation

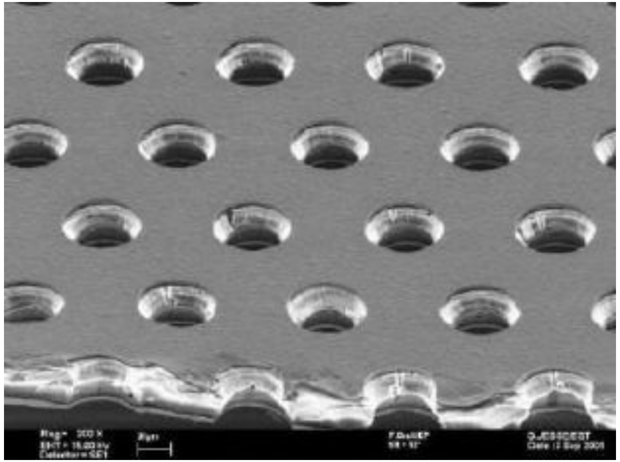
- remove gating grid
- use several amplification stages, keep total gain low, reduce ion backflow (IBF) by the choice of electric fields

implementation: 4 Gas Electron Multiplier (GEM) foils



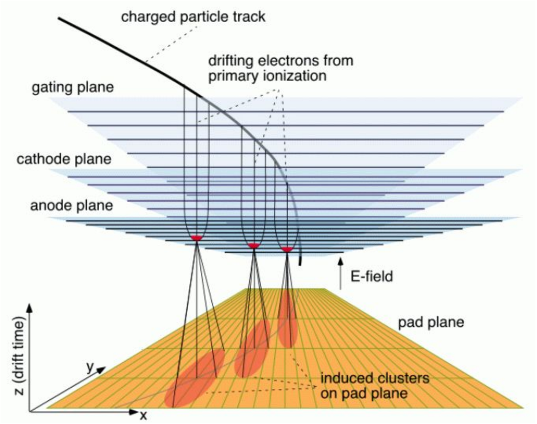
# Gas Electron Multiplier foils

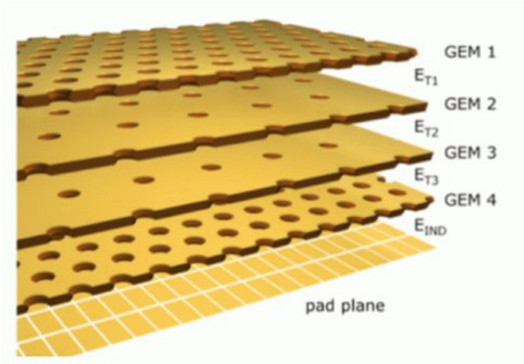


thin (50 μm) insulating foil with many small (diameter 70 μm) holes
5 μm copper coating on both sides
voltage (~300 V) across (between top and bottom copper layers)

→ high electric field inside holes
→ electrons ionize gas atoms while passing through holes
→ signal amplification

# comparison between wire chambers and GEM chambers

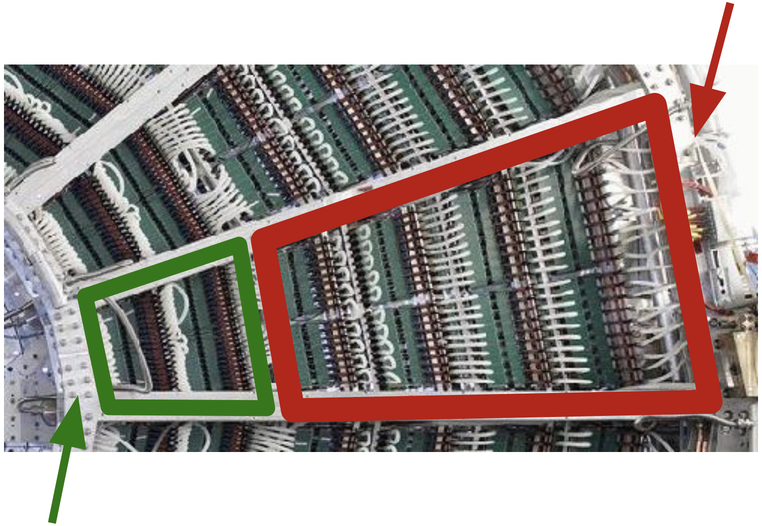


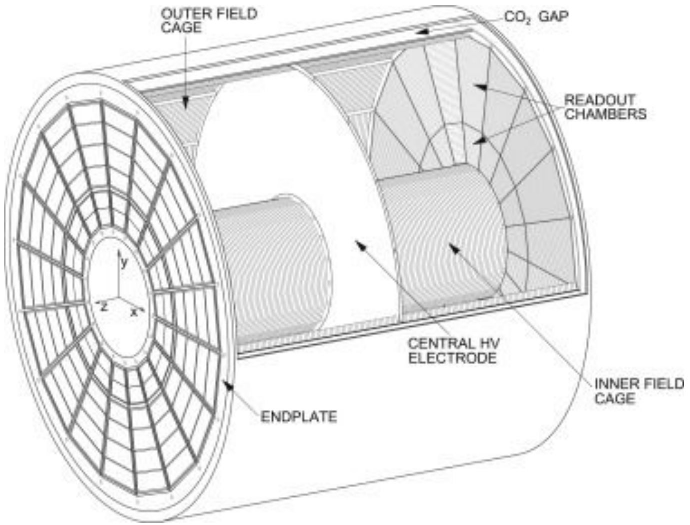

| | wire chamber | | GEM chamber |
|---|---|---|---|
| | grid open | grid closed | |
| gain | 8000 | 0 | 2000 |
| ion backflow | 0.13 | <0.0001 | <0.01 |

# upgrade of the TPC

Outer Readout Chamber (OROC)

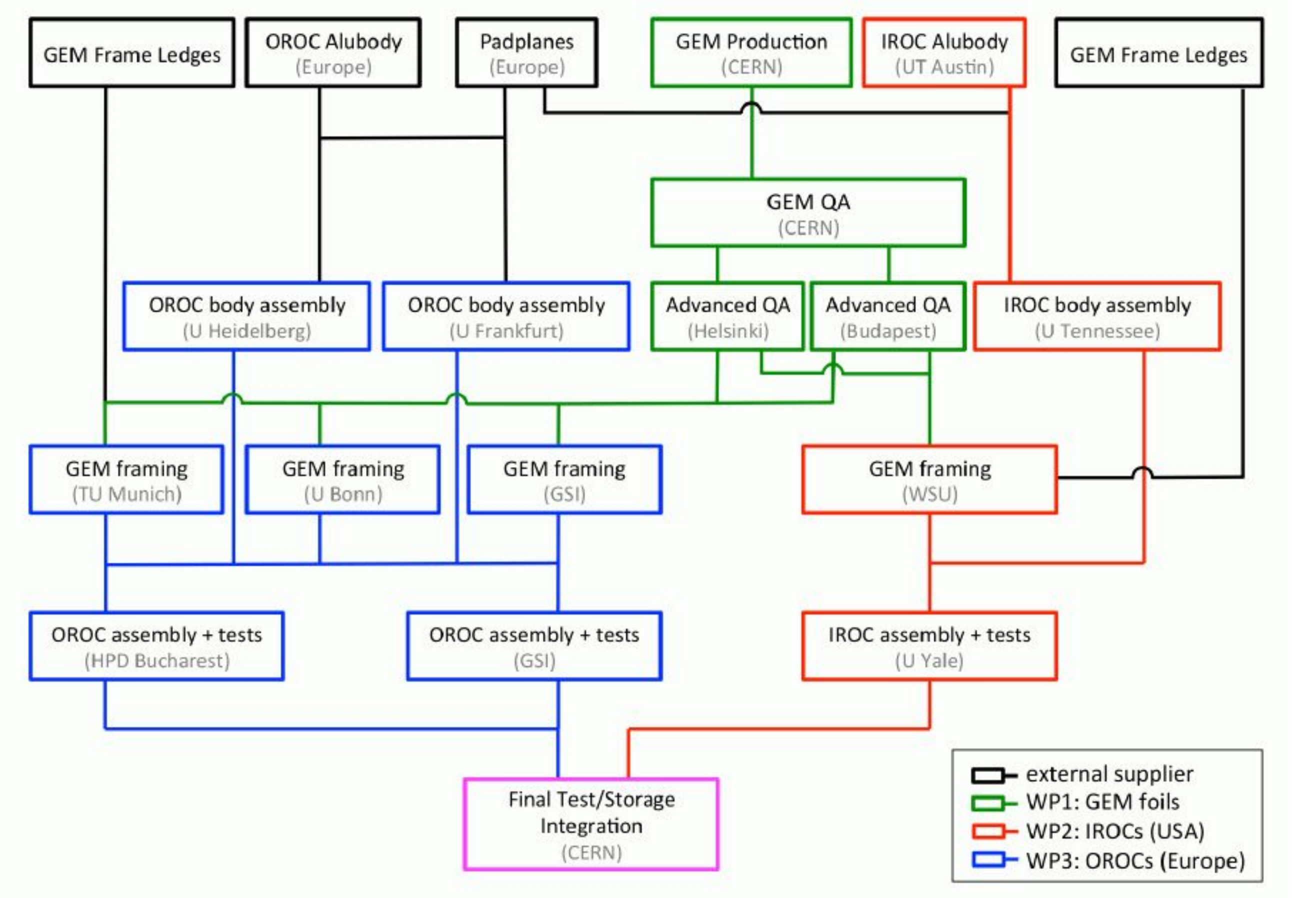


Inner Readout Chamber (IROC)




