The ALICE TPC upgrade
From R&D to Full Production

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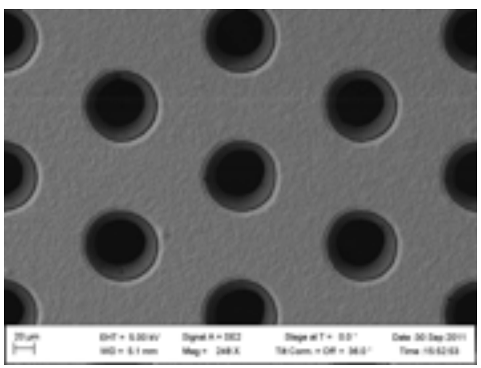
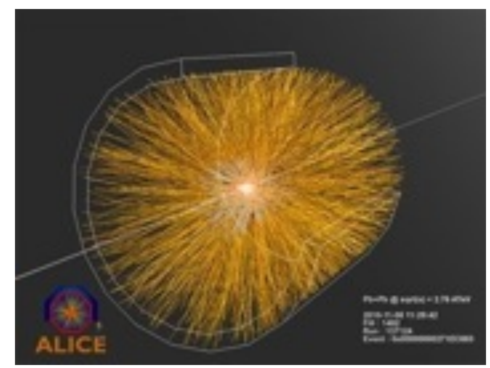


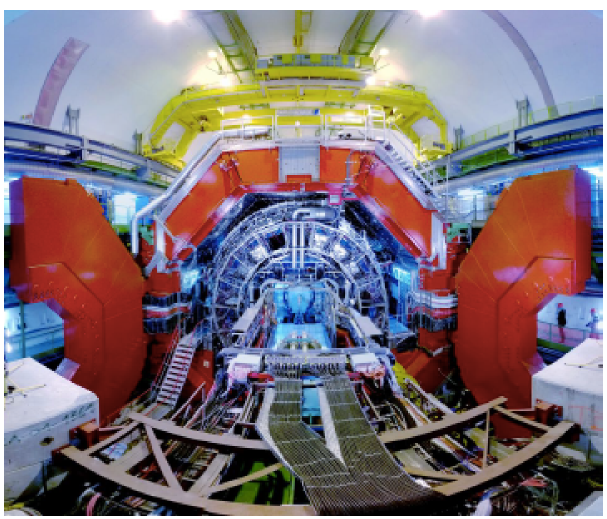


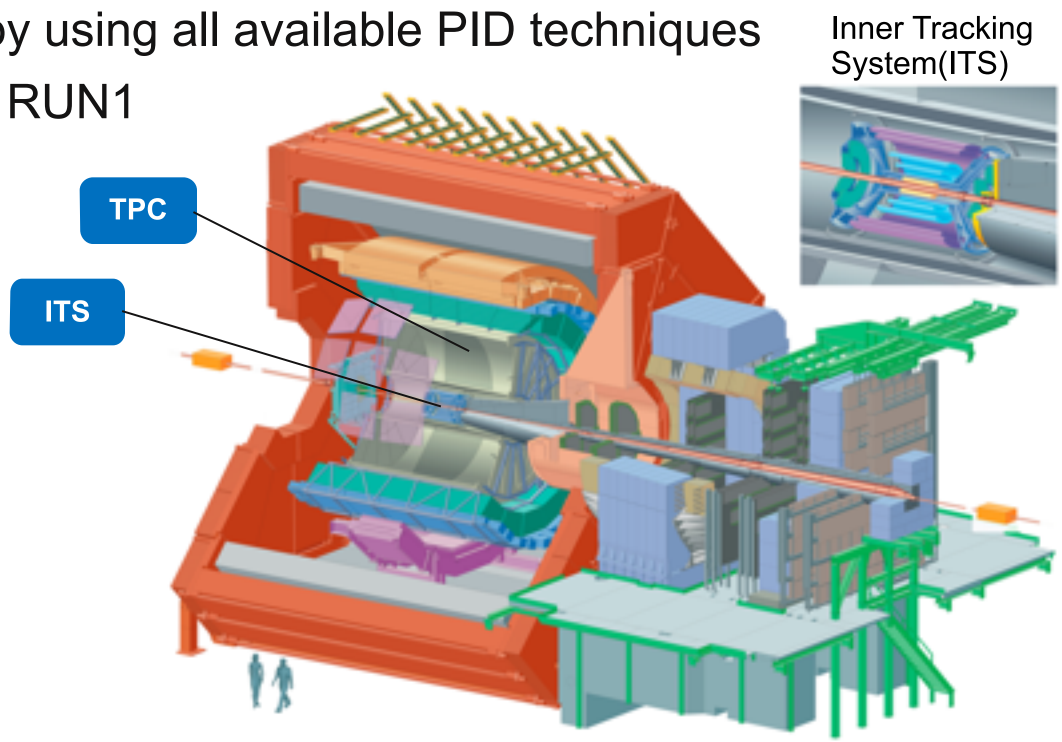
Outline

- **The ALICE TPC**
- Motivation for the GEM upgrade
- Ion backflow, energy resolution and discharge probability
- The road from TDR to PRR
- Full production
- Summary

ALICE - A Large Ion Collider Experiment

- A dedicated heavy-ion experiment at CERN - LHC
- Study of a high-density, high-temperature phase of strongly interacting matter: Quark Gluon Plasma
- Unique PID capabilities among all LHC experiments
- Covers a broad kinematic range by using all available PID techniques
- Excellent Physics performance in RUN1 and RUN2

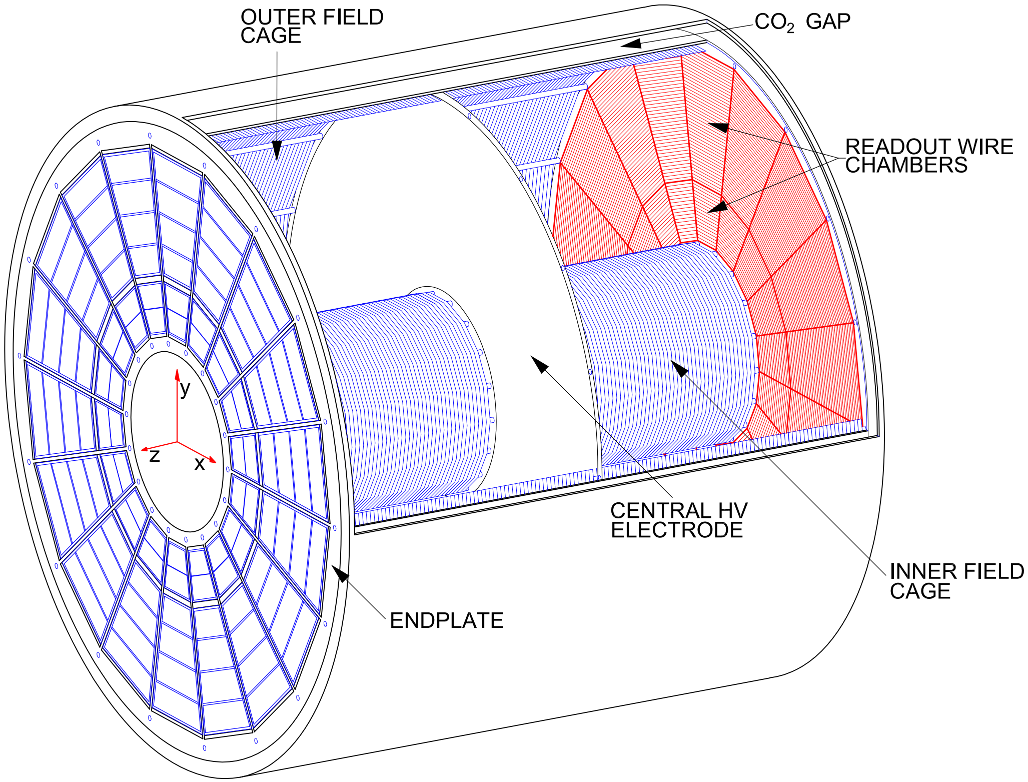




The ALICE TPC

- Original TDR: 2000
- Field cage assembly: 2002 – 2004
- MWPC installation: 2005
- Electronics installation: 2006
- Installation into ALICE L3 magnet: 2007
- Commissioning & calibration: 2007 – 2009
- Data taking: 2009 – 2013 (RUN1), restarted June 2015 (RUN2)

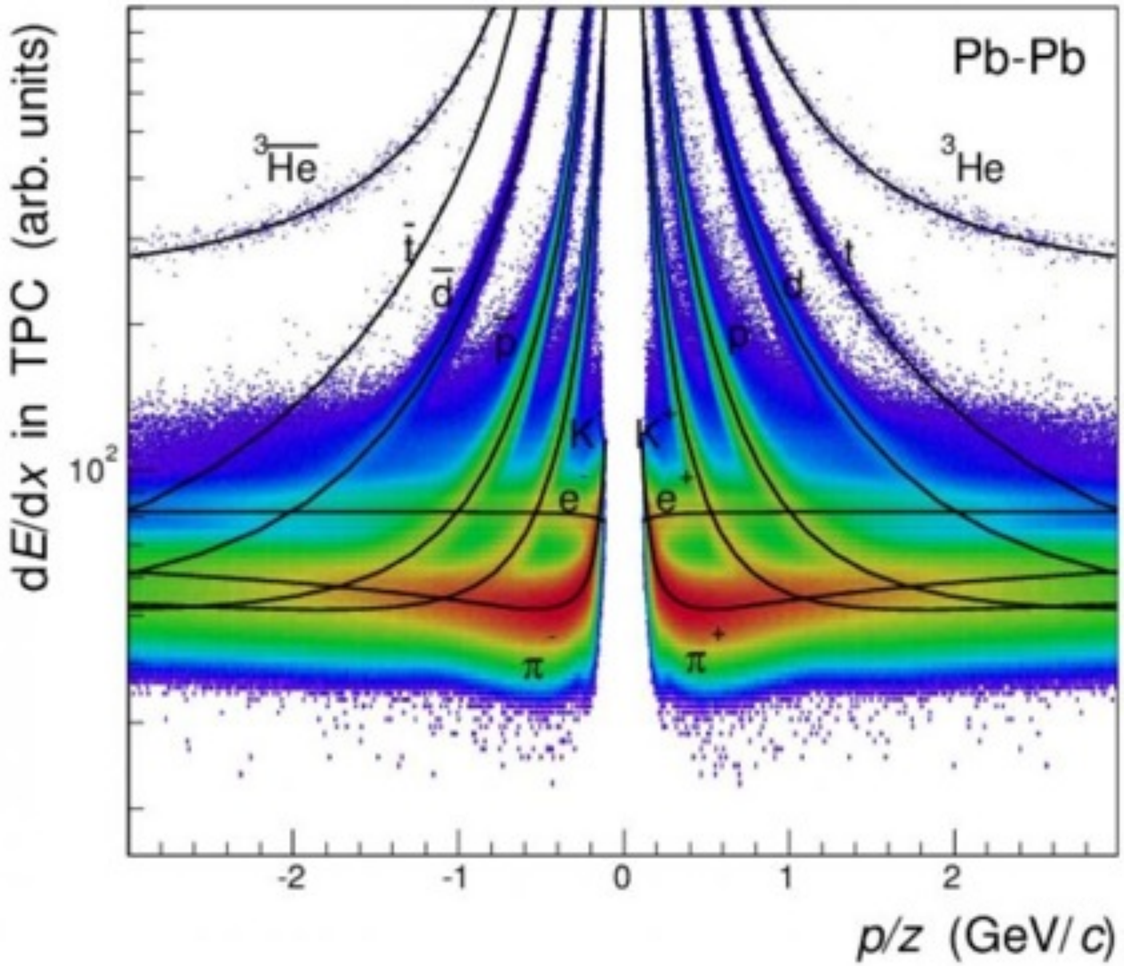
The ALICE TPC



- Acceptance: $|\eta| < 0.9$, $\Delta\Phi = 2\pi$
- low-mass, high-precision field cage
- Active volume 88 m^3
- B = 0.5 T
- Readout area 32 m^2
- Gas:
  - Ne-CO_2 (90-10) Run 1
  - Ar-CO_2 (90-10) Run2
  - Ne-CO_2-N_2 (90-10-5) Run 3
- 100 kV at central cathode
  - E_{Drift} = 400 V/cm
  - v_{Drift} = 2.7 cm/μs
  - max t_{Drift} = 92 μs

The ALICE TPC

TPC is the main device for **tracking** and **particle identification** in the central barrel !



- In pp, $\sigma_{dE/dx} \approx 5\%$
- Expected: 5.5%
  [ALICE Collaboration 2006, J. Phys. G: Nucl. Part. Phys. 32 1295]
- Resolution for the highest multiplicity HI events: $\sigma_{dE/dx} \approx 6.8\ \%$
- Expected: 7%

- The ALICE TPC
- **Motivation for the GEM upgrade**
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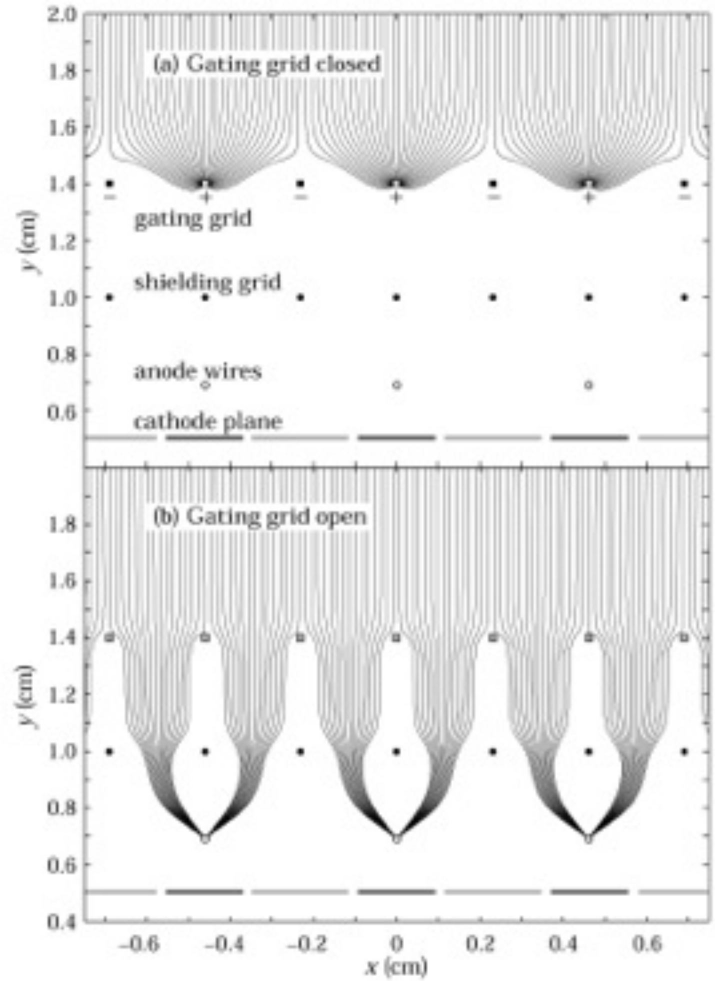
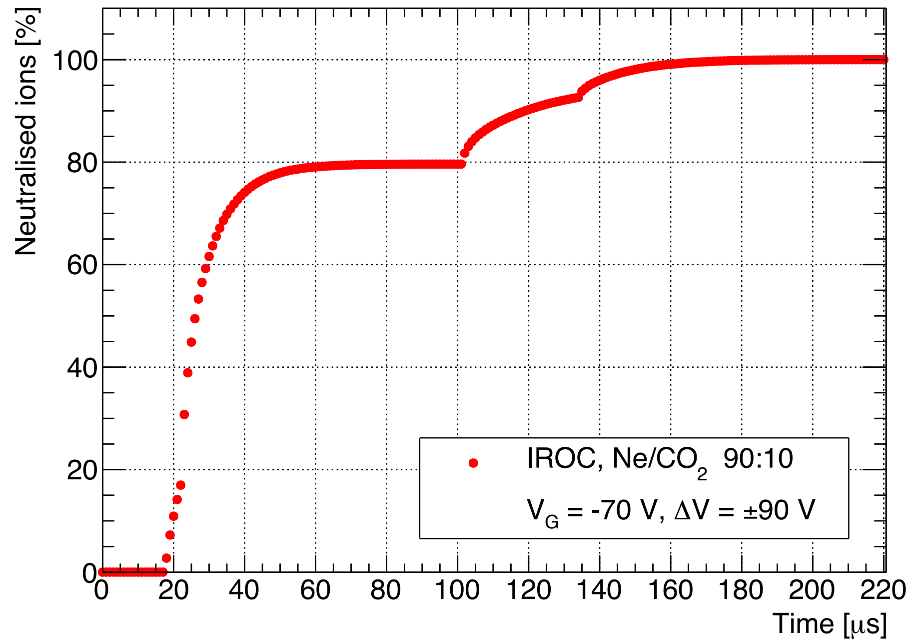
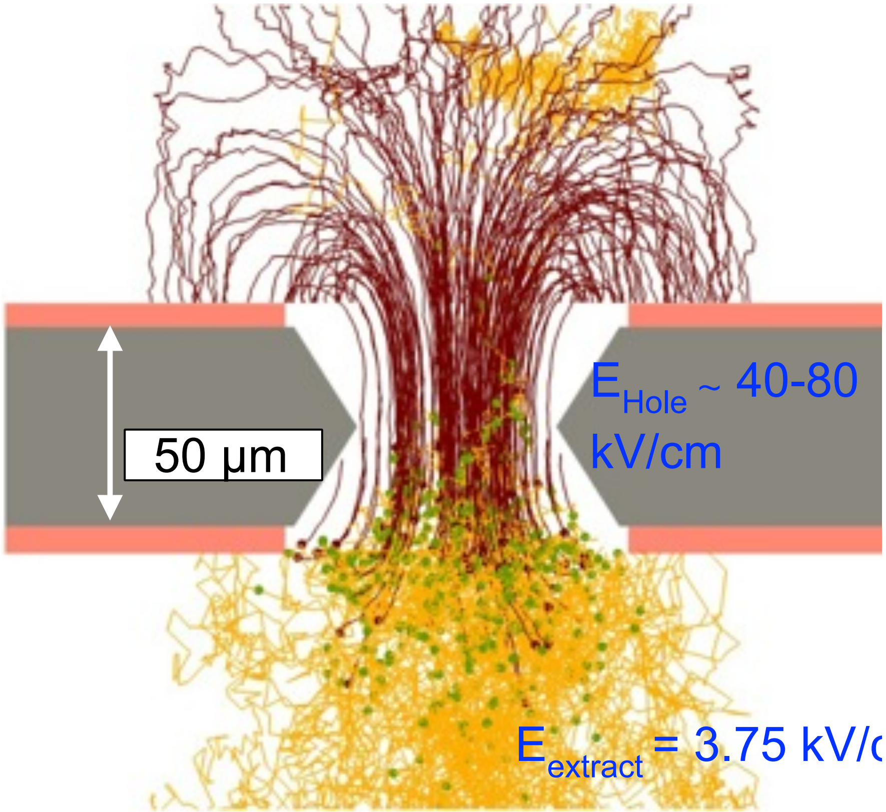
Advantages and Limitations of a TPC