36 IROCs and 36 OROCs to be replaced by new GEM chambers
GSI assembling 20 OROCs

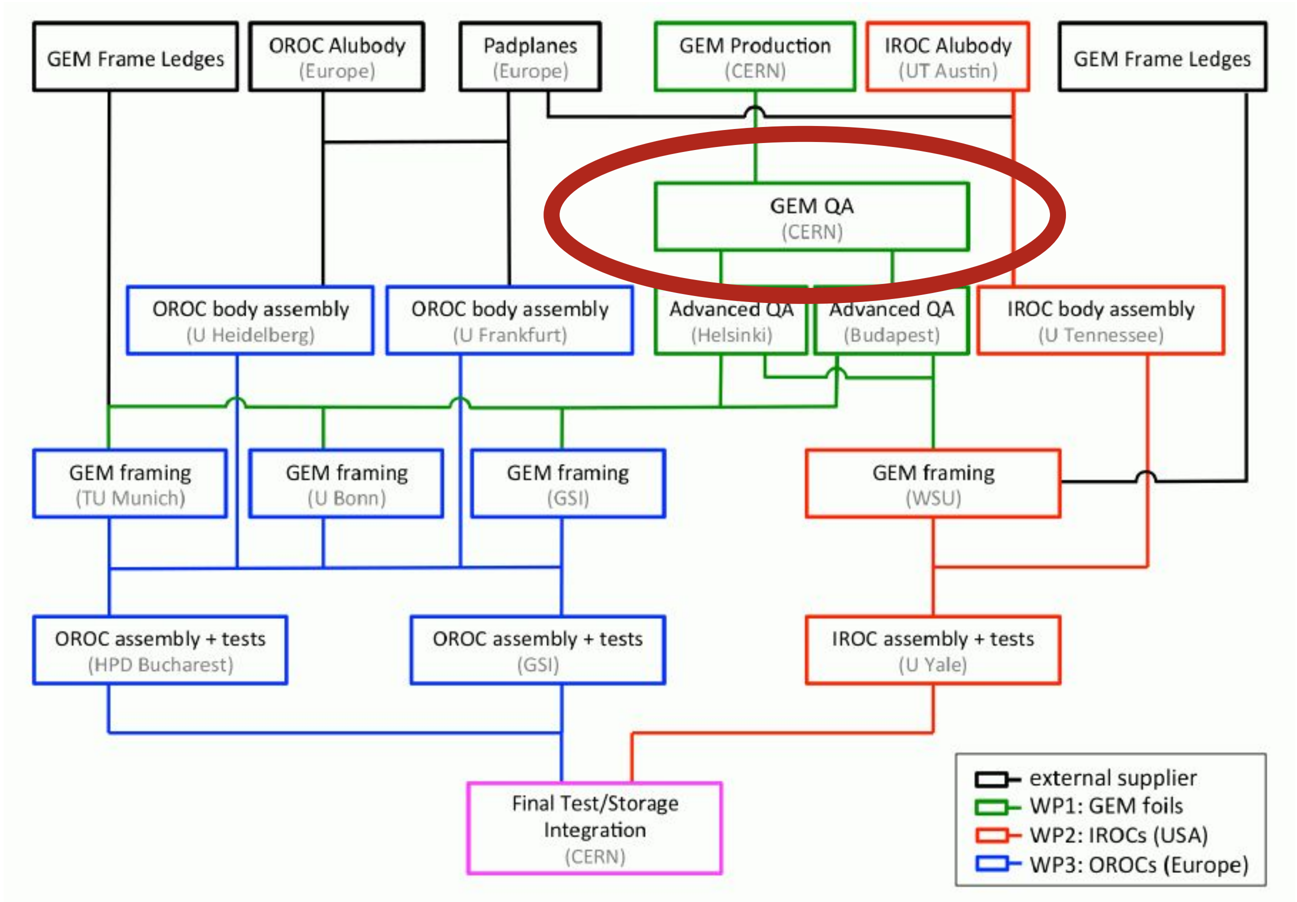
# ALICE TPC upgrade project structure



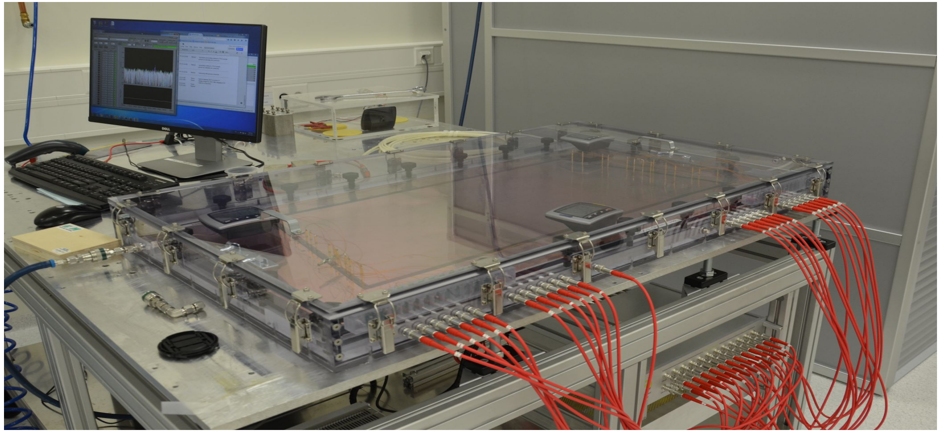
# ALICE TPC upgrade - a very logistic-intensive project

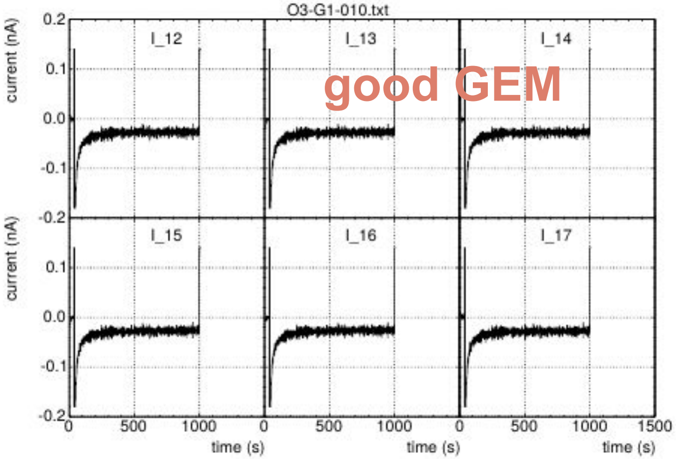


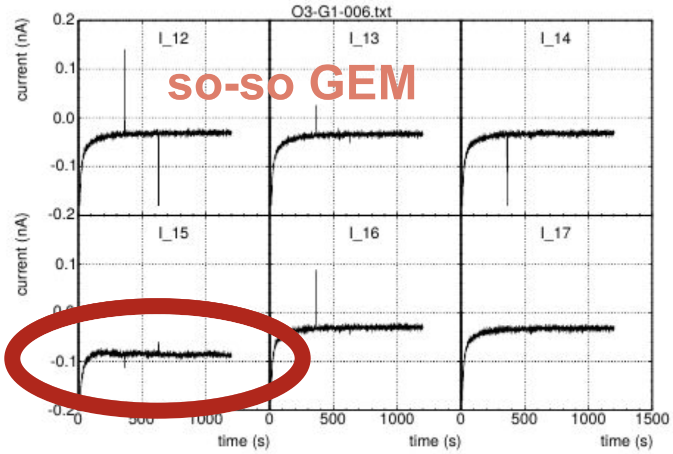
# ALICE TPC upgrade project structure



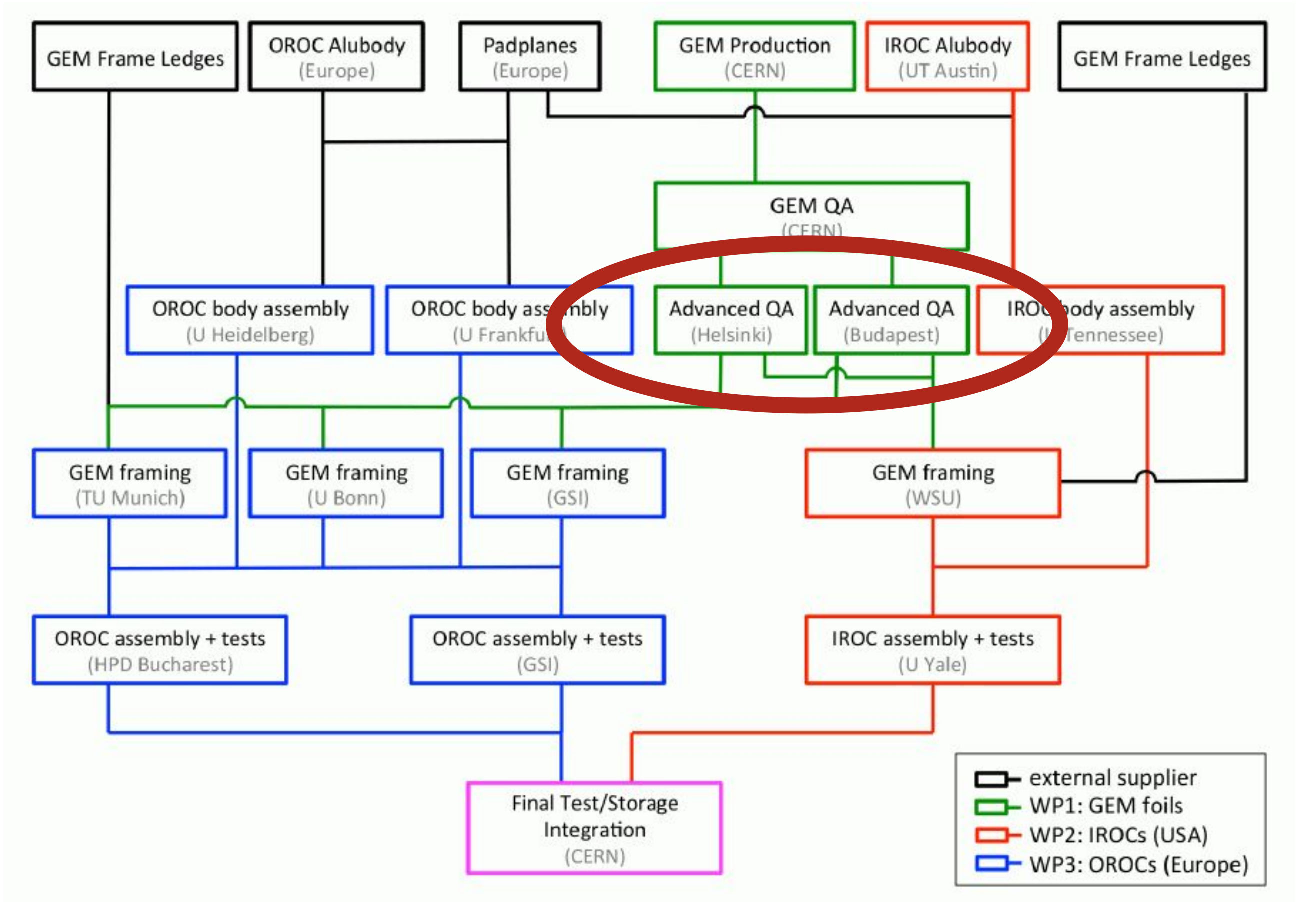
# basic GEM test: leakage current at 500 V