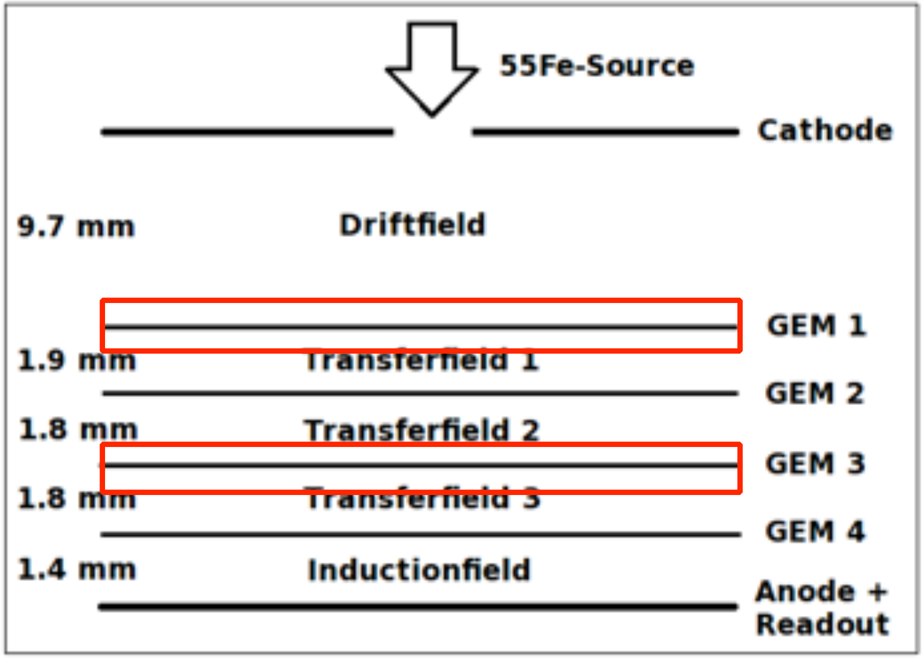




- Ion Backflow suppression of a MWPC with a Gating grid ~ 10^{-5}
- 100 μs electron drift time + 200 μs to neutralise all ions
- Total cycle time ~ 300 μs limits the maximal readout rate to ~ 3 kHz (in p-p)
- Trigger Rate ~ 600 Hz for Pb-Pb (300 Hz in Run 1)

Ion Backflow Suppression





Ion Backflow suppression of a GEM ~ 10^{-1} for a single GEM ~ 10^{-2}-10^{-3} for a GEM stack

Asymmetric field configuration can be repeated in a GEM stack !

$E_{drift} < E_{T1}, E_{T2} < E_{T3}$

$\Delta U_{G1} < \Delta U_{G2} < \Delta U_{G3} < \Delta U_{G4}$

CERN-LHCC-2013-020
Addendum:
CERN-LHCC-2015-002

Requirements for the upgrade GEM based TPC of ALICE

- Drift field: 0.4 kV/cm
- Detector gas: Ne-CO_2-N_2 (90-10-5)
- Effective gas gain: 2000
- S/N ratio ~ 20
- **IB**: < 1 %
- **ε**: < 20
- σ/E (5.9 keV): < 12 %
- Low discharge probability
- Operation at 50 kHz (Pb-Pb)

Ion Backflow
IB := Ratio of I_{Cath} / I_{Anode}

Number of back drifting ions / e^-_{prim}
ε := IB*gain - 1

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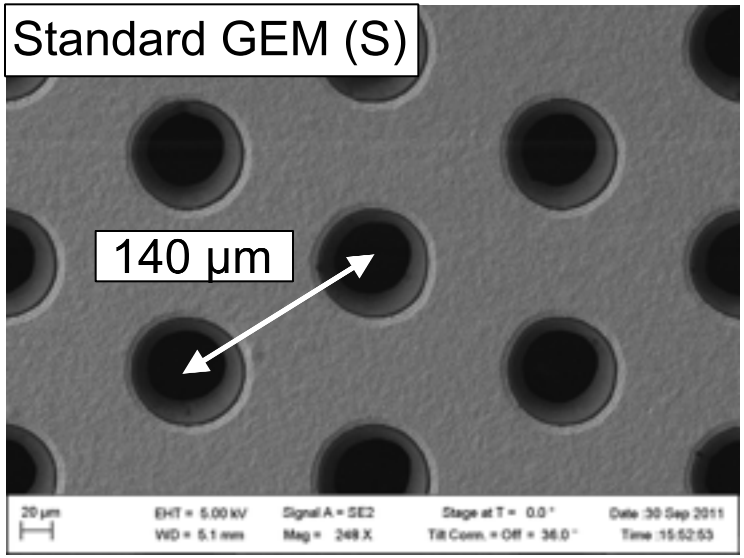
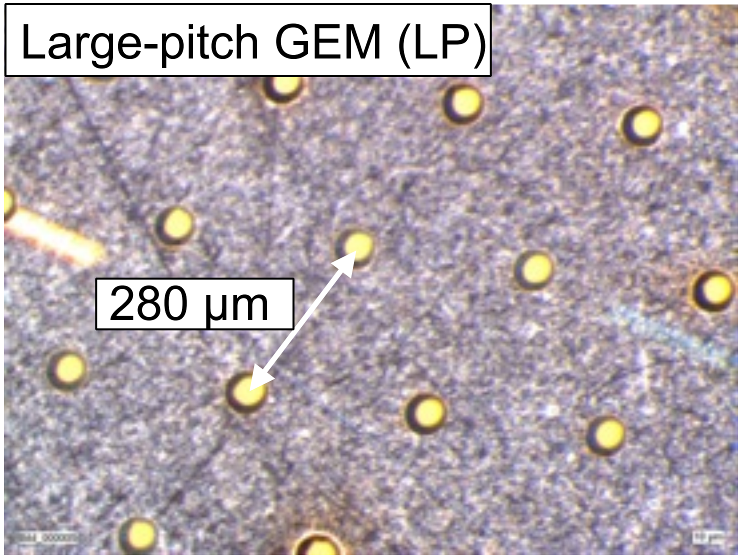
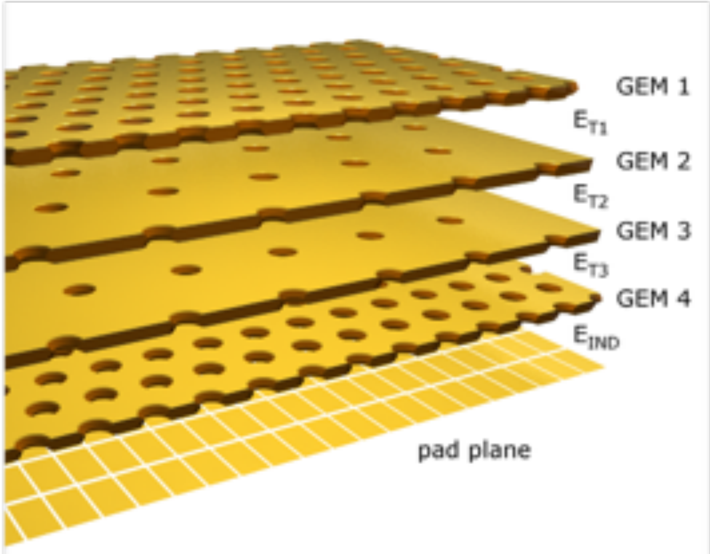
Properties of a GEM foil

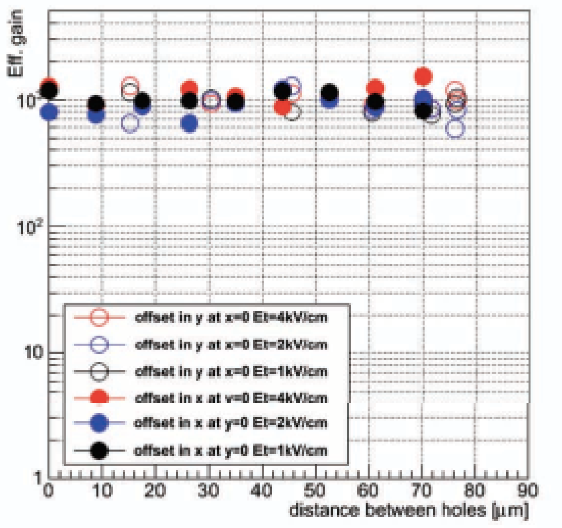


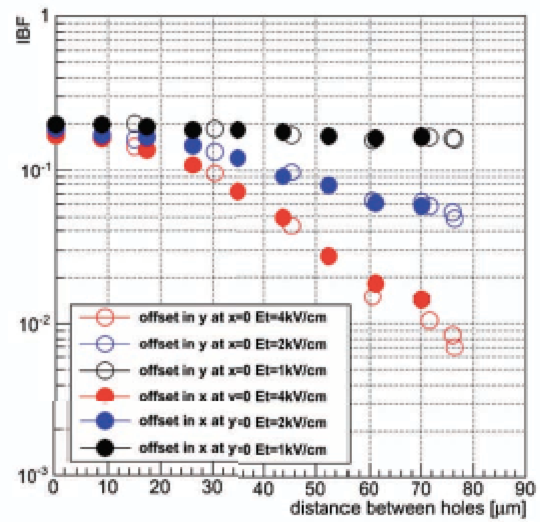


- Requirements could not be fulfilled with a triple GEM (S-S-S) setup
- New readout chambers employ standard pitch (S) and large pitch GEM foils in a S-LP-LP-S configuration
- HV configuration has to be optimal for ion back flow, energy resolution and low discharge probability at the same time



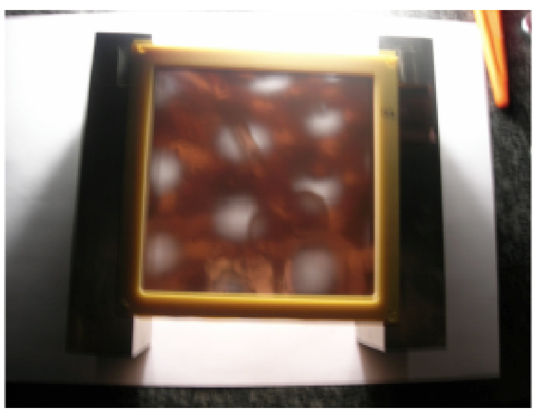
Rotation of Foils

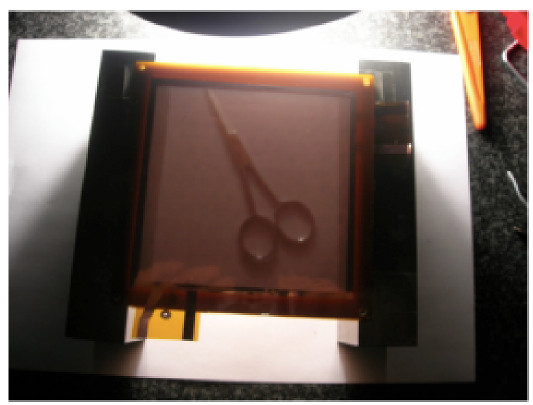




Foils not rotated

Foils rotated 90º to each other



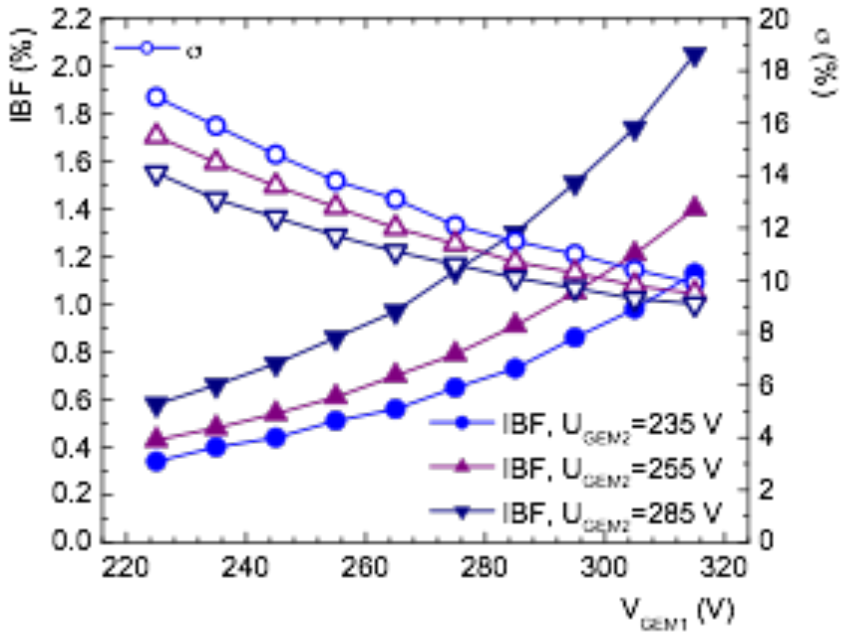


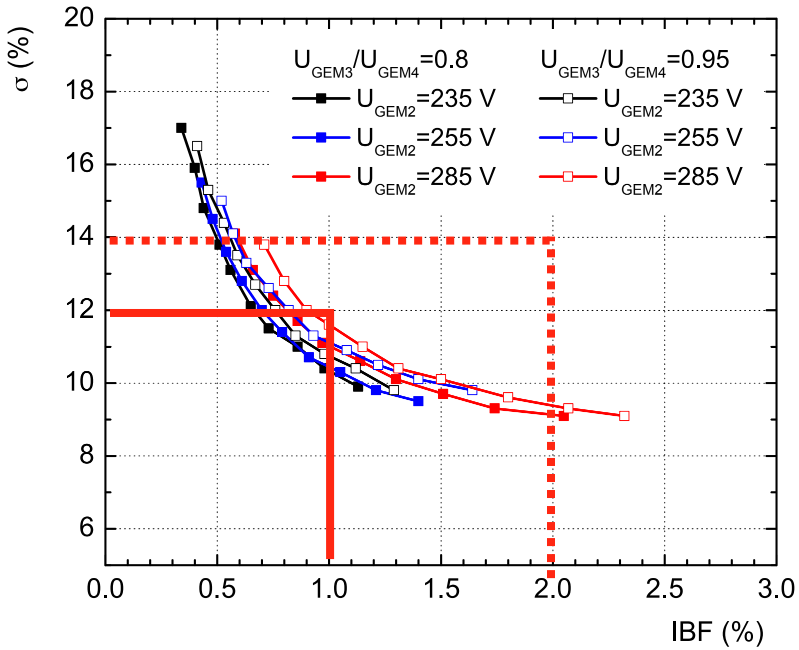
Alignment of the GEM foils

- Alignment between the GEMs is crucial to have a uniform IB
- To decrease the IB further than with the IB optimised electric field configuration → use GEM foils with different geometries (different optical transparencies)

Baseline solution for IB and Energy-resolution

(S-LP-LP-S)



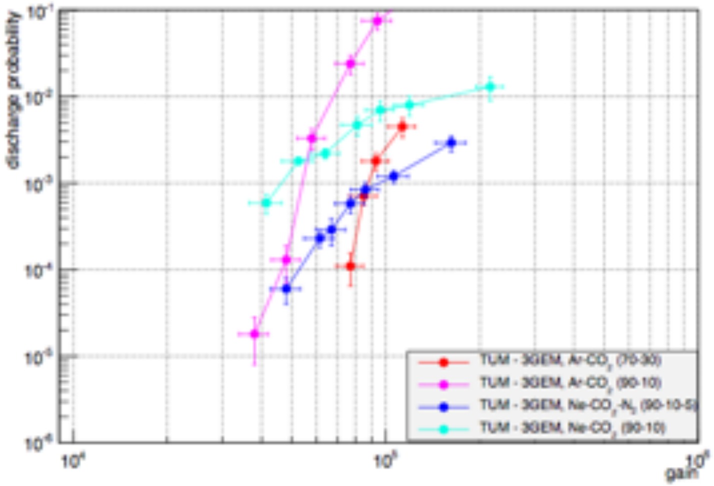


Optimisation of two parameters at the same time is conflicting:

- Best Value IB ~ 0.6 % at an energy resolution of σ/E < 12 %
- Upgrade goals have been reached with even a small margin for fine tuning (in case needed for the stability)
- Much larger phase space has been scanned no significant improvements (no order of magnitude) are expected

Discharge Probability

(S-LP-LP-S)



Stable operation under LHC conditions

- Discharge probability studies (TUM, CERN):

  $< 10^{-10}$ (4GEM, measured with alpha particles)

  $(6 \pm 4)\times10^{-12}$ (hadron beam at the SPS)
- Discharge propagation studies
- HV system stability (CERN, IKF, TUM)
- Charge density studies

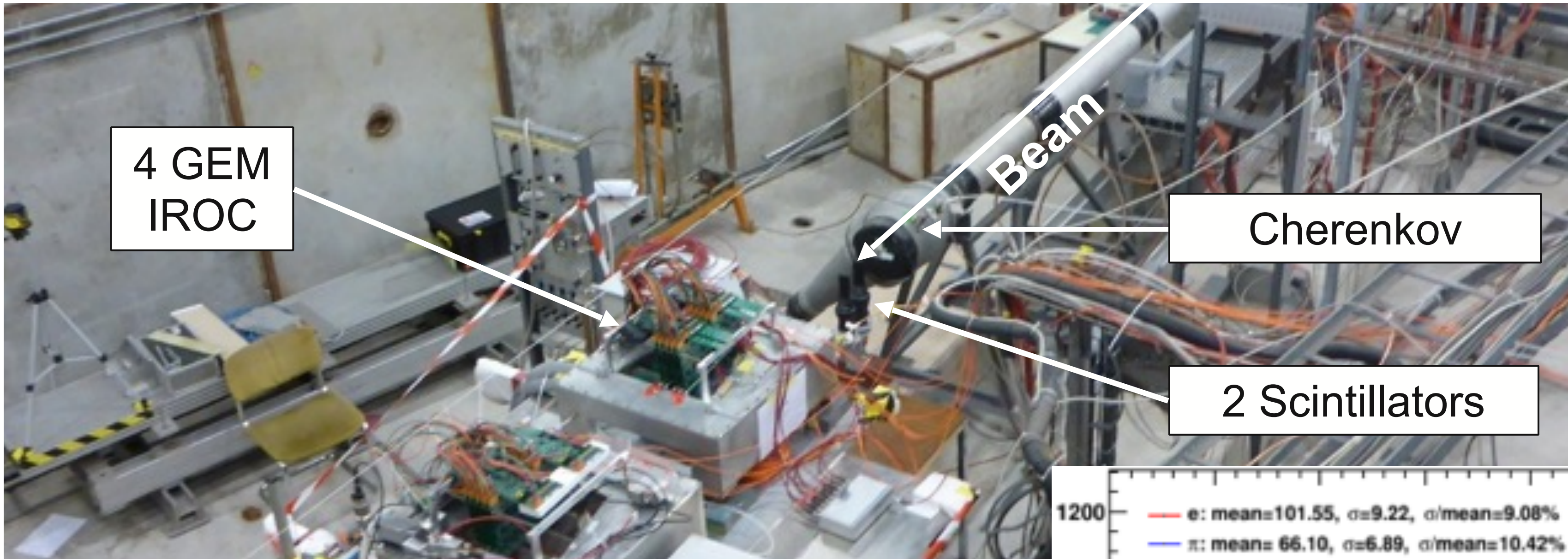
  (see P. Gasik, A. Mathis, L. Fabbietti, J. Margutti NIM **A870** (2017) 116)

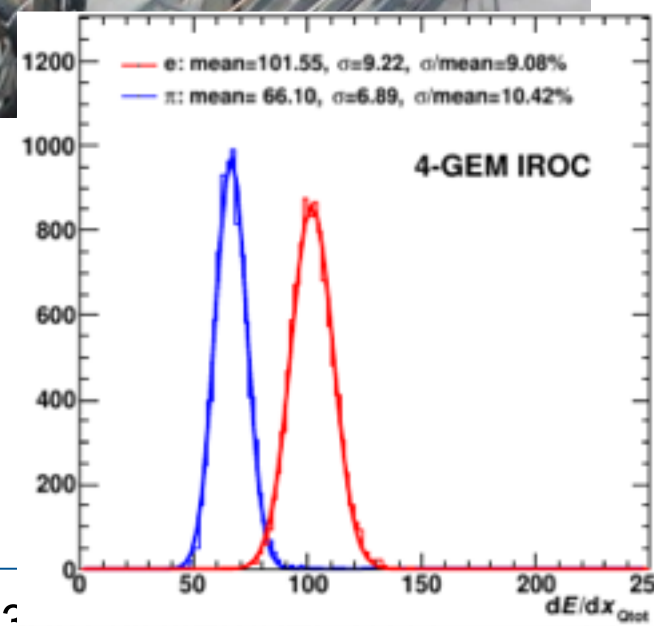
	S-S-S 'standard' HV G = 2000	S-S-S-S $IB = 2.0\%$ G = 2000	S-LP-LP-S $IB = 0.34\%$ G = 1600	$IB = 0.34\%$ G = 3000	$IB = 0.34\%$ G = 5000	$IB = 0.63\%$ G = 2000
^{220}Rn $E_\alpha = 6.4$ MeV rate = 0.2 Hz	$\sim10^{-10}$			$< 2\times10^{-6}$	$< 7.6\times10^{-7}$	
^{241}Am $E_\alpha = 5.5$ MeV rate = 11 kHz						$< 1.5\times10^{-10}$
^{239}Pu+^{241}Am+^{244}Cm $E_\alpha = 5.2$+5.5+5.8 MeV rate = 600 Hz		$< 2.7\times10^{-9}$	$< 2.3\times10^{-9}$	$(3.1\pm0.8)\times10^{-8}$		$< 3.1\times10^{-9}$
^{90}Sr $E_\beta < 2.3$ MeV rate = 60 kHz					$< 3\times10^{-12}$	

History of Prototypes

Year	ROC	Version	Assembly	Tests, beams
2012	***IROC***	***3GEM prototype***	***TU Munich***	• ***PS beam test (dE/dx resolution verified)*** • ***ALICE p-Pb run (stability issues addressed, gas mixture, HV scheme)***
2013	IROC	**3GEM** prototype	TU Munich	• MLL Garching (stability)
2014	***IROC***	***4GEM prototype***	***TU Munich***	• ***PS (dE/dx resolution with the baseline configuration)*** • ***SPS (stability in hadron beam verified, discharge probability***
2015	OROC	**4GEM** prototype	TUM/CERN	• “School of ROC” workshop • First OROC prototype, commissioning with sources
2016	***IROC***	***EDR pre-production***	***Yale***	• ***Commissioning of the test set-up and procedures*** • ***FEC+ROC tests at CERN***
	IROC	**FINAL** pre-production	Yale	• Commissioning of the test set-up and procedures • ALICE p-Pb run (chamber damaged) • Fast-track GEMs
	OROC	***FINAL pre-production***	***Bucharest***	• ***2 out of 3 stacks installed*** • ***Fast-track GEMs*** • ***Commissioning of the test set-up and procedures***
2017	OROC	**EDR** pre-production	GSI	• Commissioning of the test set-up and procedures
	IROC	***FINAL pre-production repaired***	***Yale***	• ***Final characterization*** • ***Fully qualified*** • ***1 MOhm on GEM4***
	OROC	**FINAL** pre-production *repaired*	GSI	• Final characterization • Fully qualified • 1 MOhm on GEM4

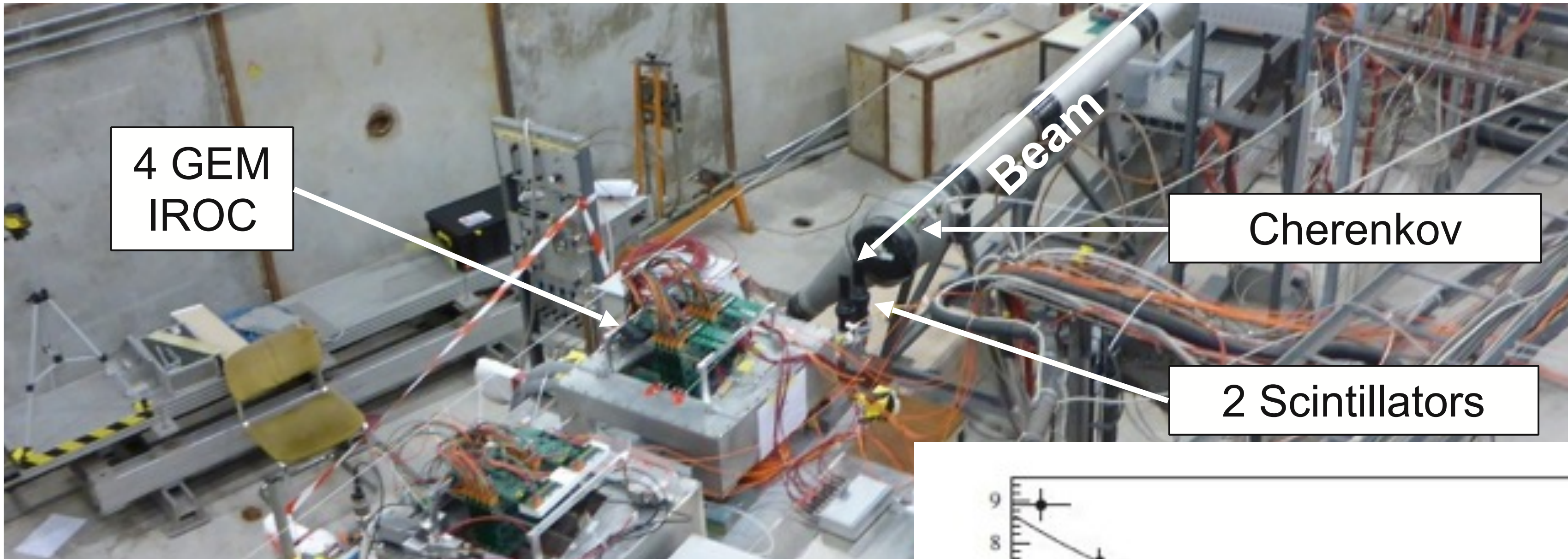
PS BEAMTIME (NOV. 2014)





- Secondary $e^{\pm}$, $\pi^{\pm}$ beam; 1, 2, 3 GeV/c
- d*E*/d*x* performance as expected from simulations
- Relative energy resolution as in present MWPC
  - $\sigma_e/\mu_e \approx 9\%$
  - $\sigma_\pi/\mu_\pi \approx 10\%$
- Physics performance not compromised up to $\sigma/E(^{55}Fe) = 14\ \%$

PS BEAMTIME (NOV. 2014)



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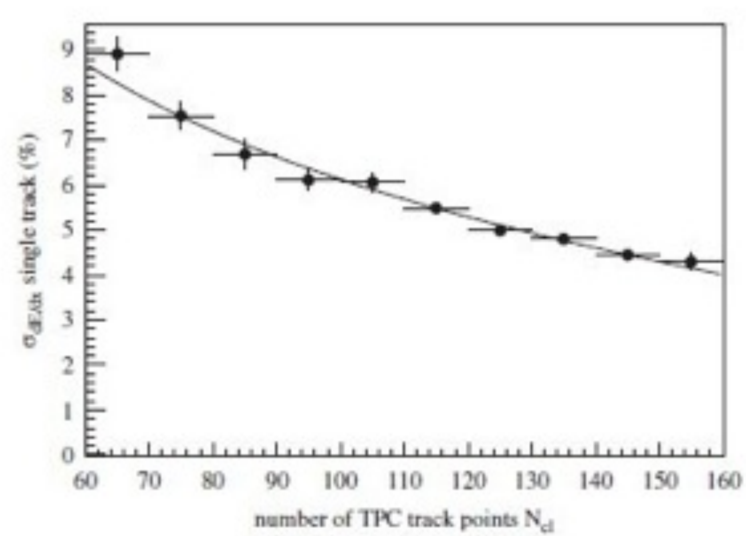
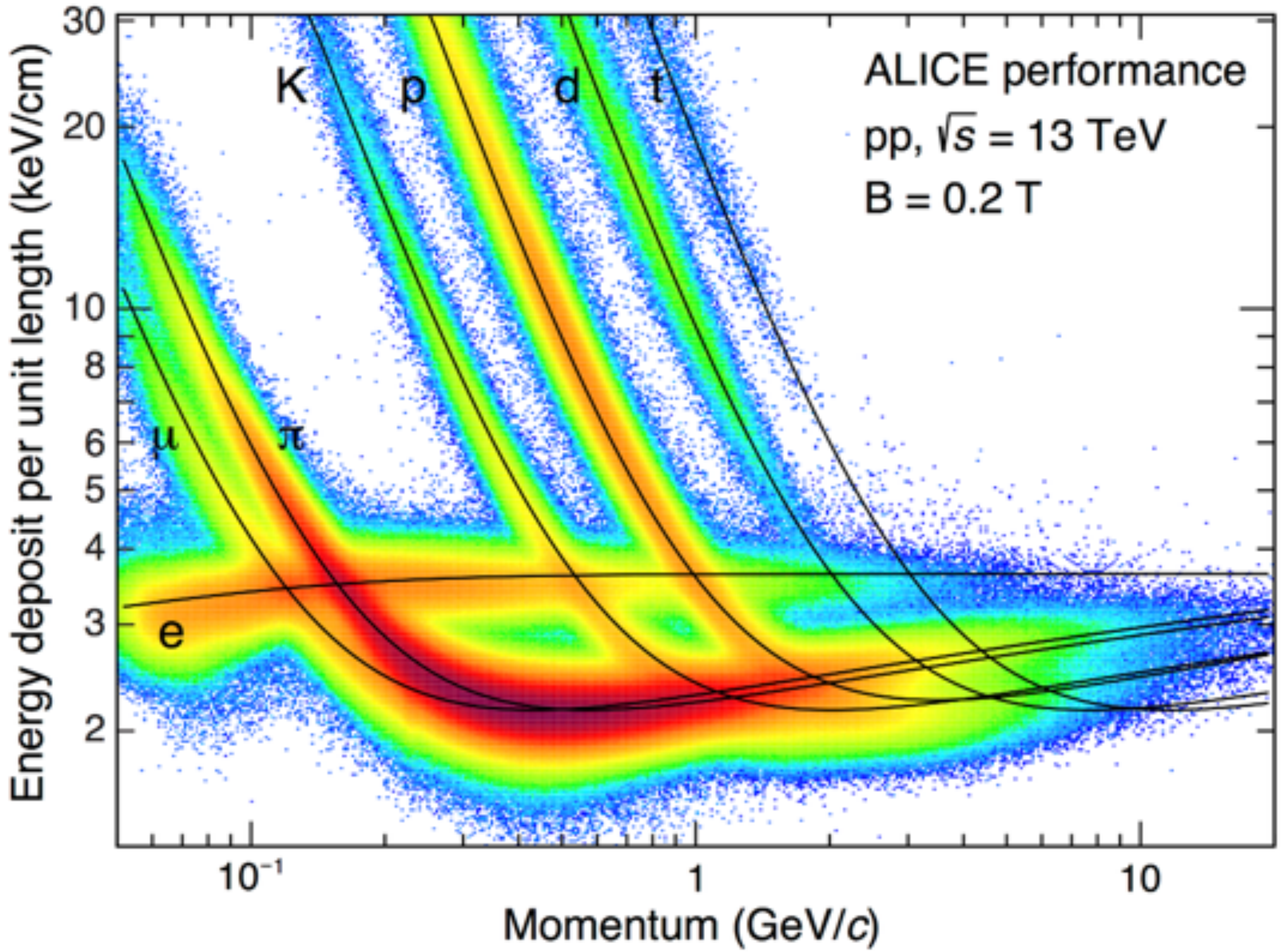
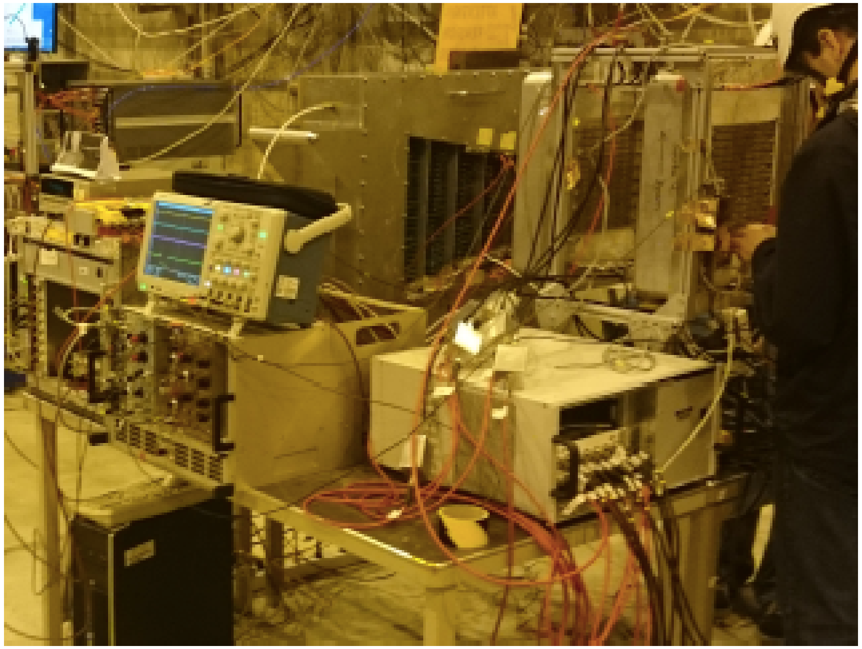
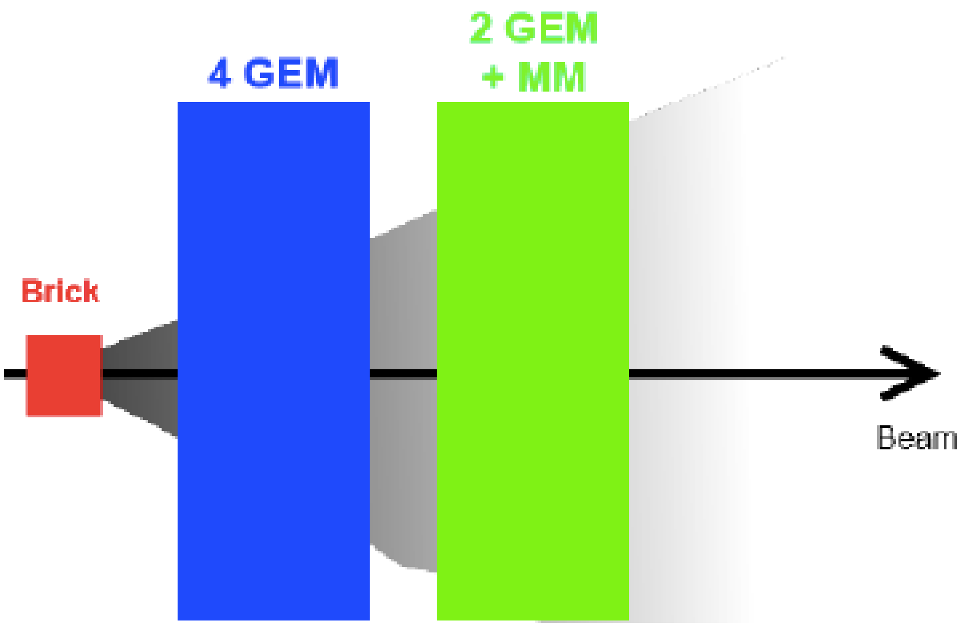