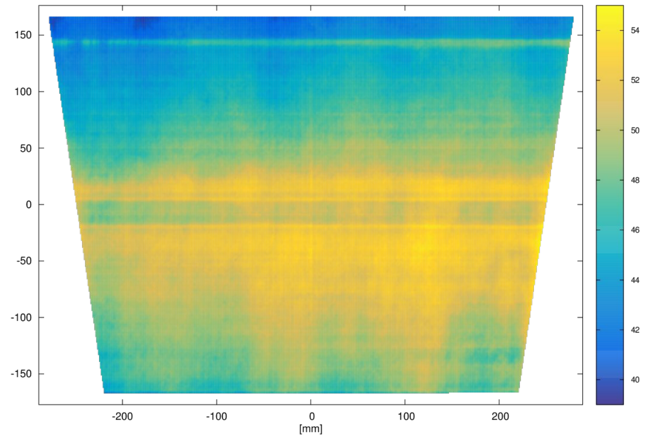



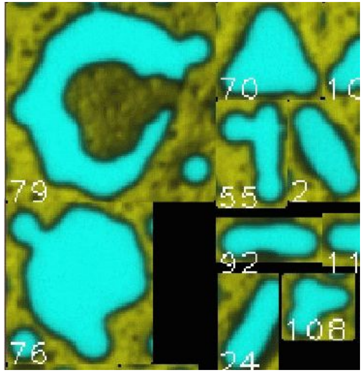
# ALICE TPC upgrade project structure



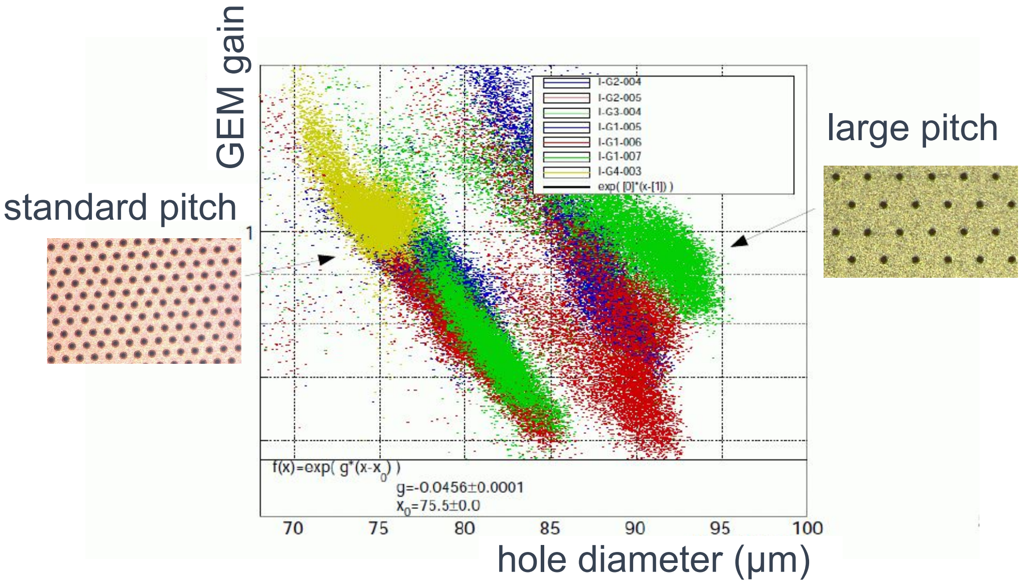
# advanced GEM tests: optical scan

hole-size map



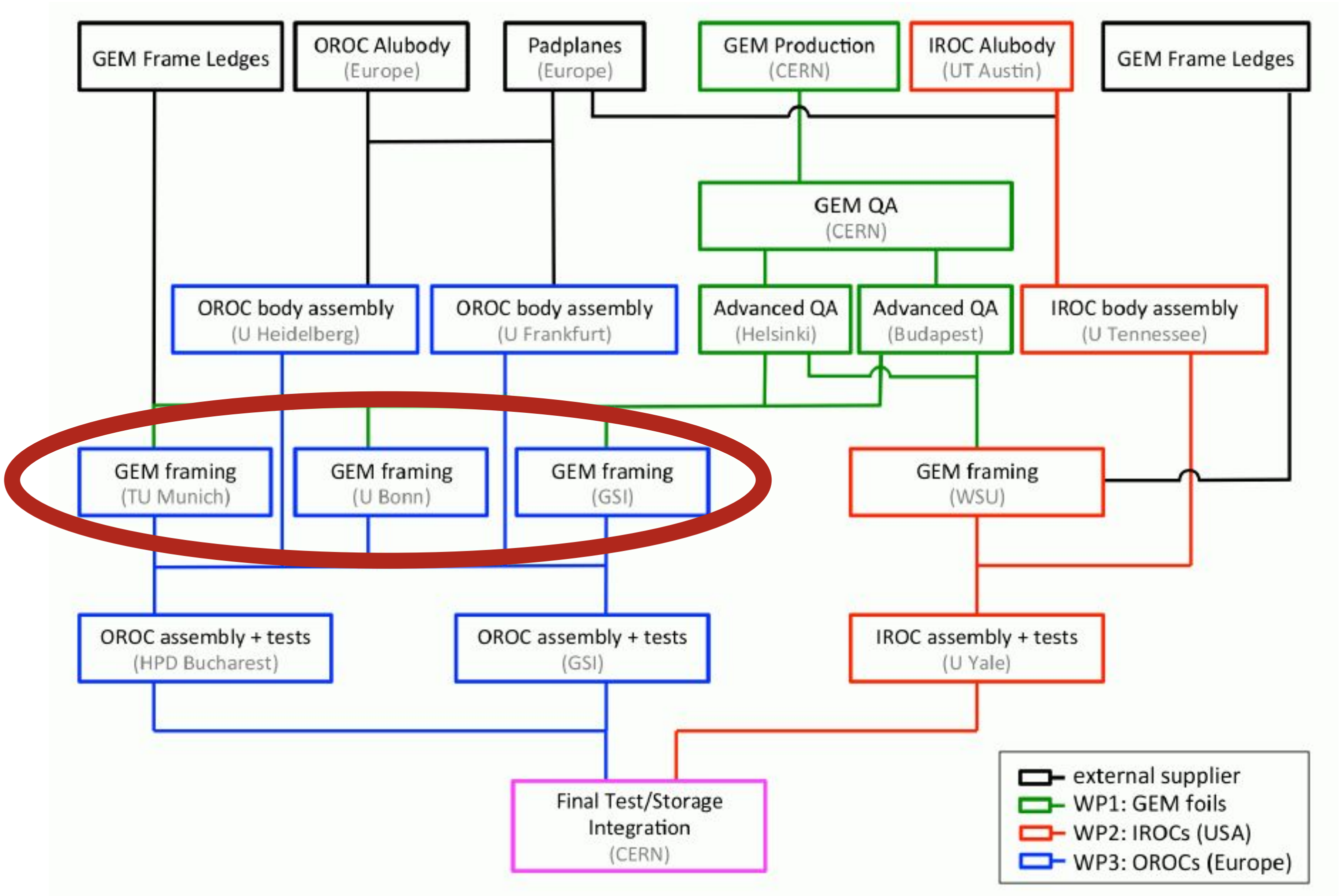

etching defects



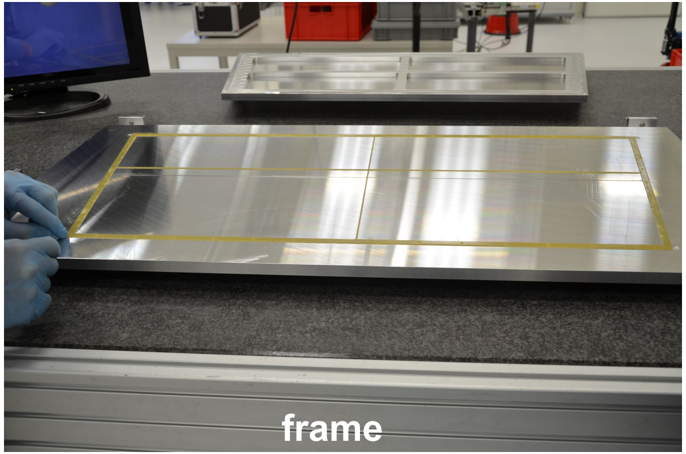

clear anticorrelation between hole size and single-GEM gain

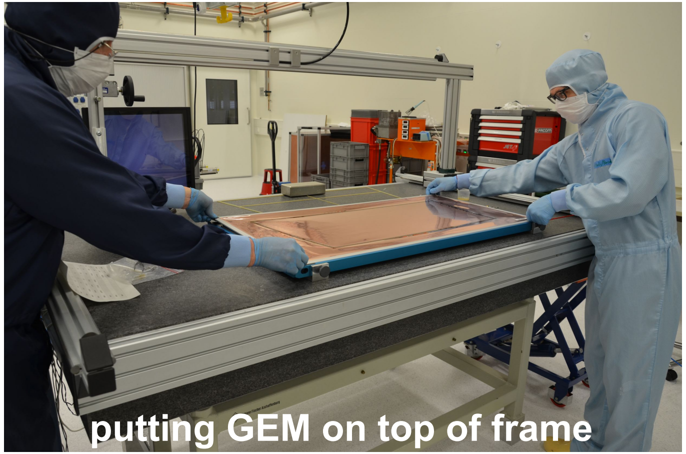
...gets lost once several GEMs are stacked together

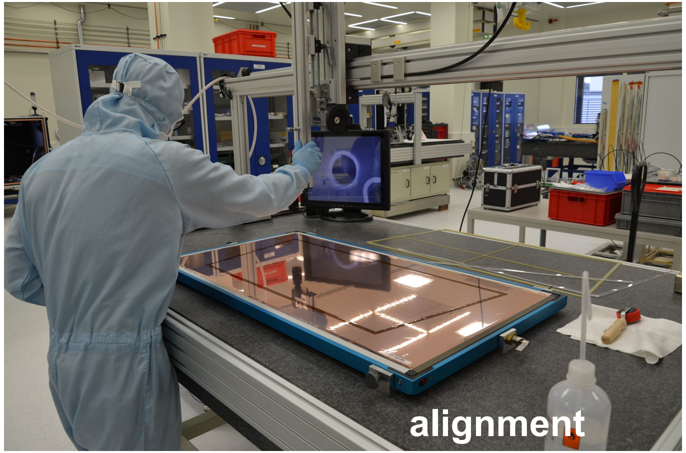
# ALICE TPC upgrade project structure

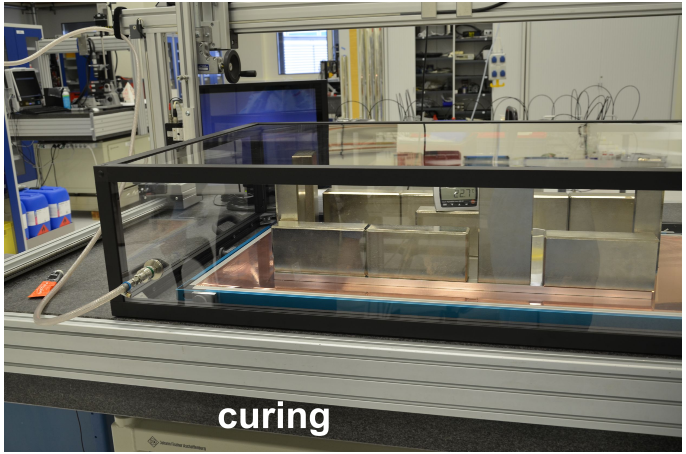


# GEM framing



# GEM database documenting 922 foils

Home | Category: OROC | Stock | Shipping | Information | logged in: Dariusz

## ALICE TPC production database

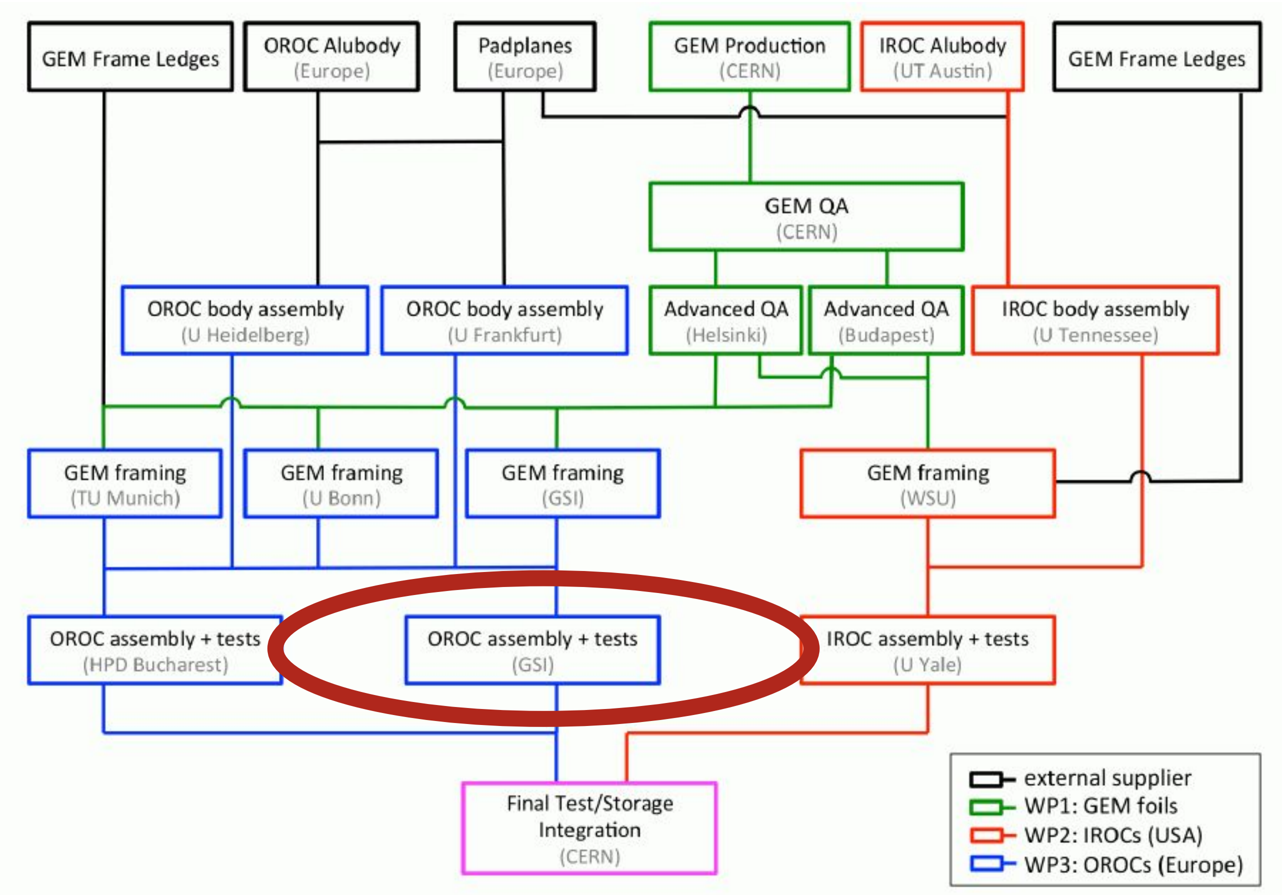
### Show selected stock items     link to bookmark this selection

Selection — specific QA step selection: (•) off ( ) not done ( ) passed ( ) failed