dE/dx resolution



Discharge Studies at the SPS



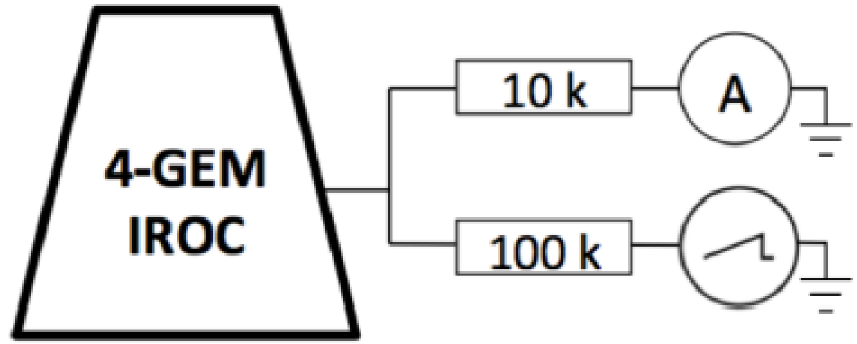


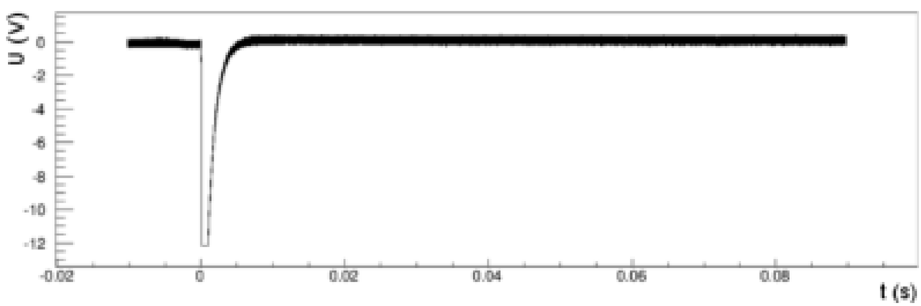
- A large GEM prototype (IROC) was irradiated over its full surface
  Setup at CERN SPS
- ~ 2 x 10^6 π/spill (150 GeV/c)
- Particle shower produced with a ^{55}Fe brick
- Line up the detectors (Readout facing the beam)

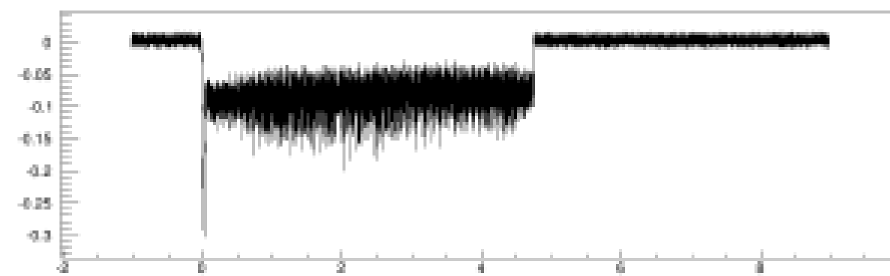
Discharge Studies at the SPS

Readout

- Current readout on the pad plane (rate measurement)
- Read out the induced signal on the pad plane (discharges)







Results

- 3 discharges seen → $(6 \pm 4) \times 10^{-12}$ Discharge probability / incoming hadron
- 5 discharges expected per year and GEM stack expected for the ALICE TPC in Run 3

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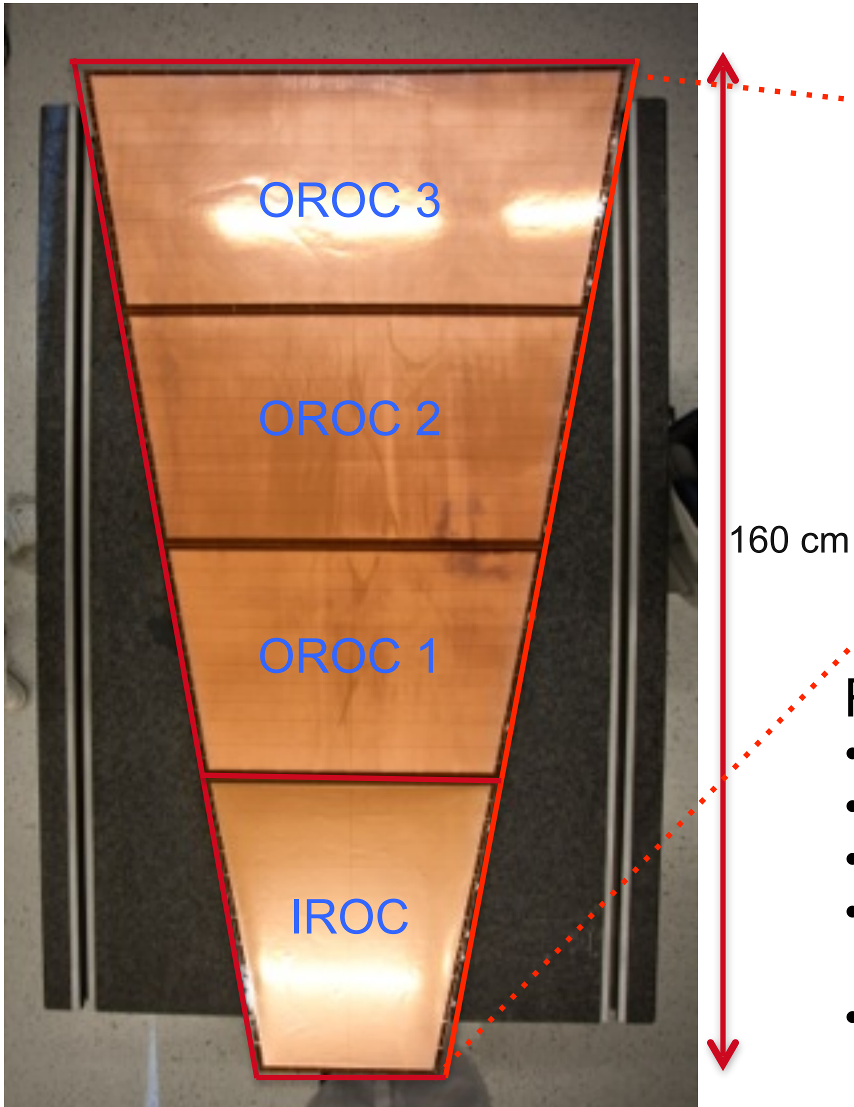
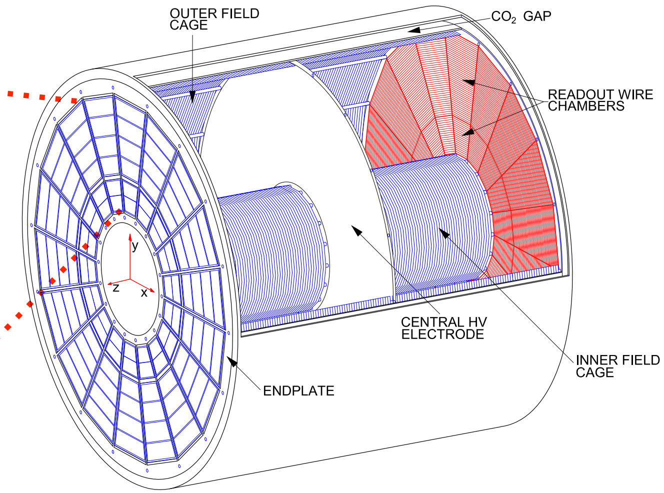


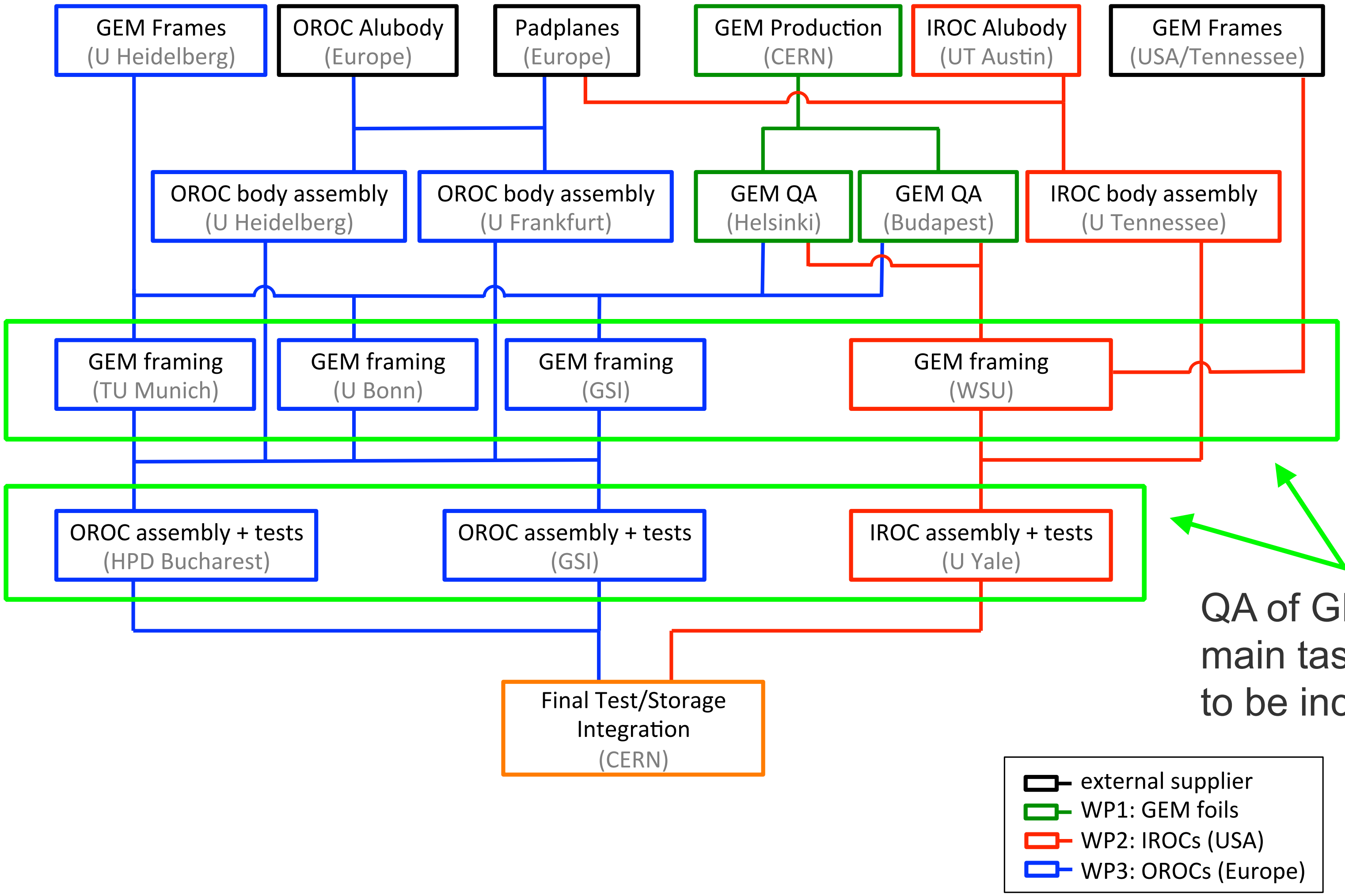


Replace 72 Readout Chambers in total !

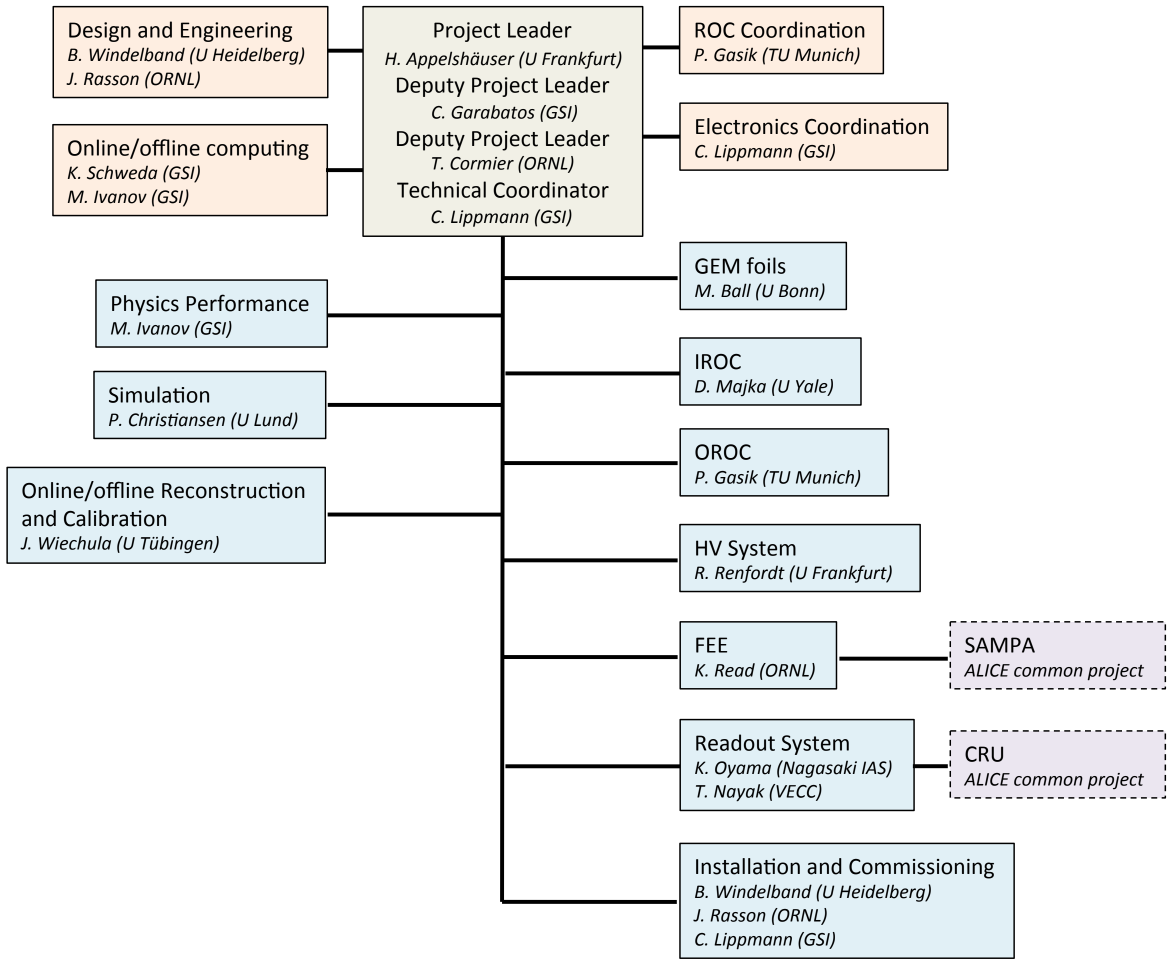
- Each IROC consists of 4 GEMs
- Each OROC consists of 3x4 GEMs
- 512 GEM foils
- (+ spare chambers, plus yield not 100 %, rather 85 %)
- → The quality of at least 720 GEM foils has to be assured

TPCU milestones

✓ **R&D and Prototyping**	2012-2015
✓ **LHCC approval** (TDR, TDR Addendum, TDR Addendum UCG)	June 2015
✓ **Engineering design Review (EDR)**	November 2015
✓ **Training (School of ROCs, Visits at all institutes, etc.)**	
✓ **GEM and chamber final design review**	June 2016
✓ **Pre-production**:	finalized
✓ **Production Readiness Review (PRR)** - full characterization of the final-design (aka PRR) chambers	10th March 2017
❑ **Mass production (40x IROCs + 40x OROCs)**	Q2.2017 – Q3.2018
❑ **ROC tests at LHC**	Q2.2017 – Q3.2018



QA of GEM foils not main task, but needs to be included.



Design and Engineering
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Deputy Project Leader
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Electronics Coordination
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CRU
ALICE common project
Installation and Commissioning
B. Windelband (U Heidelberg)
J. Rasson (ORNL)
C. Lippmann (GSI)

From EDR to PRR

- Engineering Design Review (EDR)
  - Focus on the engineering concept of the TPCU project
  - Do we have fully developed concepts for the production
  - Results shown were still based on prototypes
  - Discuss/Eradicate potential design flaws
- Production Readiness Review (PRR)
  - Proof the production readiness by demonstrating the readiness of all institutes (manpower, infrastructure of the institutes, knowledge at the institutes)
  - Demonstrate that detailed protocols have been developed
  - Show that all production steps have been qualified
  - Is there sufficient documentation of all processes
  - Demonstrate the readiness by qualification of an IROC and OROC chamber

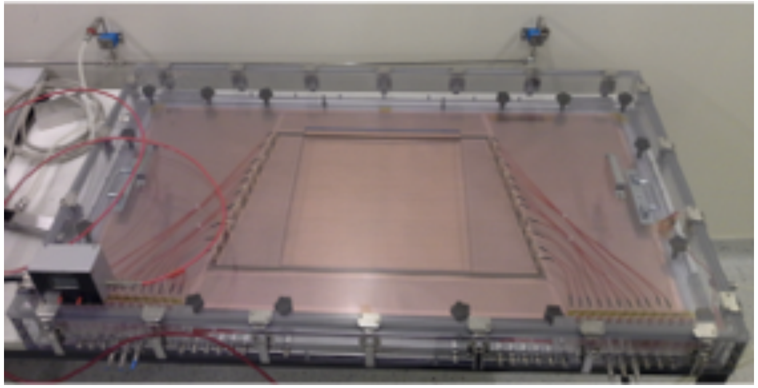
From EDR to PRR

- Most crucial changes (after discussion with the referees)
  - – Flip the segmentation of the top GEM (field distortion vs. discharge propagation probability)
  - ➡ Redesign of the GEM_1. In this context redesign of HV path of the GEM foil
  - – Loading resistor on the GEM foil: Originally considered to be soldered before final assembly. Now at CERN PCB workshop (battery effect of flux agent)
  - ➡ QA scheme (measurement of leakage current, inter segment test) had to be revised.
  - – Evaluation of QA methods (Impact water content on the measurement)

Next slides show the transition from EDR to PRR for the quality assurance (QA). You will have probably different challenges, but don't expect less !

From EDR to PRR

A. Utrobicic et al, NIM A, Vol. 801 (2015), p. 21-26,
http://www.picologic.hr/



EDR: Only demonstrator HV box existed
Now: Every institute has a HV box and drawers for final design GEM foils

EDR: Only Helsinki had the pA-meter
Now: Every institute has a its own pA-meter

EDR: Only prototype software existed
Now: Every institute has his own HV + analysis software

EDR: Only individual I_{leak} measurements possible (segment by segment) → QA very time consuming
Now: All segments can be measured in parallel QA-Basic: Measurement per foil 15 minutes

From EDR to PRR

Status table gem/L1/1001 Edit generic status table Status is A

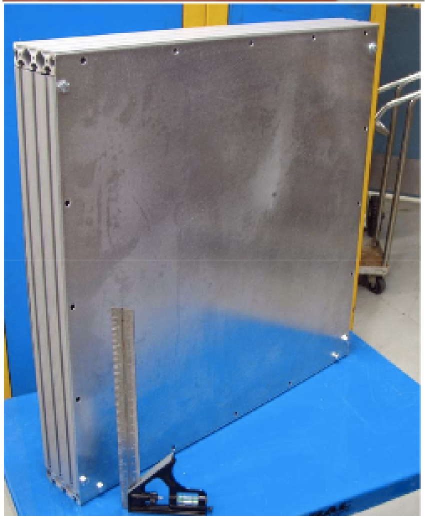
step	status	data field	value	date	comment	author	condition	true?
1	1	HV cleaning	done	2015-09-10 10:10:16		Peter	eq done	
2	2	dark current [nA]	12	2015-09-13 10:17:09		Peter	<= 14	
3	3	gas gain	2400	2015-09-13 10:17:09		Peter	>= 2.2e+3	
4	4	quality ranking	A	2015-09-13 10:17:09		Peter	le B	

submit

Status table gem/L2/2001 Edit generic status table Status is B

step	status	data field	value	date	comment	author	condition	true?
1	1	HV cleaning	done	2015-09-13 12:05:53		Peter	eq done	
2	2	dark current [nA]	13	2015-09-15 12:43:37		Peter	<= 14	
3	3	gas gain	2200	2015-09-15 12:43:37		Peter	>= 2.2e+3	
4	4	quality ranking	B	2015-09-15 12:44:28	gas gain marginal	Peter	le B	

submit



- Database, Logistics and Transport
  - Database was significantly improved
  - Logistics coordination was therefore improved accordingly
  - Final GEM Transport Systems (GTS) are available
  - Paperbacks are used to further protect the GEM foils in the GTS

From EDR to PRR

Home | Category: OROC | Stock | Shipping | Select by barcode: | Information | logged in: Markus

View and edit information on	OROC2 GEM foil: O2GF/G1, serialno O2-G1-001 batch 6	QA Status B	to next serial no O2-G1-002 / to all stock of O2-G1-nnn with serialno O2-G1-001 prefilled

part	type	prefix	serialno	batch	location
OROC2 GEM foil	G1	O2GF/G1	O2-G1-001	6	Bucharest

O2-G1-001

print label

Comment (none so far):

submit comment

QA table for O2-G1-001 Show generic QA table Status is B

failed QA steps:
2017-06-09 11:45:50: leakage current [pA] at 500 V
2017-06-29 14:08:50: leakage current [pA] at 500 V

turn QA details on (allows to repeat QA steps, edit QA file comments)

step (link)	status	data field (hover cursor for explanations)	value	n	date	QA step/file comment	author	condition	true?
1	1	quick defect map	dummyDefects.txt show		2017-01-15 15:46:31	ok, 2 scratches, and few over etched dots. / dummy defects	Renato	file txt	
2	2	HV cleaning	done		2016-12-06 16:12:59		Lilit	eq done	
3	3	intersegment test	ok		2016-12-06 16:12:59		Lilit	eq ok	
4	4	resistor values [MOhm]	resistorvalues.txt		2017-09-18 15:37:40	ok / 4.76 < R < 5.24, design value 5 [MOhm]	Philip	file txt	
5	5	funny holes	no	2	2017-05-12 14:25:57	Yellow (foil with holes close to border within a distance of less than a hole diameter)	Laszlo	eq no	
6	6	leakage current [pA] at 500 V	20.7	8	2017-10-27 13:36:07	avg all segments 9.2, sparks: 0	Viktor	<= 167	
7	7	spark map	sparkmapBonn.txt show	3	2017-10-27 13:36:44	ok, 0 sparks / Sparkmap after framing.	Viktor	file txt	
8	8	absolute humidity [ppmV]	4320	3	2017-10-27 13:36:07		Viktor	<= 6000	
10	QA-B	I_leak histo data	02_O2-G1-001_N2_framed_corrected.txt evaluate	3	2017-10-27 13:36:07	no comment | avg all segments 9.2, sparks: 0 / ok	Viktor	file txt	
12	12	hole size distribution	O2-G1-001_1D.txt evaluate 1D		2017-06-09 11:44:02	no comment	Marton	file txt	
13	13	hole size data 2D	O2-G1-001_2D.txt evaluate 2D		2017-06-09 11:44:43	no comment	Marton	file txt	
15	QA-A	long term leakage current data	O2-G1-001-20170504-15-42_sectors.txt evaluate	2	2017-06-29 14:11:17	no comment | avg all segments 3.4, sparks: 0 / sticky rolled after shorted sector, looks better although many sparks	Marton	file txt	
20	20	frame glueing	ok		2017-10-27 13:36:27		Viktor	eq ok	
25	25	quality	B	2	2017-06-10 23:01:47	Also slight problems from the HV, had to sticky roll it, but came back alive.	Marton	le C	
submit	darker field: mouse hover for more explanations								

Data fields for O2-G1-001:

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
Infrastructure	GEM TRANSPORT SYSTEM	any	all types	any			

part	item	batch	sent from	to	date	location	QA status	link	comment
GEM TRANSPORT SYSTEM	GTS-01					Bucharest		X	
GEM TRANSPORT SYSTEM	GTS-02					Helsinki		X	presently 3 layers
GEM TRANSPORT SYSTEM	GTS-03					Yale		X	inventoried with 3 layers presently 2 layers sent to WSU
GEM TRANSPORT SYSTEM	GTS-04					Bucharest		X	
GEM TRANSPORT SYSTEM	GTS-05					Bucharest		X	1st shipment from HD to CERN: 29.8.2016
GEM TRANSPORT SYSTEM	GTS-06					Bucharest		X	1st shipment from HD to CERN, 29.8.2016
GEM TRANSPORT SYSTEM	GTS-07		GSI	CERN	20.11.17			X	
GEM TRANSPORT SYSTEM	GTS-08		GSI	CERN	20.11.17			X	presently 4 layers
GEM TRANSPORT SYSTEM	GTS-09					TUM		X	
GEM TRANSPORT SYSTEM	GTS-10					TUM		X	
GEM TRANSPORT SYSTEM	GTS-11		CERN	Budapest	27.11.17			X	
GEM TRANSPORT SYSTEM	GTS-12					Bucharest		X	
GEM TRANSPORT SYSTEM	GTS-13					Bucharest		X	
GEM TRANSPORT SYSTEM	GTS-14					Yale		X	
GEM TRANSPORT SYSTEM	GTS-15					Yale		X	
GEM TRANSPORT SYSTEM	GTS-16					Yale		X	
GEM TRANSPORT SYSTEM	GTS-17		GSI	CERN	20.11.17			X	
GEM TRANSPORT SYSTEM	GTS-18		GSI	CERN	20.11.17			X	
GEM TRANSPORT SYSTEM	GTS-19					Budapest		X	
GEM TRANSPORT SYSTEM	GTS-20					Bonn		X	
GEM TRANSPORT SYSTEM	GTS-21		TUM	GSI	21.11.17			X	Two small metal pieces that support the foils from the side are missing.
GEM TRANSPORT SYSTEM	GTS-22		WSU	Yale	28.11.17			X	
GEM TRANSPORT SYSTEM	GTS-23					Helsinki		X	
GEM TRANSPORT SYSTEM	GTS-24					Bonn		X	
GEM TRANSPORT SYSTEM	GTS-25		Helsinki	GSI	29.11.17			X	
GEM TRANSPORT SYSTEM	GTS-26					Helsinki		X	
GEM TRANSPORT SYSTEM	GTS-27		CERN	Budapest	22.11.17			X	

27 items

From EDR to PRR

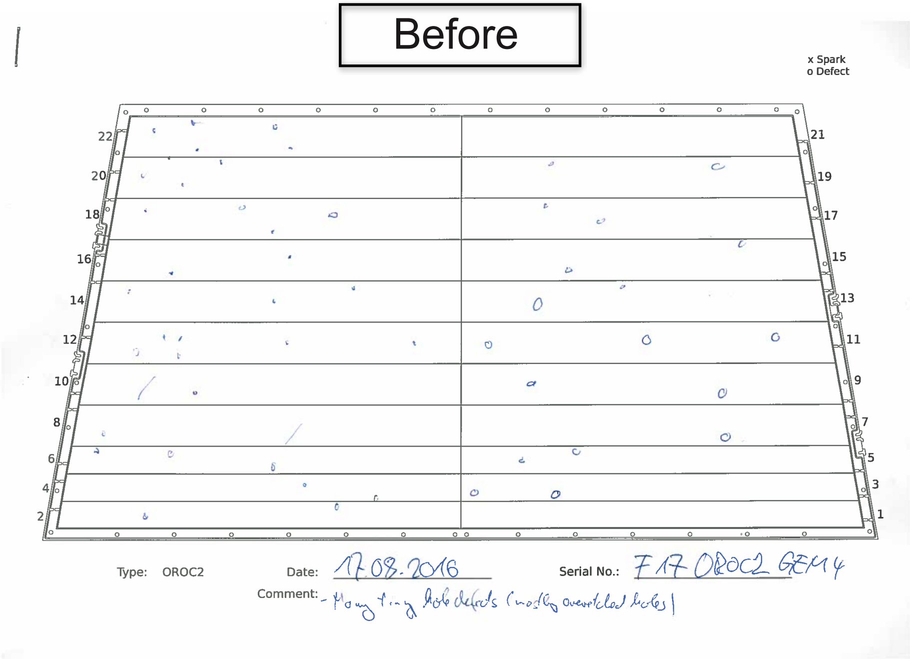
Basic QA consists of:

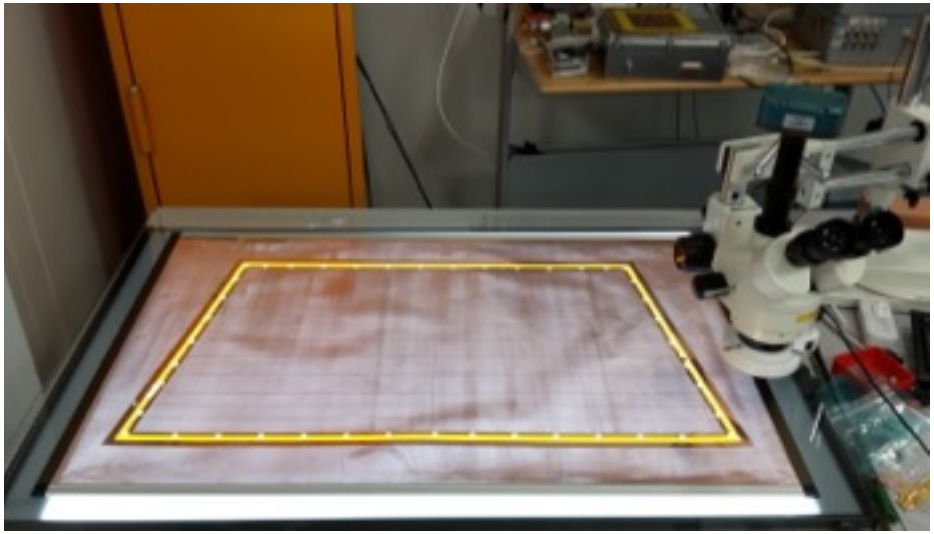
- Coarse optical inspection (re-inspection) including map of optical defects
- Include environmental parameters in the database
- Intersegment test (CERN workshop)
- HV cleaning (at 500 V) including spark map
- $I_{leakage}$ measurements for 15 minutes, data is stored in a leakage current file with common data format