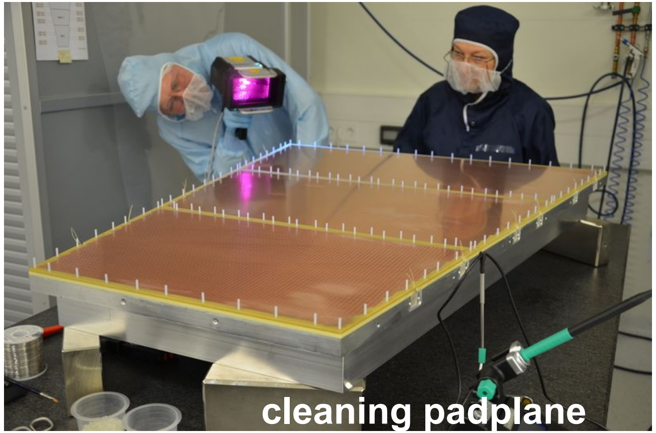
| category | part | batch | type | QA status | serialno/bc wildcards %, _ | sent? | select location or 'used' | search string within comment regular expressions accepted |
|---|---|---|---|---|---|---|---|---|
| OROC | OROC3 GEM foil | any | all types | any | | | | |

| part | item | batch | sent from | sent to | date | location or link to parent | QA status | link | comment |
|---|---|---|---|---|---|---|---|---|---|
| OROC3 GEM foil | O3-G1-001 | 5 | | | | OROC/02 | A 20.07.17 CERN | X | |
| OROC3 GEM foil | O3-G1-002 | 5 | | | | OROC/01 | 3 15.01.17 CERN | X | |
| OROC3 GEM foil | O3-G1-003 | 5 | | | | OROC/04 | B 30.01.18 CERN | X | |
| OROC3 GEM foil | O3-G1-004 | 7 | | | | Bonn | QA-A 05.11.18 CERN | X | |
| OROC3 GEM foil | O3-G1-005 | 7 | | | | GSI | 3 17.01.17 CERN | X | GSI: GEM stripped from frame |
| OROC3 GEM foil | O3-G1-006 | 7 | | | | GSI | QA-A 23.11.18 CERN | X | GSI long term tested |
| OROC3 GEM foil | O3-G1-007 | 8 | | | | OROC/35 | B 19.12.18 CERN | X | GSI long term tested. from CERN |
| OROC3 GEM foil | O3-G1-008 | 8 | | | | OROC/05 | C 30.10.17 CERN | X | GSI tested, framed, tested |

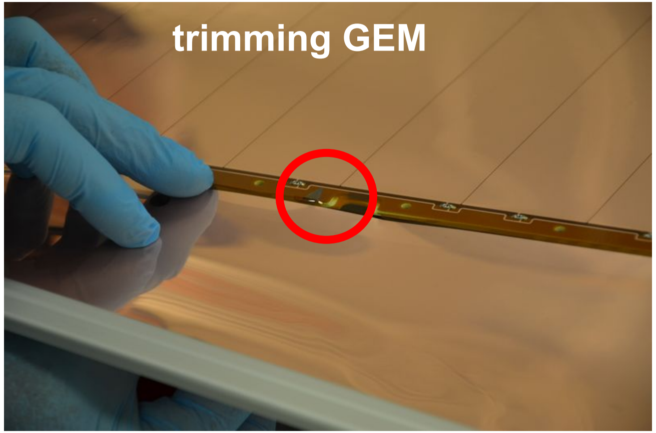
# ALICE TPC upgrade project structure

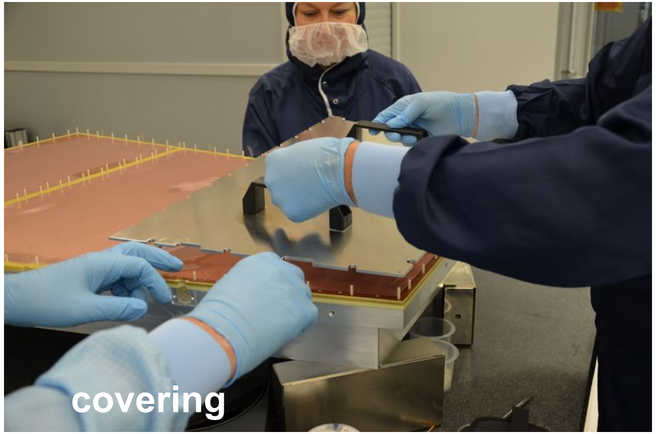


# OROC assembly







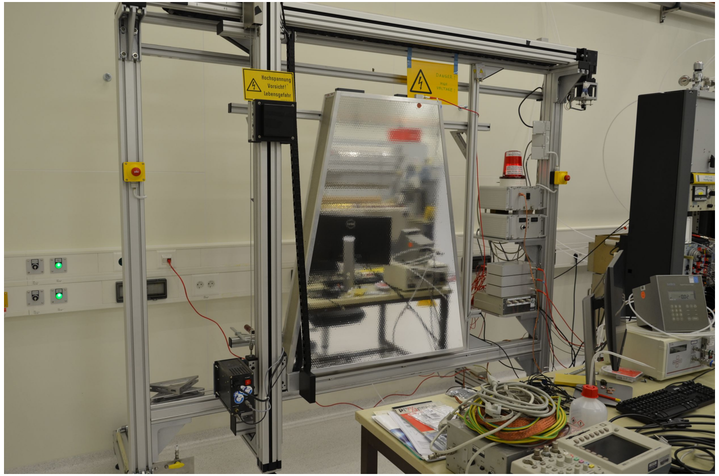


covering


soldering HV connections

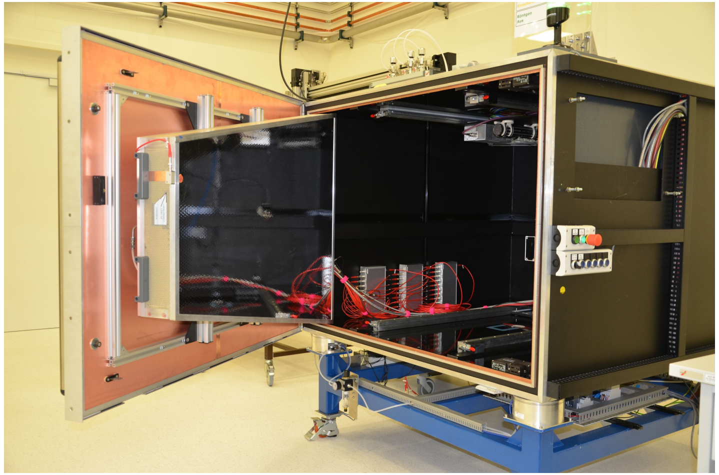

SUPER DRY
tightening nylon screws


SUPER DRY
done

# OROC tests at GSI

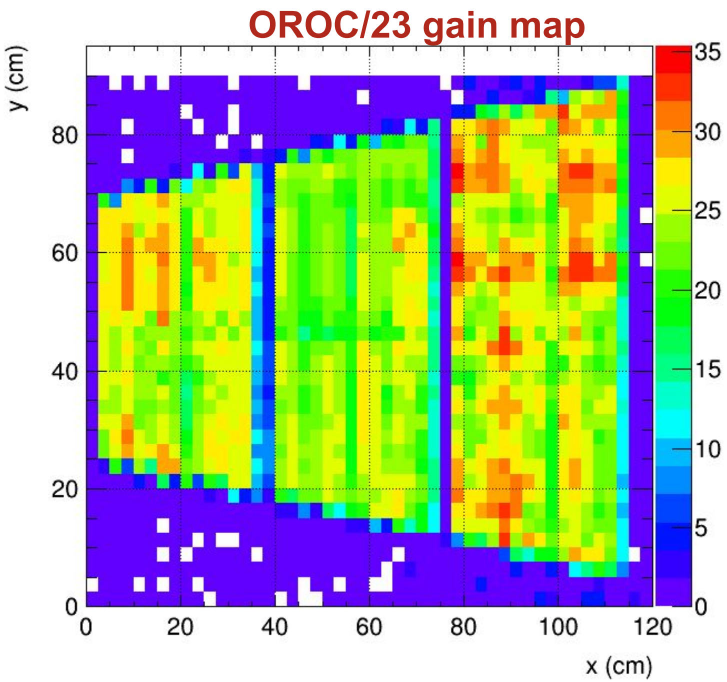


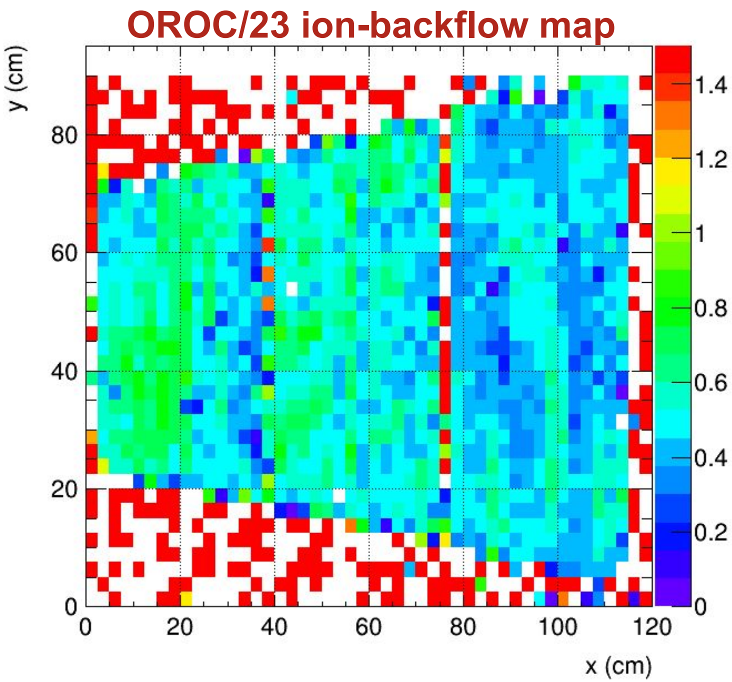
moving x-ray gun 10 kV
moving $^{55}Fe$ source 6 keV
monitoring currents of padplane and cathode



two x-ray guns 60 kV, full illumination
monitoring currents of padplane and cathode

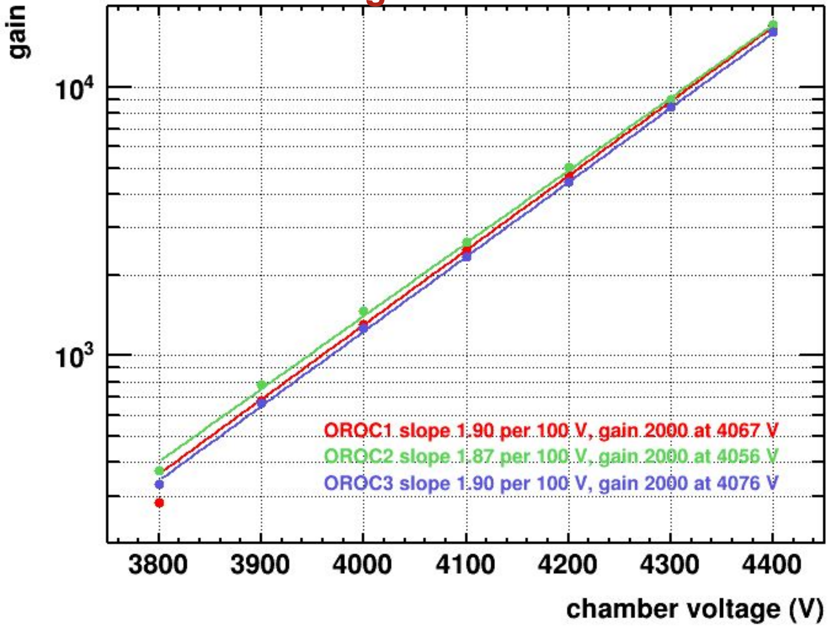
# OROC tests



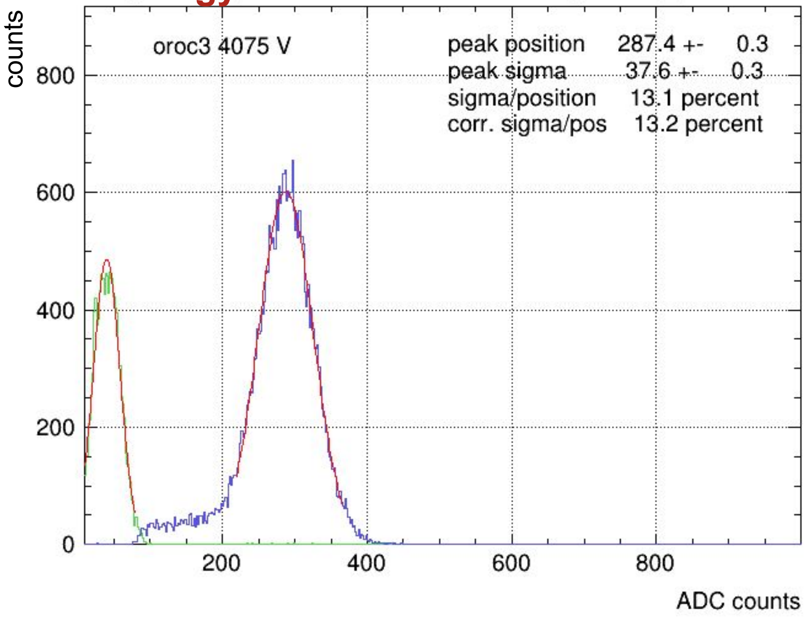




- gain uniformity 11% (standard deviation), requirement <20%
- average ion backflow 0.5%, requirement <1%