QA table for O2-G1-003 Edit generic QA table Status is QA-B turn QA details on (allows to repeat QA steps, edit QA file comments)

step (link)	status	data field (hover cursor for explanations)	value	n	date	QA step/file comment	author	condition	true?
1	1	**quick defect map**	dummyDefects.txt show		2017-01-15 15:46:31	ok, Black mark on the edges and several over etched dots. / dummy defects	Lilit	file txt	
2	2	**HV cleaning**	done		2016-11-30 10:51:13		Lilit	eq done	
3	3	**intersegment test**	ok		2016-11-30 10:51:13		Lilit	eq ok	
4	4	**leakage current [pA] at 500 V**	38.4	3	2017-02-01 13:08:41	Average current = -15.4	Markus	<= 167	
5	5	**spark map**	sparkmapBonn.txt show	3	2017-02-20 09:05:54	ok, 2 sparks / uploaded again for coordinate conversion	Peter	file txt	
6	6	**absolute humidity [ppmV]**	2570	3	2017-02-01 13:08:41		Markus	<= 6000	
7	QA-B	**I_leak histo data**	02_O2-G1-003_N2_framed.txt evaluate	3	2017-02-01 13:12:12	ok / ok	Markus	file	

From EDR to PRR



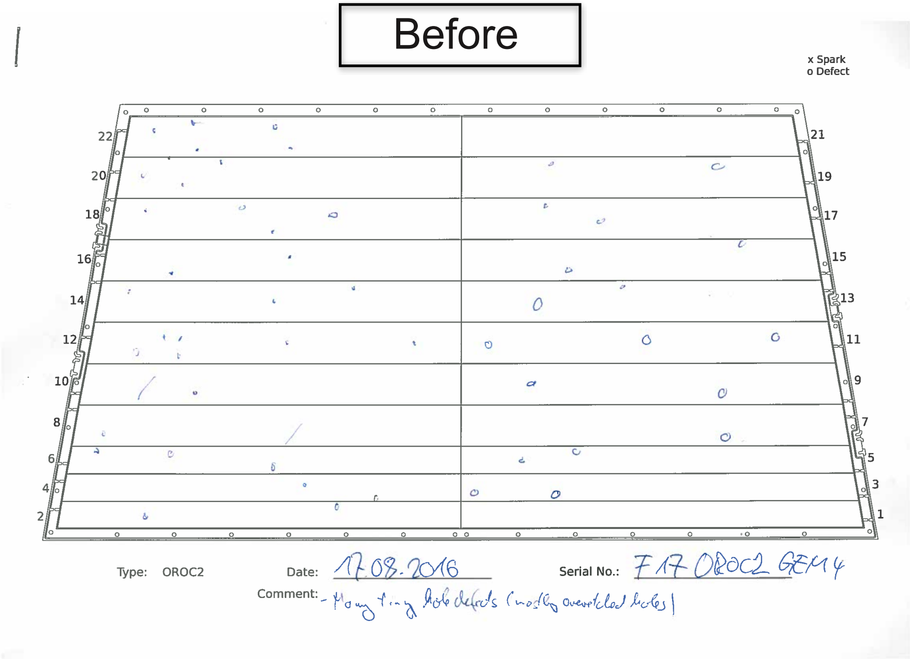


M. Ball et al, JINST Vol. 12 C01081

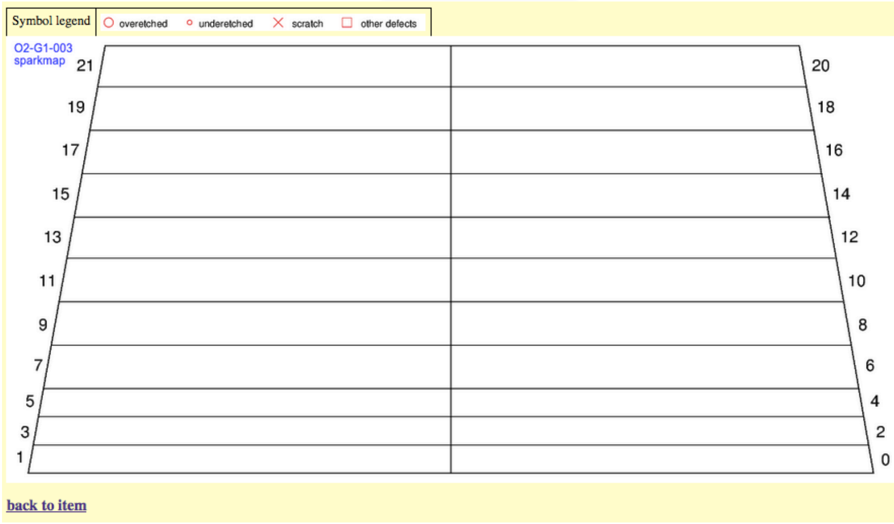
- Basic QA: Coarse optical inspection
  - Note visible defects by eye (CERN)
  - 5-10 minutes per GEM
  - Quick crosscheck after transportation (framing & assembly centres)
  - Enter the values directly in the database (no paper in the cleanroom)

From EDR to PRR

Before



Now



- Basic QA: Coarse optical inspection
  - Note visible defects by eye (CERN)
  - 5-10 minutes per GEM
  - Quick crosscheck after transportation (framing & assembly centres)
  - Enter the values directly in the database (no paper in the cleanroom)

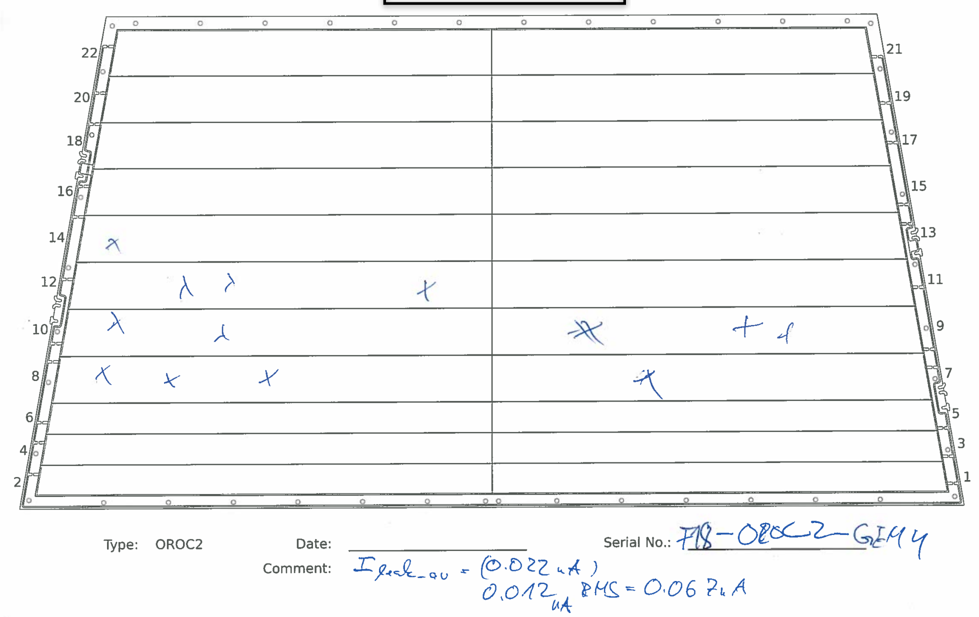
From EDR to PRR

ALICE

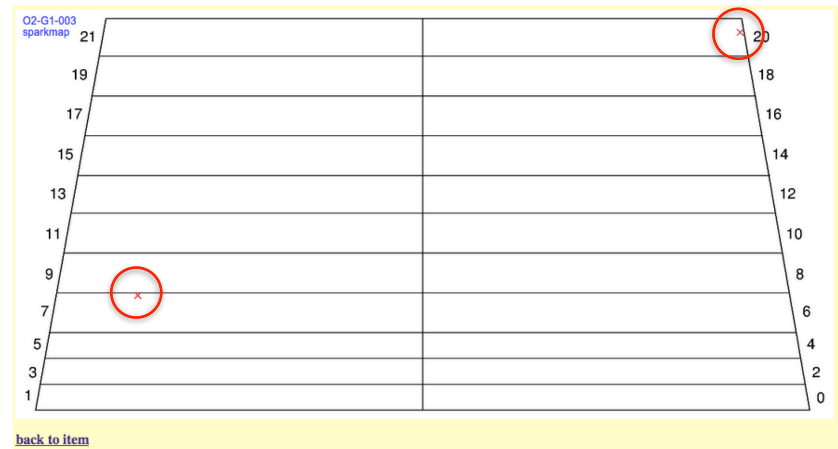
QA-Basic - HV cleaning

Before

x Spark
o Defect

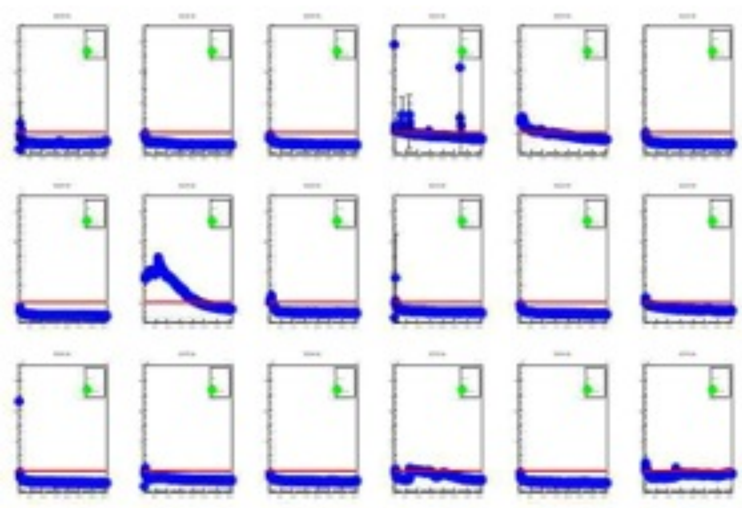


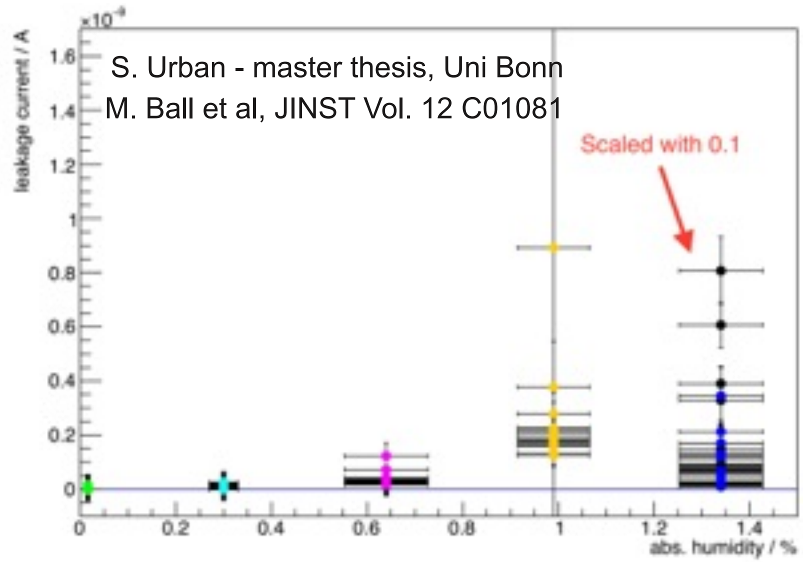
Now



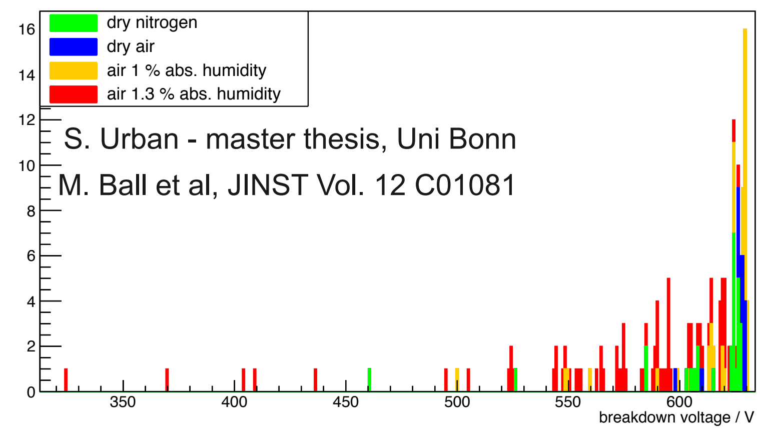
- Basic QA: HV cleaning of the GEM
  - HV cleaning of the GEM foils at 500 V
  - Watch the sparks per eye, enter N sparks, position in the database by hand
  - If sparking does not stop or sparks at one position, terminate measurement, send for re-cleaning

From EDR to PRR



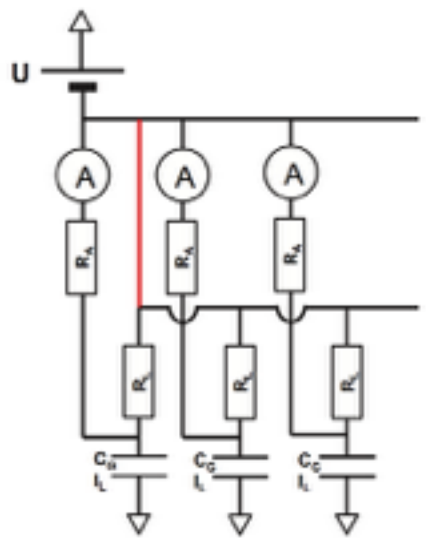


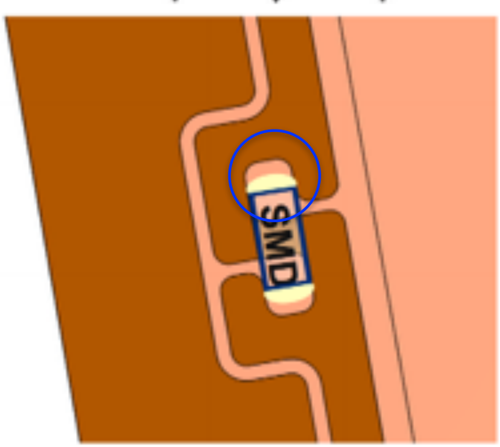
EDR: Open question N_2 vs wet air
Now: Clear protocol for I_{leak} and HV-cleaning as well as for the environmental boundary conditions: water content in nitrogen < 0.6 % abs. humidity



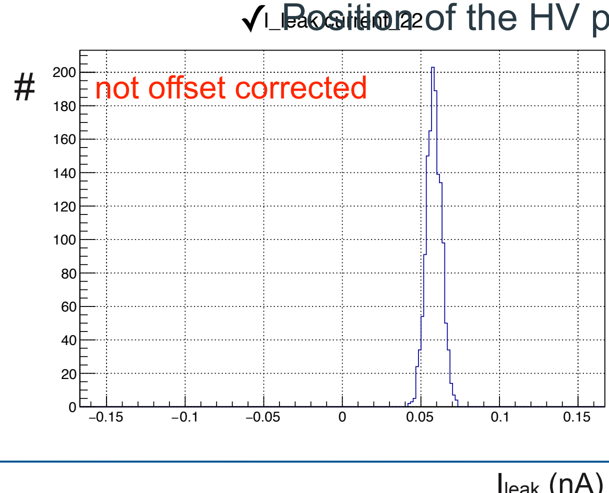
From EDR to PRR

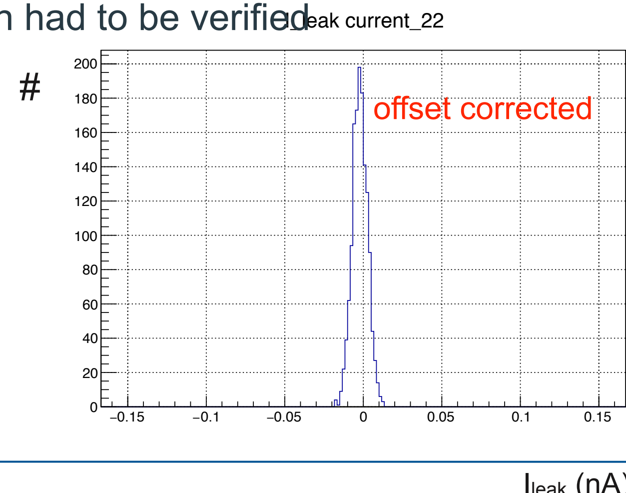
Scheme of D. Majka (Yale)

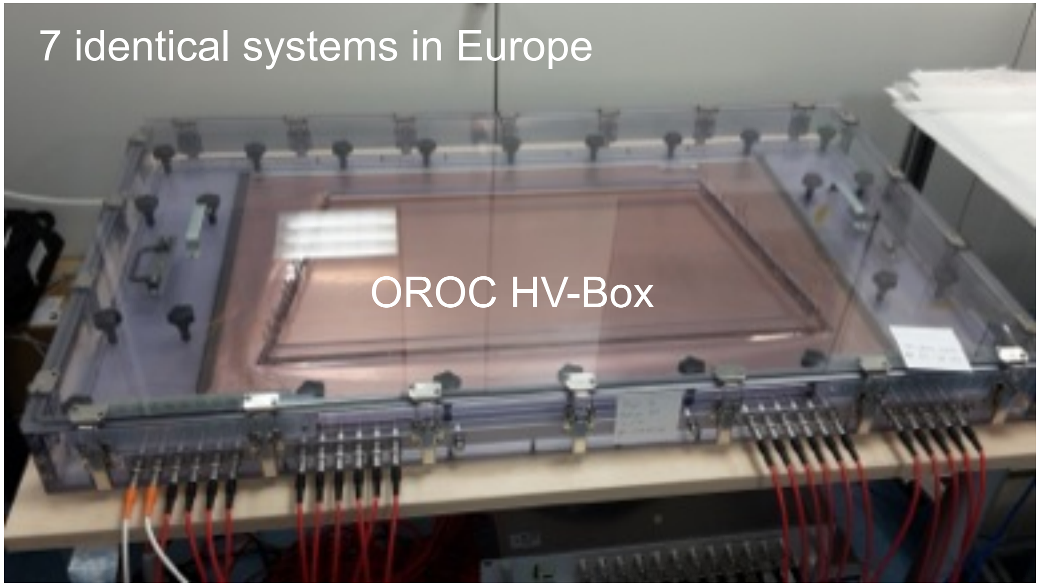


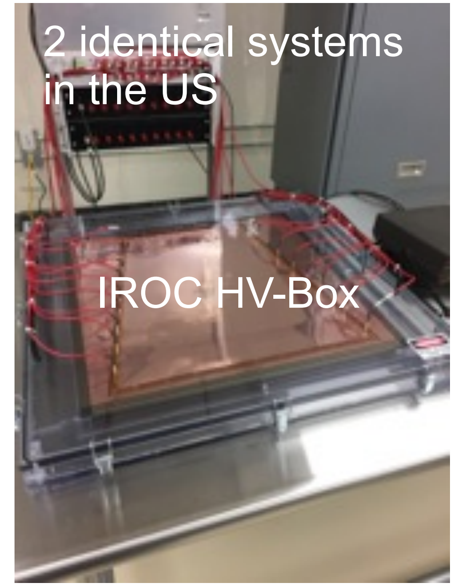


- Some challenges introduced by the EDR
  - ✓ Resistors are now soldered already at the CERN workshop, not - as initially planned - at the assembly centres
  - ✓ Testing scheme had to be modified
  - ✓ Sensitivity of the pA-meter had to be evaluated
  - ✓ Offset correction mandatory (due to lower I_{leak} thresholds)
  - ✓ Alternative to the flat HV pin had to be found. Conical HV pins (Europe), round HV pins (US), sharp HV pins (discarded)
  - ✓ Position of the HV pin had to be verified

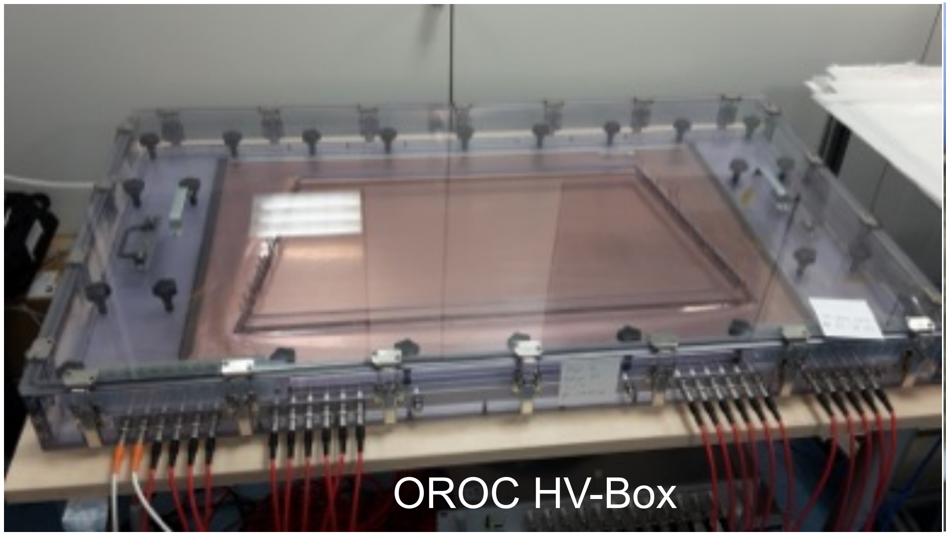








- Basic QA: Leakage Current measurements
  - Procedure established with resistors already soldered
  - Carefully check all connections/resistors before drawer is put in the HV Box (R_{load} must not deviate more than ± 5 % of the nominal value)
  - I_{leak} threshold no resistors = 0.5 nA/segment (5 MΩ = 0.167 nA/segment)



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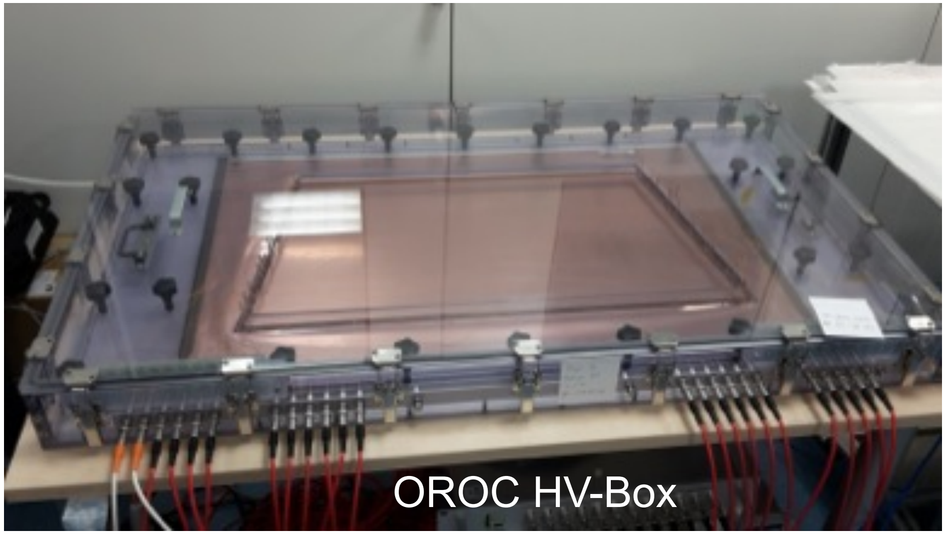
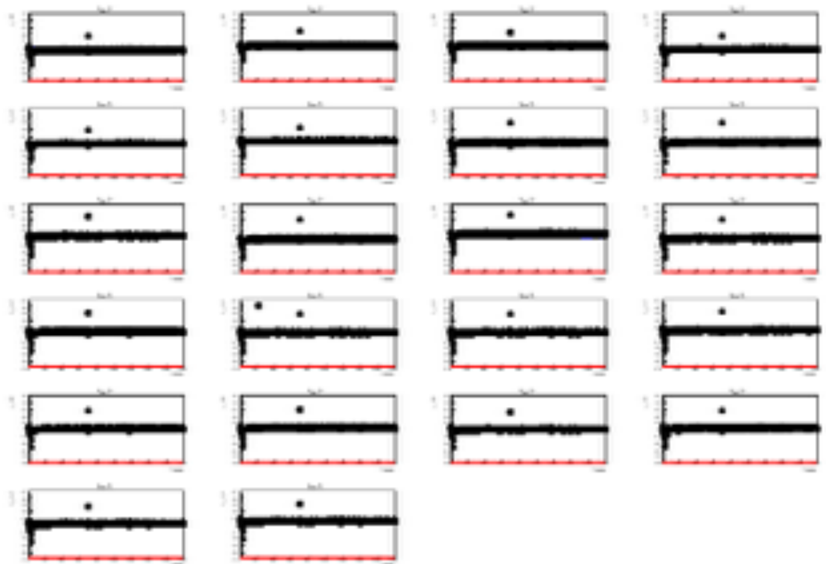
From EDR to PRR





- Basic QA: Leakage Current measurements M. Ball et al, JINST Vol. 12 C01081
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  - I_{leak} threshold no resistors = 0.5 nA/segment (5 MΩ = 0.167 nA/segment)

From EDR to PRR

QA Basic

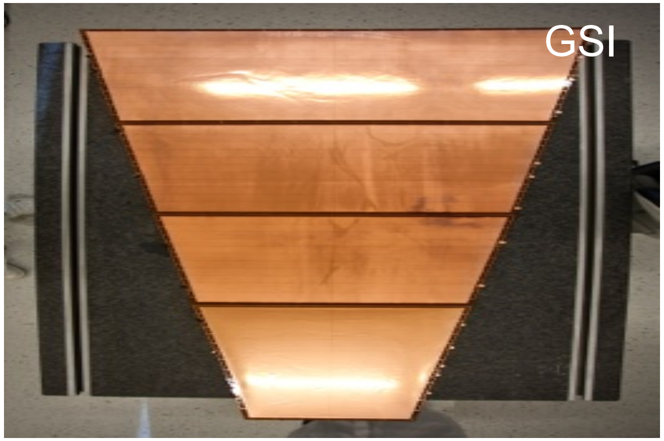
Institutes	Contact Persons	Infrastructure	Manpower
CERN	C. Garabatos , R. Aparecido	Existing	Existing
WSU	B. Llope, Oleg Grachov	Existing	Existing
Yale	D. Majka	Existing	Existing
Bonn	M. Ball, V. Ratza	Existing	Existing
GSI	D. Miskowiec	Existing	Existing
TUM	P. Gasik, S. Winkler	Existing	Existing
Bucharest	M. Petrovici, M. Petris	Existing	Existing

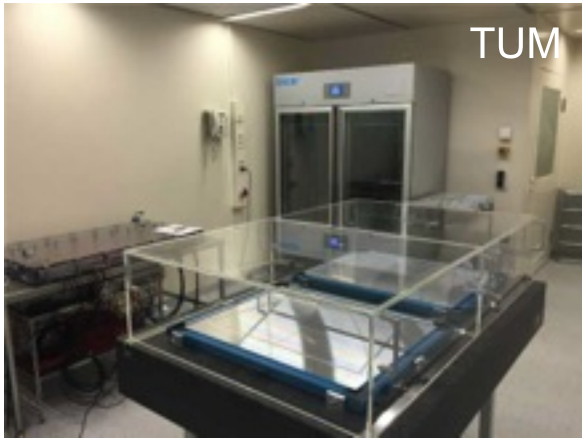
- All basic QA centres are fully equipped and in operation
- For all institutes except CERN, QA is only part of their task.
- Manpower in all institutes laid out for current rate (40-48 GEM foils per month)

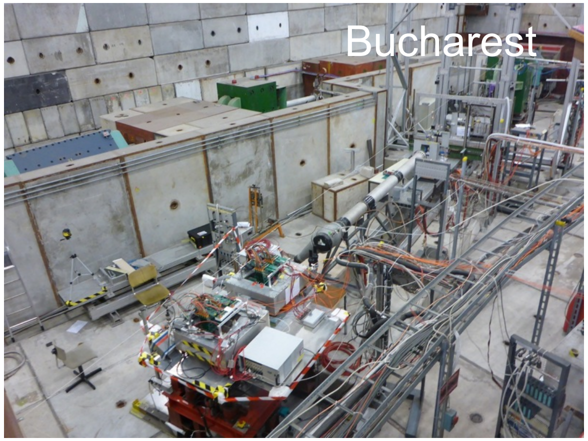
From EDR to PRR

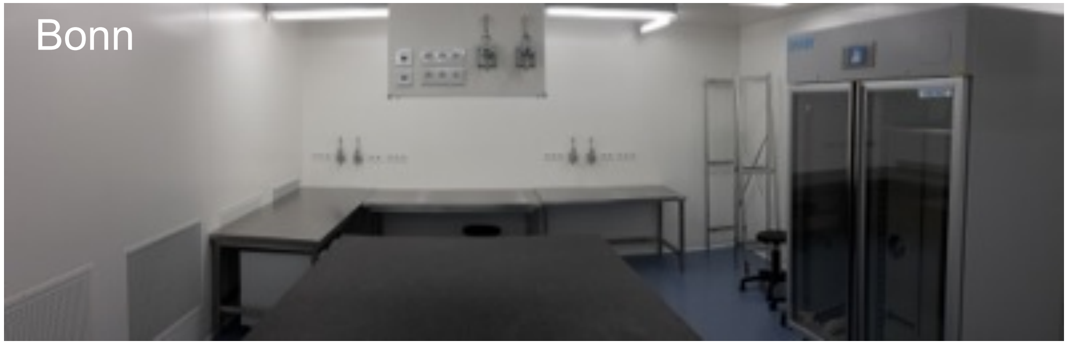
- If GEM foils are contaminated with dust use sticky roller to clean them
- Procedure suggested and used at CERN workshop

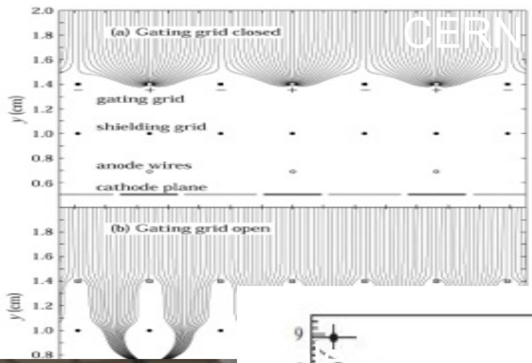
From EDR to PRR

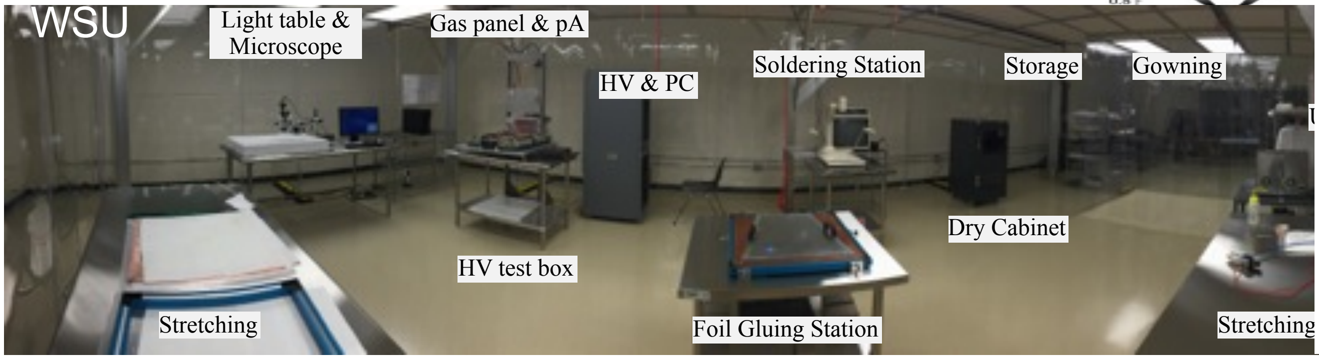


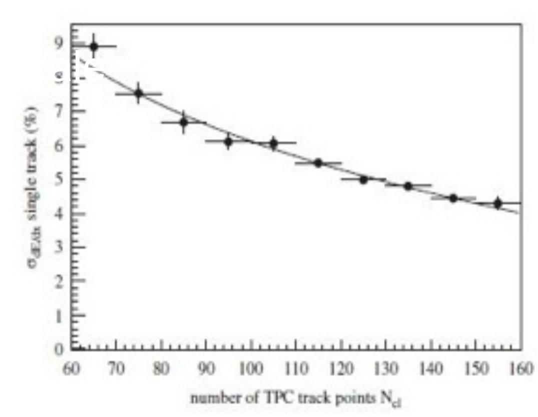










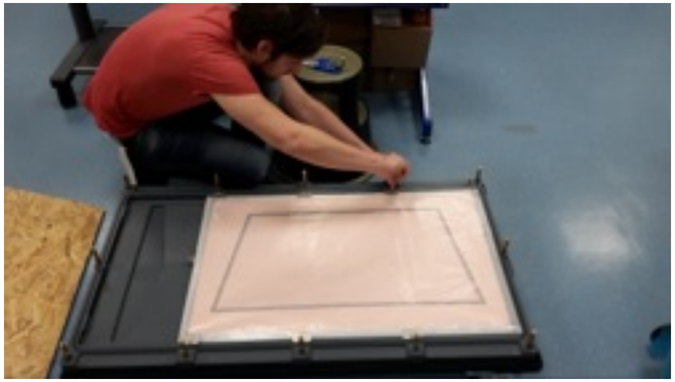


From EDR to PRR

Institutes	Contact Persons	Cleanroom Class	Size of the Cleanroom (sqm)
CERN	C. Garabatos, R. Aparecido	ISO 6 (ISO 5)	28
WSU	B. Llope, Oleg Grachov	ISO 5 (ISO 4)	48
Yale	D. Majka	ISO 6 (ISO 5)	22
Bonn	M. Ball, V. Ratza	ISO 6 (ISO 4)	36
GSI	D. Miskowiec	ISO 7 (ISO 5/6)	600
TUM	P. Gasik, S. Winkler	ISO 5 (ISO 4)	34
Bucharest	M. Petrovici, M. Petris	ISO 6 (GEM), ISO 7 (Assembly)	26, 24