## gain curves

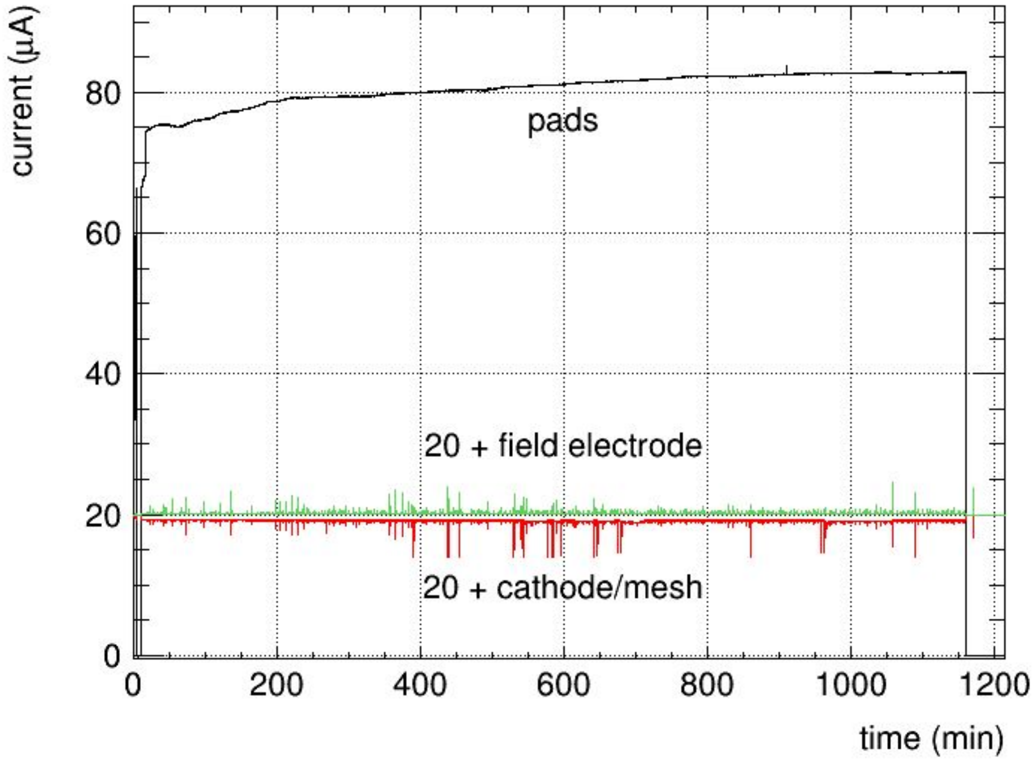



## energy resolution with $^{55}Fe$ source




- gain exponential within 300-15000, nominal gain 2000
- energy resolution 12-14%, requirement <12%

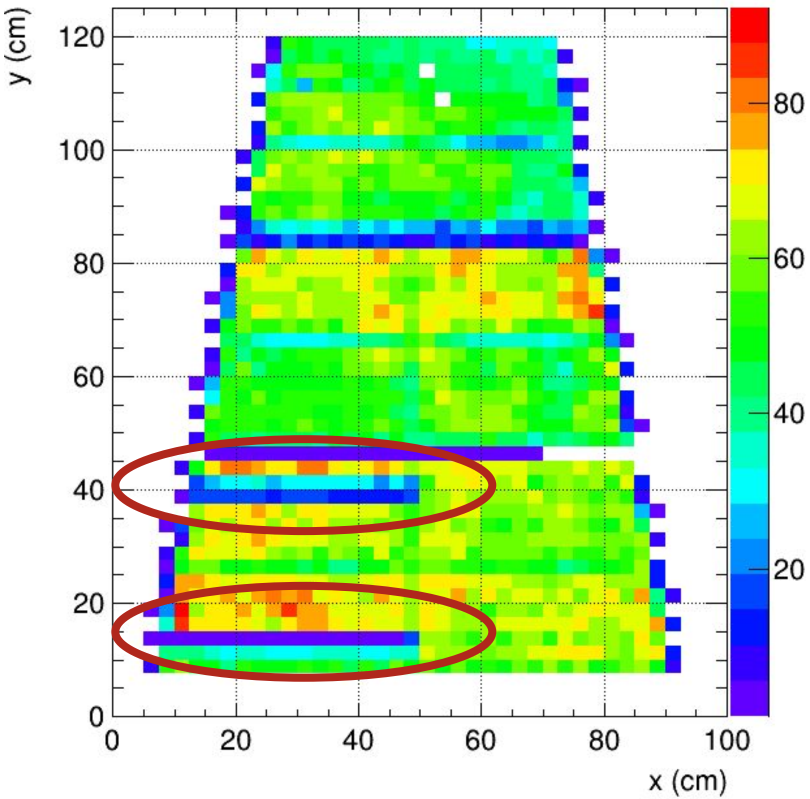
## full illumination with x-rays, pad current 10 nA/cm$^2$



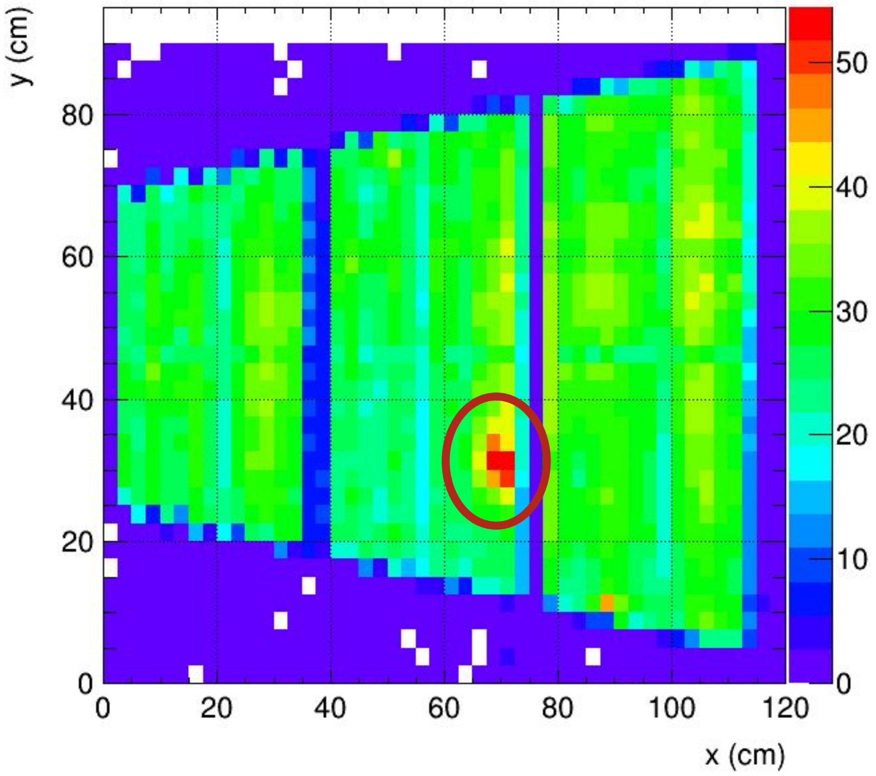

long x-ray irradiation at high intensity, chamber stable

# encountered problems

OROC/00 missing segments

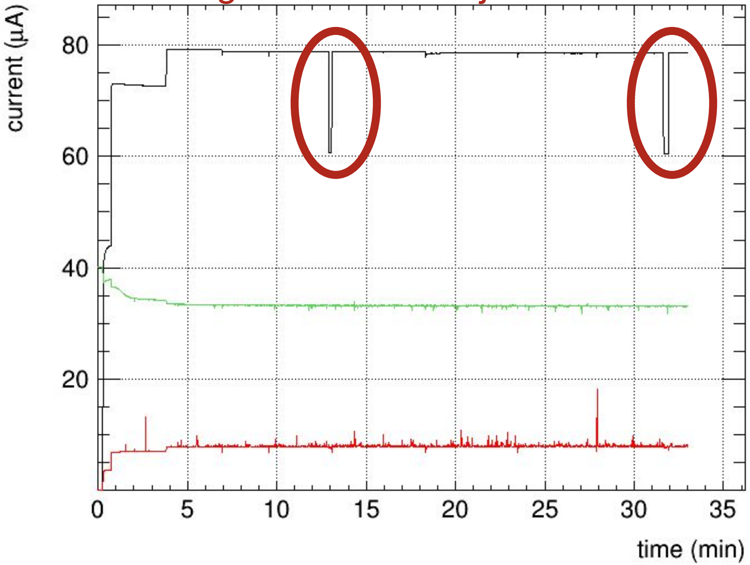


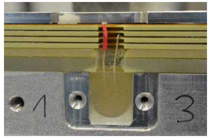

OROC/10 gain hotspot



# encountered problems

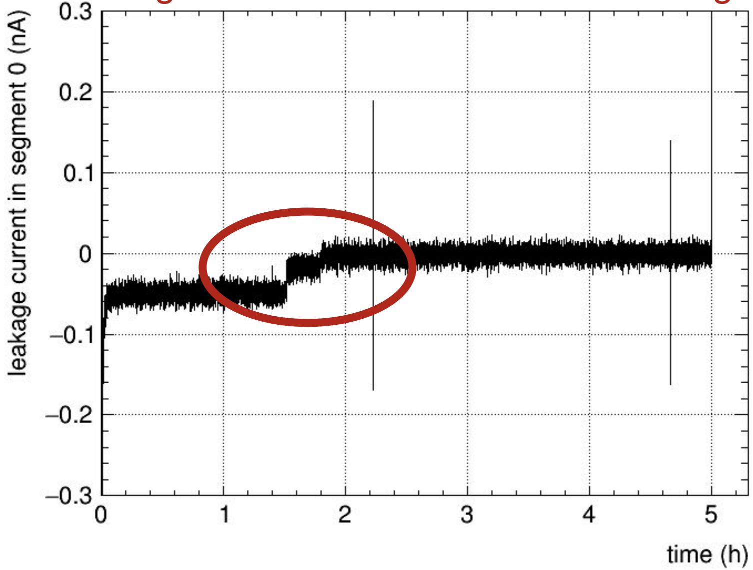
discharges between adjacent HV wires



2.1 kV between GEM3 top
poor fix of the GEM1 top wire

leakage current test sensitive to room light



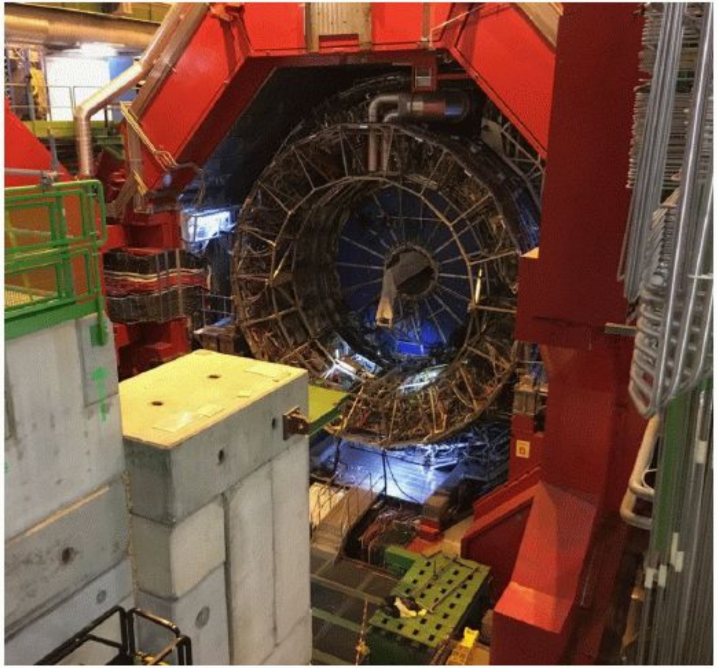

not really a problem

# TPC upgrade project motto: as ~~late~~ early as possible

- 2015 planning
- 2016 planning and preparing
- 2017 3 OROCs assembled
- 2018 17 OROCs assembled

# next steps in 2019

- uncable and extract TPC (Jan-Feb)
- bring it to the surface (March)
- bring it to a cleanroom (April)
- replace chambers one by one (Apr-Jun)




Alena
Andre
Andreas
Bernd
Bogdan
Daniel
Dariusz
Holger
Joerg
Lilit
Lukas
Manuel
Michael
Pascal
Pradip
Rajendra
Sebastian
Silvia
Thomas
Thomi
Vladimir

# backup

# TPC upgrade project motto: as ~~late~~ early as possible

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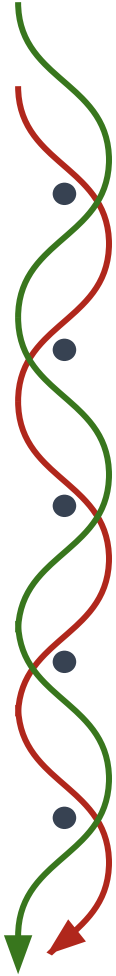
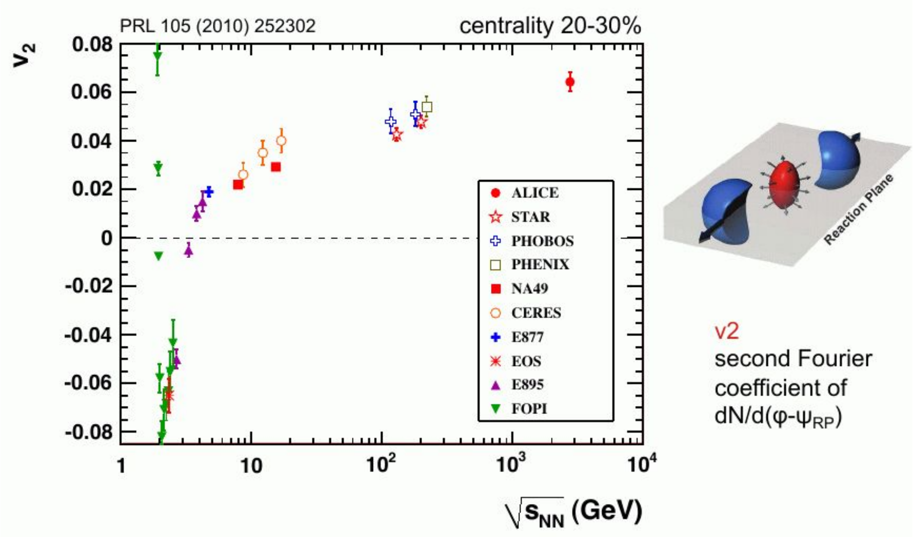
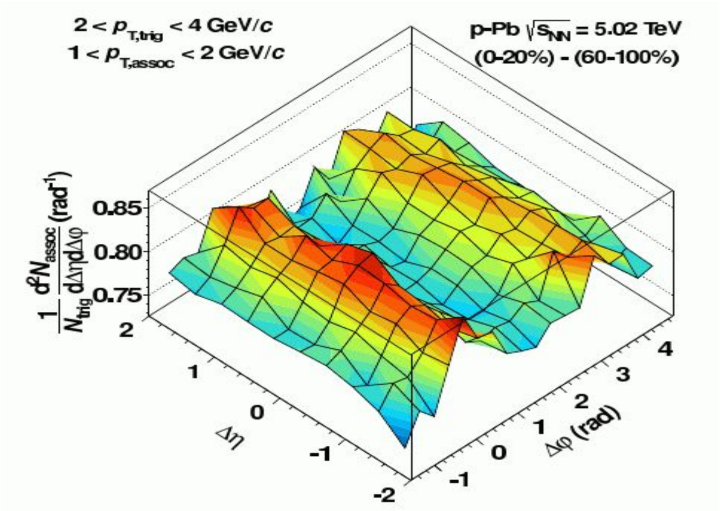


# ALICE highlights from Run 1 and 2 (personal selection)



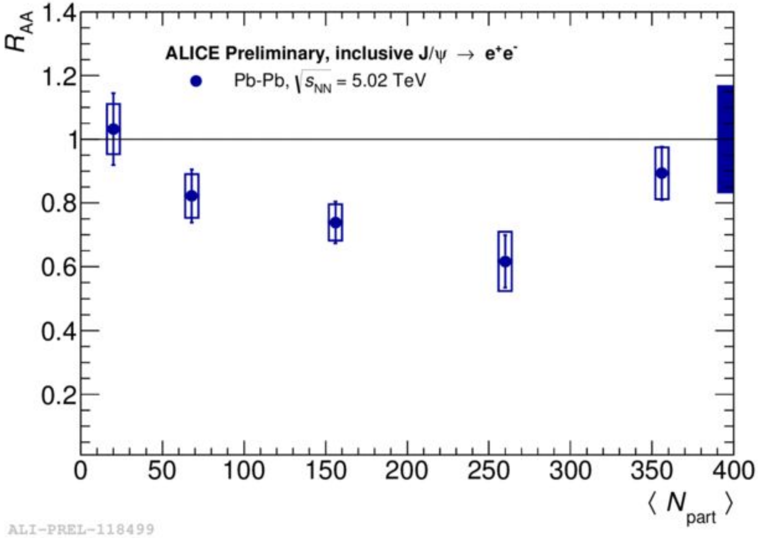

v2
second Fourier coefficient of $dN/d(\varphi-\psi_{RP})$

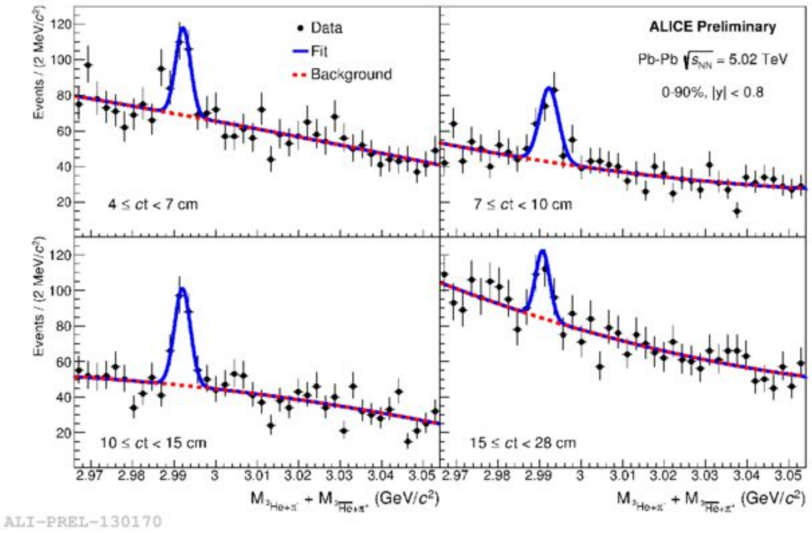
PLB 719 (2013) 29




flow continues at high energy
QGP is NOT a gas of free quarks

collectivity in violent pp and pA collisions (modification of $p_T$ spectra, elliptic flow, $p_T$ dep. of HBT radii) → QGP in small systems?

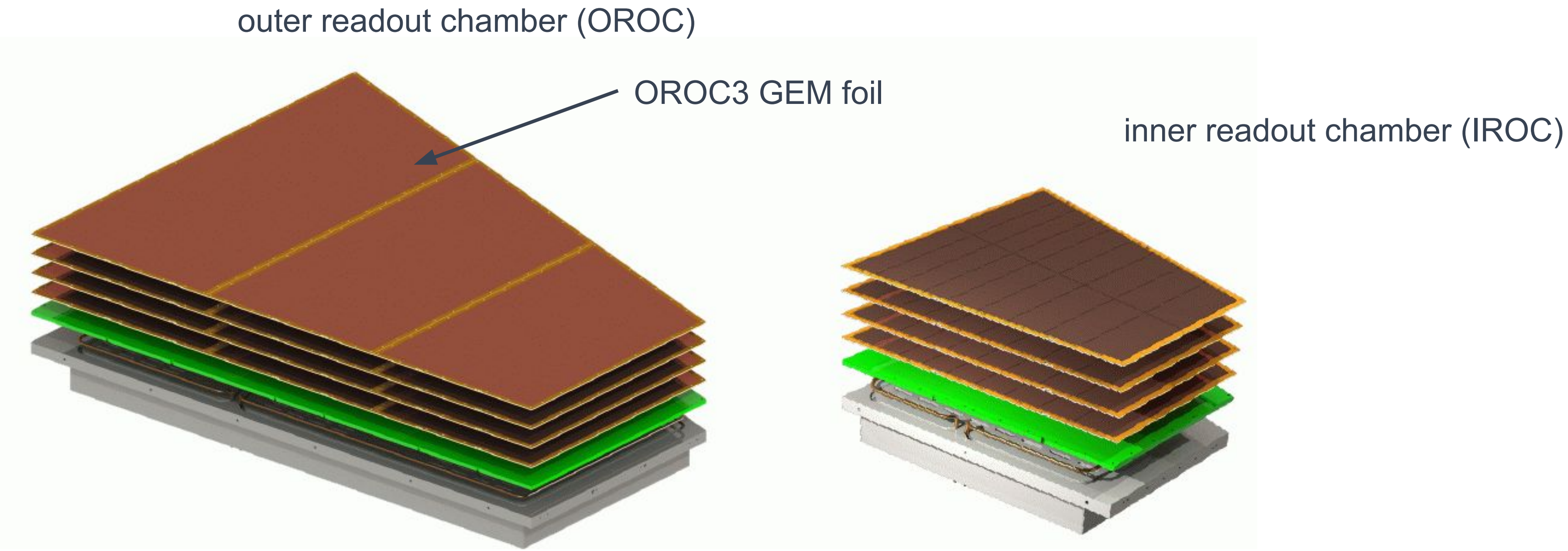



J/ψ enhancement in central Pb-Pb collisions: c + anti-c coalescence

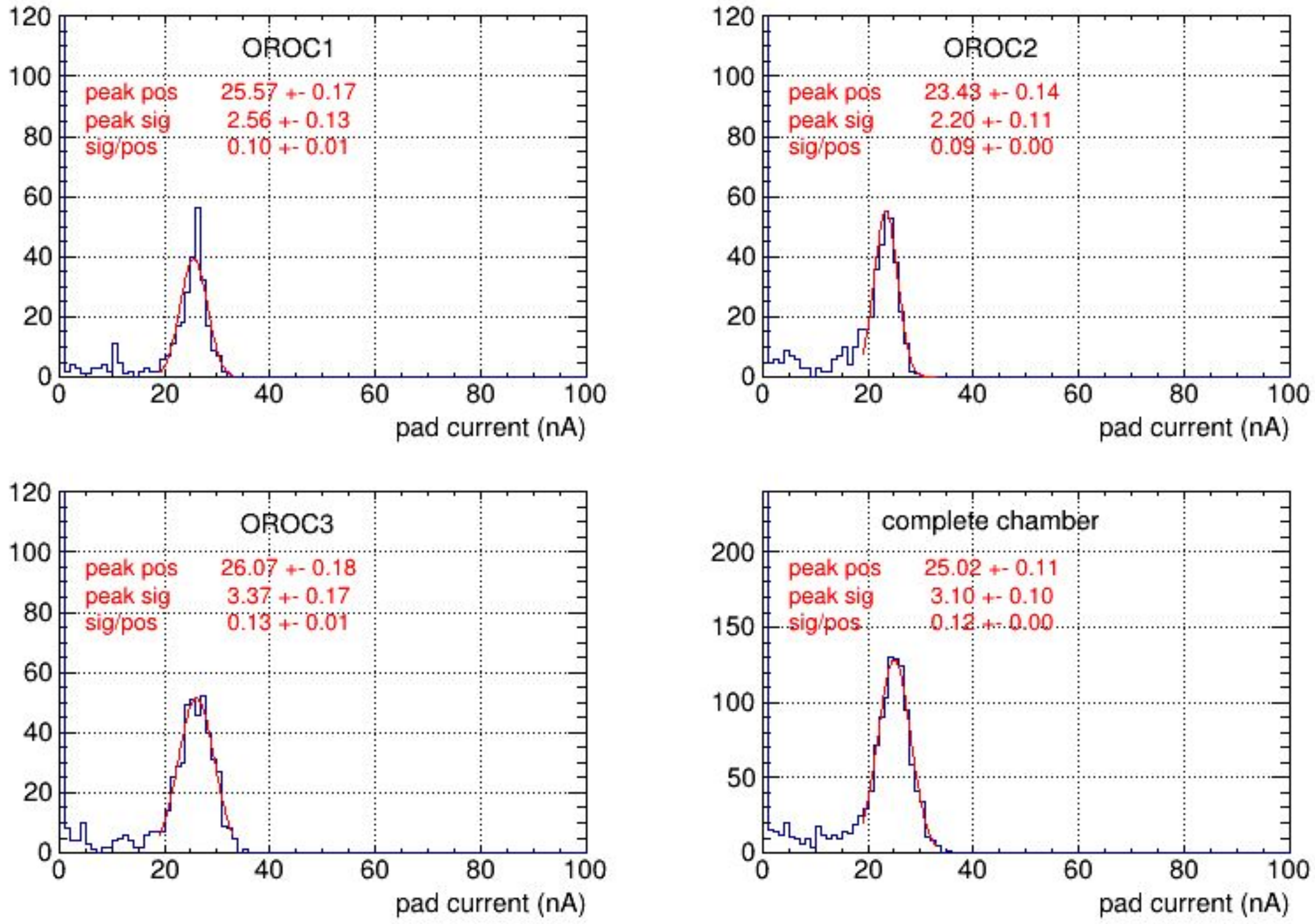
light nuclei and exotica production (eg. hypertriton ${}^{3}_{\Lambda}H$)

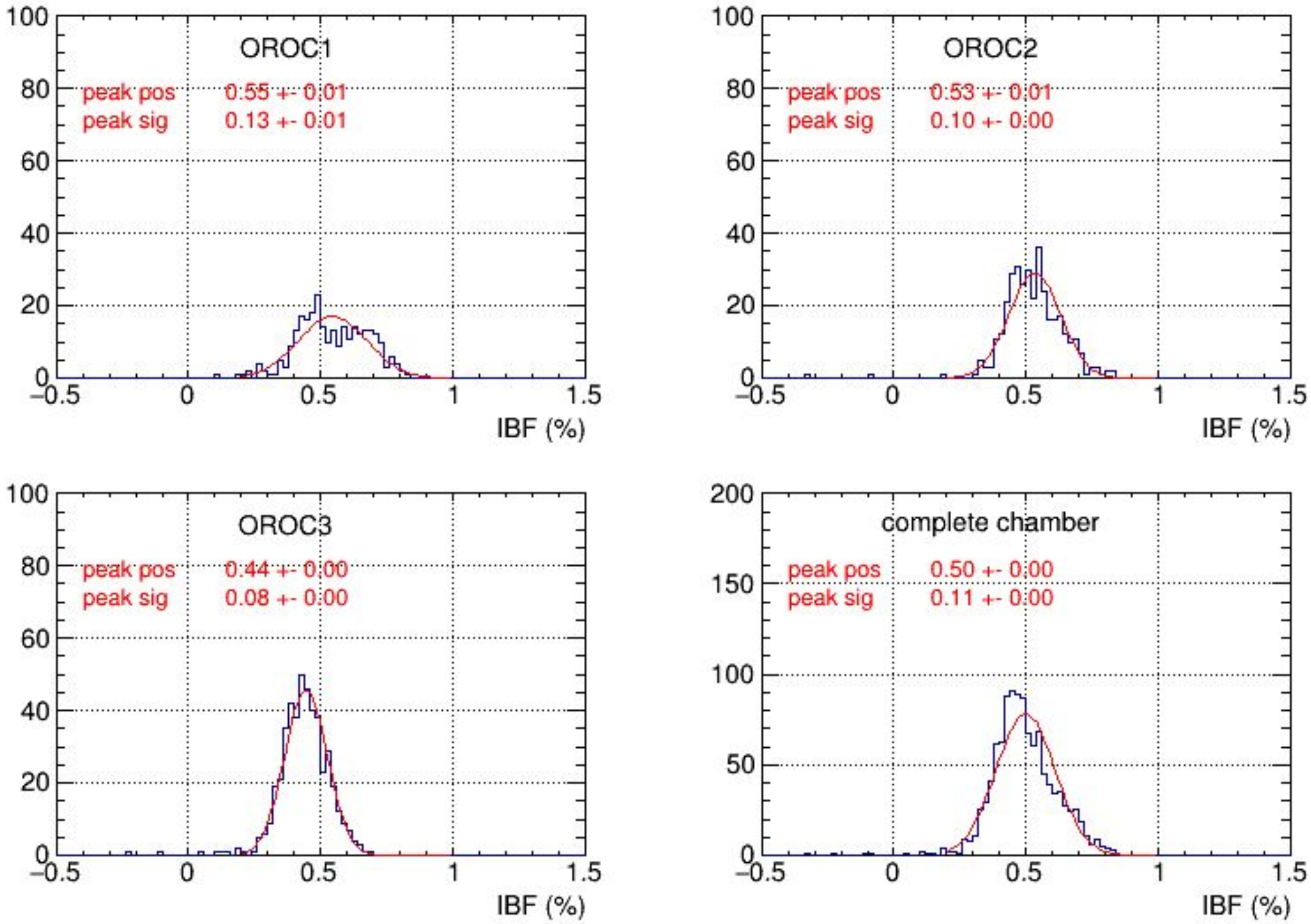
# ALICE Time Projection Chamber upgrade 2019




GSI contribution:

- frame 160 OROC3 GEM foils (= 100% of all)
- assemble and commission 20 OROCs (= 50% of all)


OROC1
peak pos 25.57 +- 0.17
peak sig 2.56 +- 0.13
sig/pos 0.10 +- 0.01
pad current (nA)
OROC2
peak pos 23.43 +- 0.14
peak sig 2.20 +- 0.11
sig/pos 0.09 +- 0.00
pad current (nA)
OROC3
peak pos 26.07 +- 0.18
peak sig 3.37 +- 0.17
sig/pos 0.13 +- 0.01
pad current (nA)
complete chamber
peak pos 25.02 +- 0.11
peak sig 3.10 +- 0.10
sig/pos 0.12 +- 0.00
pad current (nA)


OROC1
peak pos 0.55 +- 0.01
peak sig 0.13 +- 0.01
IBF (%)
OROC2
peak pos 0.53 +- 0.01
peak sig 0.10 +- 0.00
IBF (%)
OROC3
peak pos 0.44 +- 0.00
peak sig 0.08 +- 0.00
IBF (%)
complete chamber
peak pos 0.50 +- 0.00
peak sig 0.11 +- 0.00
IBF (%)

# personal summary: how well did things work?

| what | expectation | reality |
| --- | --- | --- |
| bringing life into things ("Frankenstein effect") | put things together, apply HV, wake them up to live | yes! |
| flushing volumes with gas | rest gas = exp(-t/tau) | so-so |
| building tight volumes | you can debug by sniffing | sniffing worked only for big holes |
| keeping things clean | if you keep things clean, nothing can happen | if you keep things clean, you reduce the probability that something happens |
| electric discharges in equipment | just keep distance and isolation, then OK | calculate and test carefully, then OK |
| electric discharges in gas | absent | statistical |

# bringing life into things ("Frankenstein effect")

But life functions very differently from the standard condensed-matter fare of metals or superconductors, which are "dead" things whose behaviors are predetermined. Living creatures can respond in seemingly disparate ways to the same stimulus. "Biological systems have this feedback loop that makes them very difficult to analyze using standard differential equations," Goldenfeld says, adding that he doesn't yet know how to address that problem.

*APS Physics, "Life is Physics", January 11, 2019*

following this definitions, gaseous chambers are living beings

under HV, they always wake up

# Collectivity in pp has been predicted!

Quar Matter 2008, Jaipur, panel discussion with Blaizot, Kharzeev, Mueller, Schukraft

Jurgen Schukraft:

- Multiplicity distribution at LHC
  - ⇨ quite respectable particle densities
    - $dN_{ch}/d\eta \sim 50 - 100$ can be reached !
    - > central S+S @ SPS, mid-central Cu-Cu @ RHIC
  - ⇨ naïvely, energy density $\varepsilon > 5 - 10$ GeV/fm$^3$
    - $\tau_0 = 1$ fm, $V = 5$ fm$^3$
- even protons get obese these days
  - ⇨ p@LHC ~ small (but very dense) nucleus@SPS

| | SPS | RHIC | LHC |
|---|---|---|---|
| # of partons in proton<br>$3 + \int g(x > 2\mathrm{GeV})$ | 4 | 10 | **30** |

- 'QGP' physics with protons
  - ⇨ at least: onset of hadronic FS interactions
  - ⇨ maybe: collective hadronic/partonic dynamics
  - ⇨ why not: the QGP, mini serving

# test run with open GG

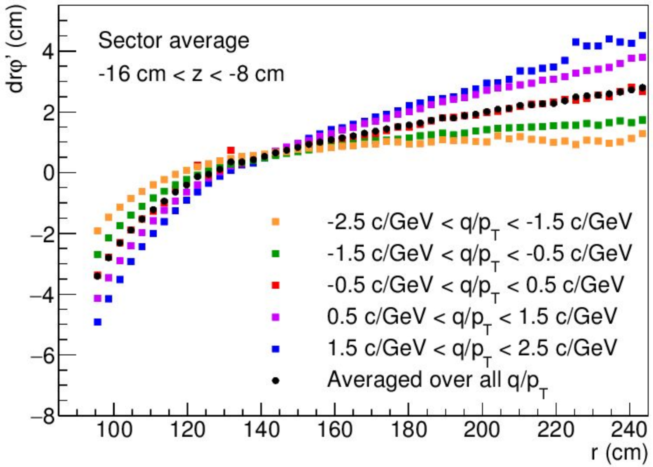
Ernst Hellbär, Marian Ivanov

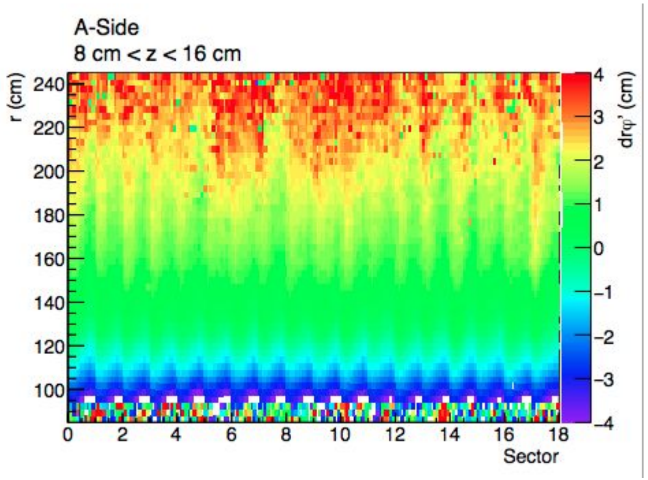
analysis of the special run with open GG taken in pp collisions at 200 kHz

- IBF = 13% (compare to ~0.01% with closed GG, ~1% with four GEMs)
- ε = 900 (compare to ~1 with closed GG, 20 with four GEMs)

⇒ space charge comparable to Pb-Pb in Run 3

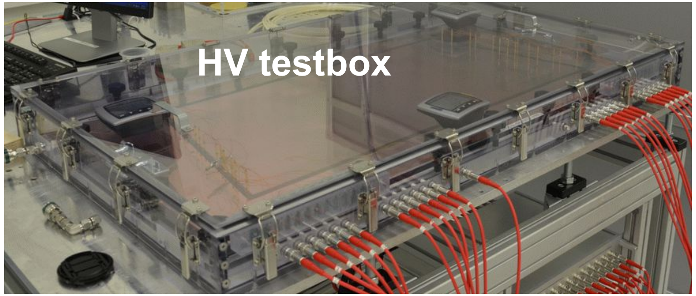
azimuthal distortions observed

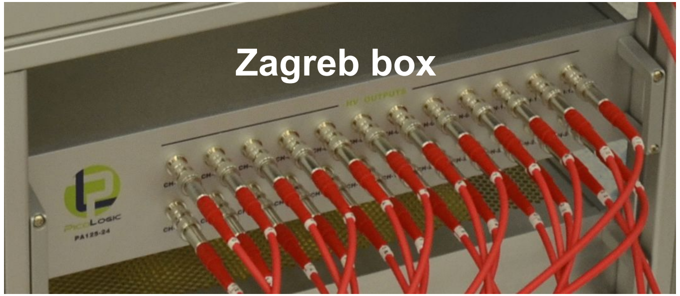


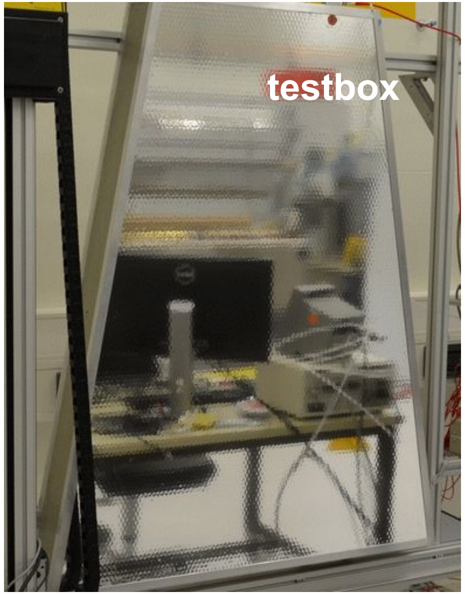




observed distortions agree with simulations with ε ≈ 15

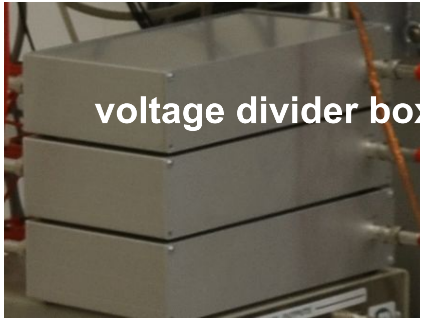
# project equipment





# LHC long-term schedule

# fastest TPC?

| experiment | max event rate | act. event rate | multiplicity | max track rate |
|---|---|---|---|---|
| STAR | | 100 Hz | 500 | 50 kHz |
| ALICE now | 3 kHz | 500 Hz | 1000 | 500 kHz |
| DELPHI | <45 kHz | a few Hz | a few | <~100 kHz |
| T2K | | 20 Hz | a few | ~100 Hz |
| ALICE in Run 3 | 50 kHz | 50 kHz | 1000 | 50 MHz |

parameters of Time Projection Chambers, from presentation of A. Delbart, 12-Apr-2017

Upgrade with MPGD readout (2015-2018)

**Table 3.** Characteristics and performance of some TPCs.

| Parameter/Experiment | PEP4 | TRIUMF | TOPAZ | AlEPH | DELPHI | STAR | ALICE[a] |
|---|---|---|---|---|---|---|---|
| Operation | 1982/1984 | 1982/1983 | 1987 | 1989 | 1989 | 2000 | 2009 |
| Inner/Outer radius (m) | 0.2/1.0 | ~ 0.15/0.50 | 0.38/1.1 | 0.35/1.8 | 0.35/1.4 | 0.5/2.0 | 0.85/2.5 |
| Max. driftlength ($L/2$) (m) | 1 | 0.34 | 1.1 | 2.2 | 1.34 | 2.1 | 2.5 |
| Magnetic field (T) | 0.4/1.325 | 0.9 | 1 | 1.5 | 1.23 | 0.25/0.5 | 0.5 |
| Gas : | $Ar/CH_4$ | $Ar/CH_4$ | $Ar/CH_4$ | $Ar/CH_4$ | $Ar/CH_4$ | $Ar/CH_4$ | $Ne/CO_2/N_2$ |
| Mixture | 80/20 | 80/20 | 90/10 | 91/9 | 80/20 | 90/10 | 90/ 10/ 5 |
| Pressure (atm) | 8.5 | 1 | 3.5 | 1 | 1 | 1 | 1 |
| Drift field ($kV\,cm^{-1}\,atm^{-1}$) | 0.088 | 0.25 | 0.1 | 0.11 | 0.15 | 0.14 | 0.4 |
| Electron drift velocity ($cm\,\mu s^{-1}$) | 5 | 7 | 5.3 | 5 | 6.69 | 5.45 | 2.7 |
| $\omega\tau$ (see section 2.2.1.3) | 0.2/0.7 | 2 | 1.5 | 7 | 5 | 1.15/2.3 | <1 |
| Pads: Size $w \times L$ (mm × mm) | 7.5 × 7.5 | (5.3–6.4) × 19 | (9–11) × 12 | 6.2 × 30 | ~7 × 7 | 2.85 × 11.5 | 4 × 7.5 |
| | | | | | | 6.2 × 19.5 | 6 × 10/15 |
| Max. no. 3D points | 15—straight | 12 | 10—linear | 9 + 12—circular | 16—circular | 13 + 32—straight | 63 + 64 + 32 |
| $dE/dx$: Max. no. samples/track | 183 | 12 | 175 | 148 + 196 | 192 | 13 + 32 | 63 + 64 + 32 |
| Sample size (mm atm); $w$ or $p$ | 4 × 8.5; wires | 6.35; wires | 4 × 3.5; wires | 4; wires | 4; wires | 11.5 + 19.5; pads | 7.5 + 10 + 15; pads |
| Gas amplification | 1000 | 50 000 | | 3000–5000 | 5000 | 3000/1100 | 20 000 |
| Gap a–p; a–c; c–gate[b] | 4; 4; 8 | 6 | 4; 4; 8 | 4; 4; 6 | 4; 4; 6 | 2; 2; 6/4; 4 ; 6 | 2; 2; 3/3; 3; 3 |
| Pitch a–a; cathode; gate | 4; 1; 1 | | 4; 1; 1 | 4; 1; 2 | 4; 1; 1 | 4; 1; 1/ 4; 1; 1 | 2.5; 2.5; 1.5 |
| Pulse sampling (MHz/no. samples) | 10/455, CCD | only 1 digitiz., ADC | 10/ 455, CCD | 11/ 512, FADC | 14/300, FADC | 9.6/400 | 5–10/500–1000, ADC |
| Gating[c] | ⩾1984 o.on tr. | ⩾1983 o.on tr. | o. on tr. | synchr. cl.wo.tr | static | o.on tr. | o.on tr. |
| Pads, total number | 15 000 | 7800 | 8200 | 41 000 | 20 000 | 137 000 | 560 000 |
| Performance | | | | | | | |
| $\Delta x_T$ ($\mu$m)-best/typ. | 130–200 | 200/ | 185/230 | 170/200–450 | 180/190–280 | 300–600 | spec:800–1100 |
| $\Delta x_L$ ($\mu$m)-best/typ. | 160–260 | 3000 | 335/900 | 500–1700 | 900 | 500–1200 | spec:1100–1250 |
| Two-track separation (mm), $T/L$ | 20 | | 25 | 15 | 15 | 8 - 13/30 | |
| $\partial p/p^2$ $(GeV/c)^{-1}$ : TPC alone; high $p$ | 0.0065 | | 0.015 | 0.0012 | 0.005 | 0.006 | spec:0.005 |
| $dE/dx$ (%) Single tracks/ in jets | 2.7/4.0 | | 4.4 / | 4.4 / | 5.7/7.4 | 7.4/7.6 | spec:4.9/6.8 |
| Comments | | a in single PCs | chevron pads | circular pad rows | circular pad rows | No field wires | No field wires |
| | | strong $E \times B$ effect | | | | >3000 tracks | ⩽20 000 tracks |

[a] Expected performance.
[b] a = anode, p = pads, c = cathode grid.
[c] o. on tr.: gate opens on trigger; cl.wo.tr. : opens before collision and closes without trigger; static : closed for ions only (see text).

H. J. Hike, "Time Projection Chambers", Repot On Progress In Physics (2010) p73-109

TPC Review and associated electronics , Workshop on "A TPC for MeV Astrophysics" Polytechnique, april 12th-14th , 2017, (alain.delbart@cea.fr)| PAGE 13/36

# parameters of Time Projection Chambers, from presentation of A. Delbart, 12-Apr-2017

MPGD readout

**Table 3.** Continued.

| Parameter/Experiment cont. | NA35 | EOS/HISS | NA49 VTX | NA49 MAIN | CERES/NA45 | HARP | T2K[a] |
|---|---|---|---|---|---|---|---|
| Operation | 1990 | 1992 | 1995 | 1995 | 1999 | 2001 | 2009/10 |
| Inner/Outer radius or L/W (m) | 2.4/1.25 (L/W) | 1.5/0.96 (L/W) | 2.5/1.5 (L/W); 2× | 4/4 (L/W); 2× | 0.6/1.3; $L = 2$ | 0.1/0.41 | 2.2/0.7 (H/L); 3× |
| Max. driftlength ($L/2$) (m) | 1.12 vert. | 0.75 (H) | 0.67 vert. | 1.1 vert. | 0.7 rad. | 1.6 | 0.9 W |
| Magnetic field (T) | 0 | 1.3 | 1.5 | 0 | $B_z < 0.7$; $B_r < 0.3$ | 0.7 | 0.2 |
| Gas : | $Ar/CH_4$ | $Ar/CH_4$ | $Ne/CO_2$ | $Ar/CH_4/CO_2$ | $Ne/CO_2$ | $Ar/CH_4$ | Ar/CF4/i-C4H10 |
| Mixture | 91/ 9 | 90/ 10 | 90/10 | 90/ 5/5 | 80/ 20 | 91/ 9 | 95/ 3/ 2 |
| Pressure (atm) | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Drift field ($kV\ cm^{-1}\ atm^{-1}$) | 0.12 | 0.12 | 0.19 | 0.175 | 0.2-0.6 | 0.111 | 0.2 |
| Electron drift velocity ($cm\ \mu s^{-1}$) | 5 | 5.5 | 1.3 | 2.3 | 0.7-2.4 | 5.2 | 7 |
| $\omega\tau$ (see section 2.2.1.3) | 0 | 0.5 | 1 | 0 | | 3.3 | 0.7 |
| Pads: size ($w \times L$, mm × mm) | 5.5 × 40 | 8 × 12 | 3.5× (16 , 28) | (3.6, 5.5)×40 | 10 chevron | 6.5 × 15 | 6.9 × 9.7 |
| Max. no. 3D points | 60 + 30 | 128 | <150 | 90 | | 20 | 72 × 3 |
| $dE/dx$: Max. no. samples/track | 60 | 128 | <150 | 90 | | 20 | 72 × 3 |
| Sample size (mm atm); $w$ or $p$ | 40; pads | 12 | 16, 28 | 40 | | 15 | 9.7 |
| Gas amplification | | 3000 | 20 000 | 5000 | 8000 | 20 000 | ~1000 |
| Gap a–p; a–c; c–gate[b] | | 4; 4; 6 | 3 , 2; | 2,3; 3;6 | 3;3;6 | 5;5;6 | 0.128 |
| Pitch a–a; cathode; gate | 4; 1; 2 | 4; 1; 2 | 4; 1; 1 | 4; 1;1 | 6; 2; 2 | 4; 2; 2 stagg. | |
| Pulse sampling (MHz/no. samples) | 12.5 / | 10/256, SCA | /512 | / 512 | | 10/>300, FADC | /512 SCA |
| Gating[c] | | o. on tr. | o. on tr. | o. on tr. | o. on tr. | o.on tr. | none |
| Pads, total number | 11 000 | 15 000 | 74 000 | 108 000 | 78 000 | 4000 | 125 000 |
| **Performance** | | | | | | | |
| $\Delta x_T$ ($\mu$m)-best/typ. | 300–800 | 300 | 150 | 150 | 230/340 | 600–2400 | 600 (1m drift) |
| $\Delta x_L$ ($\mu$m)-best/typ. | 250–450 | | | | $dr = 400/640$ | 3.5 | |
| Two-track separation (mm) | 18 | 25 | | 10 | | | |
| $\partial p/p^2$ (GeV/c) $^{-1}$ : TPC alone; high $p$ | | 1 | | | 1 | 0.2/0.45–0.50 | spec: <10; |
| $dE/dx$ (%) : single tracks/in jets | / 6 | / 4 | <4 : VTX + Main | | | 16 | spec: <10 / |
| Comments | $B = 0$ only pad r.o. | only pad r.o. | Kr[m] calibration only pad r.o. | up to1200 tr. only pad r.o. | Radial TPC No field wires | el. crosstalk | Micromegas r.o. |

[a] Expected performance.
[b] a = anode, p = pads, c = cathode grid.
[c] o. on tr.: gate opens on trigger; cl.wo.tr. : opens before collision and closes without trigger; static : closed for ions only (see text).

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