- Cleanrooms classes ISO 6 (except GSI) or better. Work places have even better cleanliness
- GEM foils are only unpacked or packed in clean environment to keep dust contamination at a manageable level

GEM Transport System (Heavy duty)



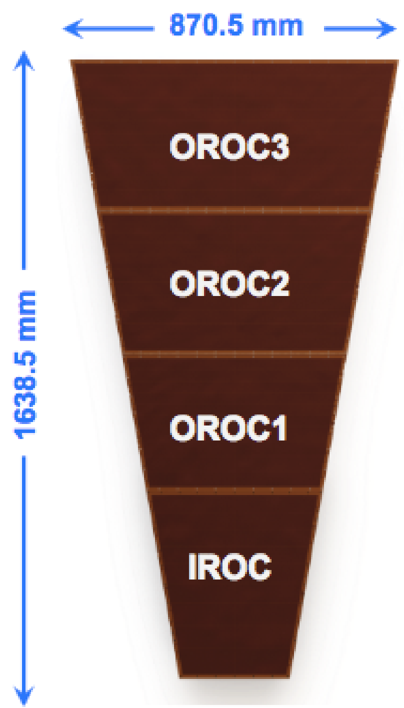
- Now 3rd version of the system exists. Contains space for three GEM foils per frame. Total weight ~ 150 kg
- Tested in practice with regular shipments already.
- Price is under control if negotiated with a delivery company (Europe, US)
- No GEM foil damage could so far be related to the shipment
- GEMs in paper bags minimises dust contamination, allows handling the GTS outside the cleanroom

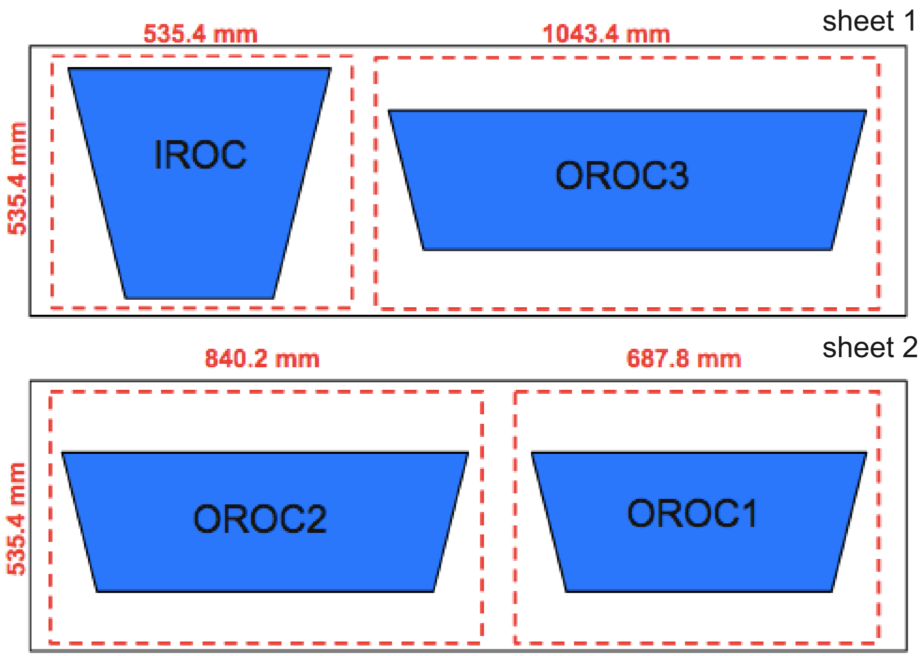
From EDR to PRR

My personal resume

- The changes introduced after the EDR lead to quite time consumptive redesign of our GEM foils and reevaluation of our QA scheme, but crucial for the safety of operation
- To coordinate production of such a size between several institutes and people, it was imperative to have clear protocols of each production step, a common documentation tool, that everyone uses as well as regular exchange and qualification of the personnel
- Don’t underestimate the continuous production mode. Delays, setbacks unexpected problems, miscommunication can cost a lot of time and not everything can be solved with more work of the same people

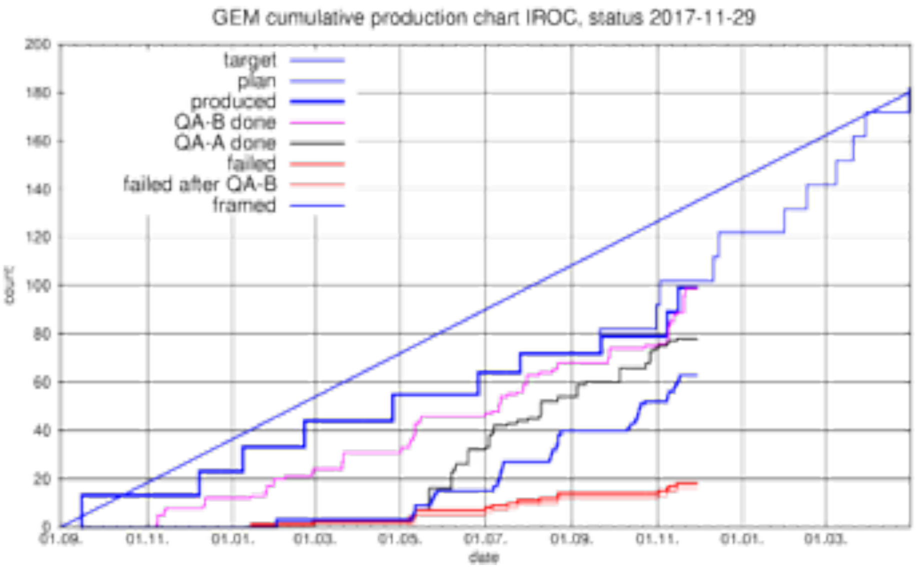
- The ALICE TPC
- Motivation for the GEM upgrade
- Ion backflow, energy resolution and discharge probability
- The road from TDR to PRR
- **Full production**
- Summary

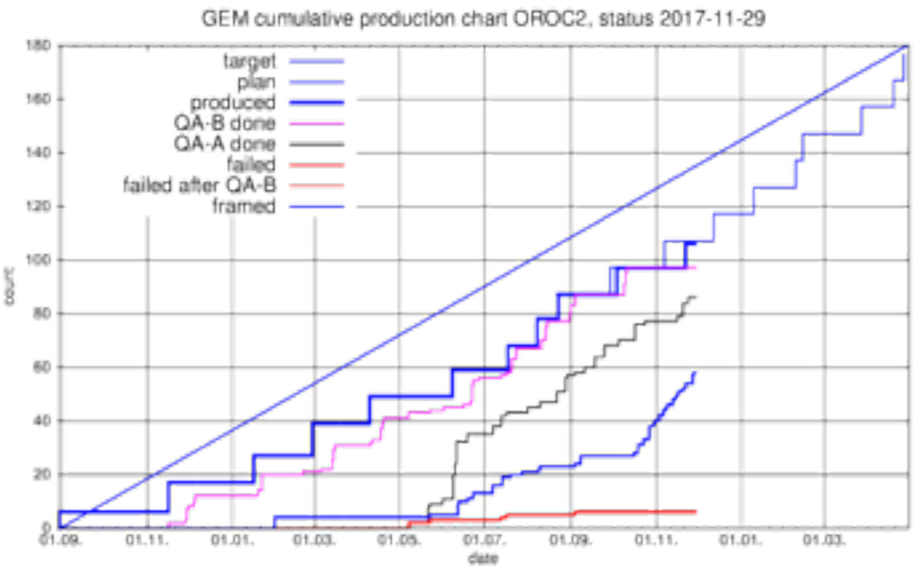




- GEM production at CERN
  - 144 GEMs of each type: IROC, OROC 1, 2, 3
  - 720 individual GEMs (including 25 % spares) = 2 x 180 sheets (IROC + OROC3, OROC1 + OROC2)

Production Progress





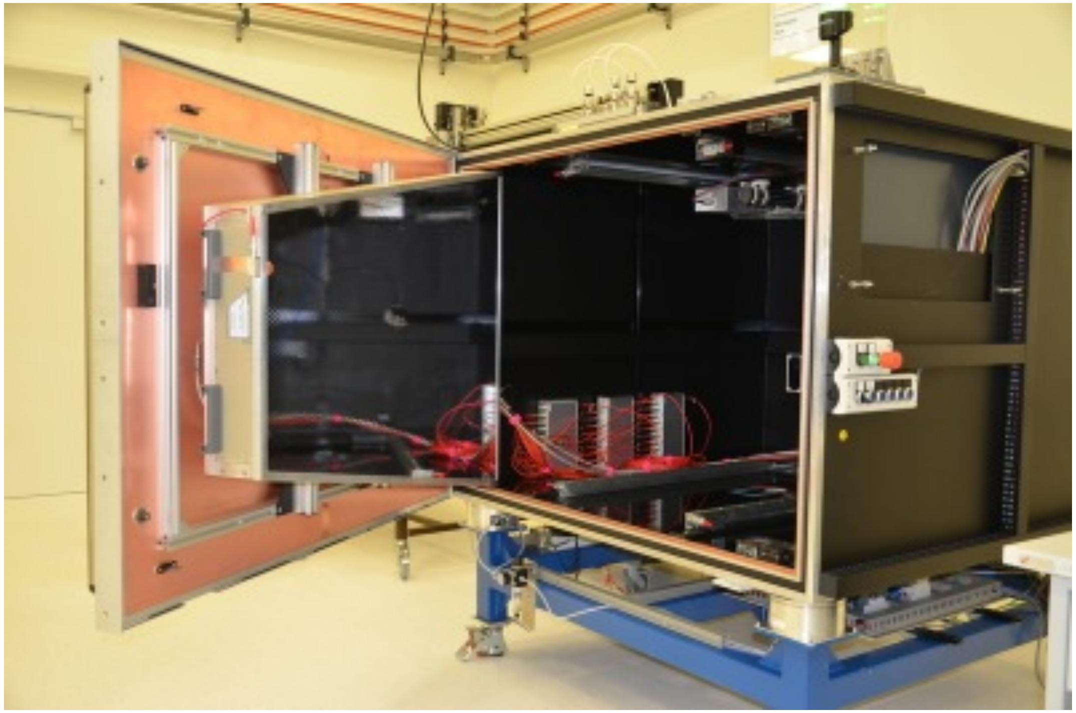
- November 2017: **422 foils produced** (target: 720 = 640+80 spares)
- GEM production 3 **months behind schedule**
- Updated production plan: end of production in 4/2018

- Projected yield: ~90% (constantly monitored)
- 720 produced GEM foils will be sufficient to finish ROC production (need 640 GEMs for 40+40 ROCs)

- very powerful database system is in place
- keeps track of all GEMs, components and QA results

FINAL CHAMBER PERFORMANCE

1. Chamber commissioning at the assembly sites
2. Stability tests at LHC
3. Energy resolution measured at PS with new electronics



LIST OF TESTS

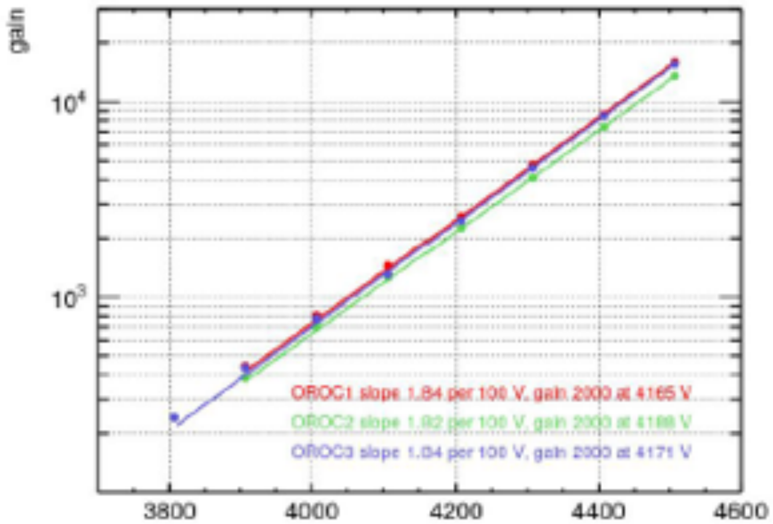
1. Gas tightness (< 0.5 ml/h)
2. Gain curve
3. Gain uniformity (<20 %)
4. IBF uniformity (IBF = 0.7%, Δε < 20%)
5. Full X-ray irradiation (10 nA/cm^2) for 6h

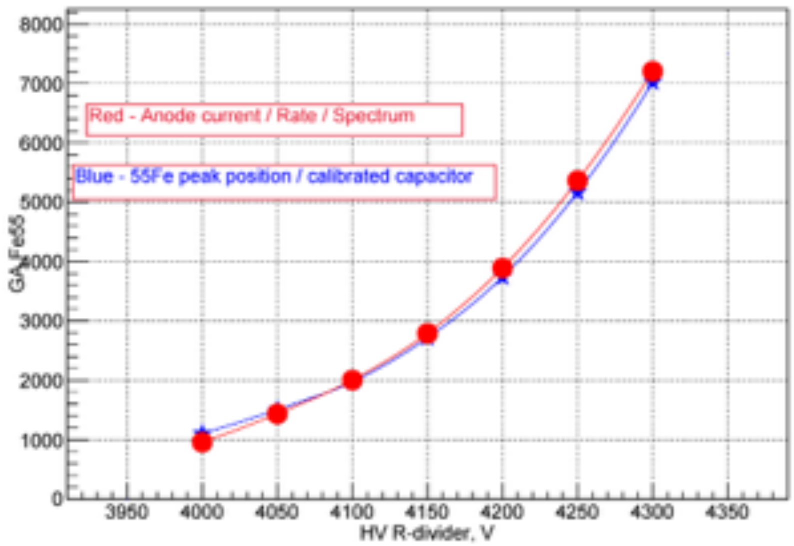
Gas: Ne-CO_2-N_2 (90-10-5)

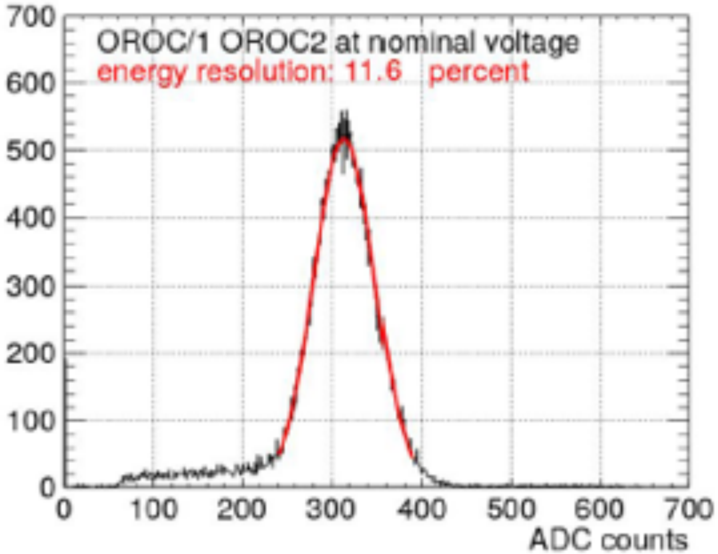
HV: resistor chain

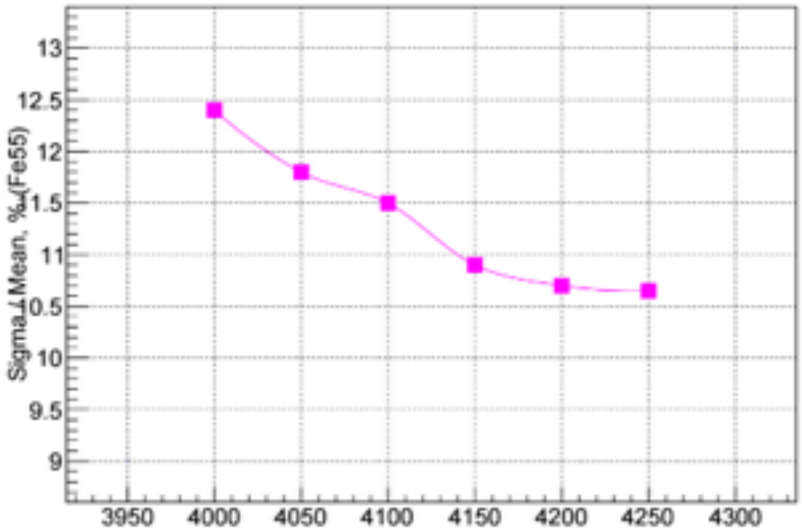
Settings: GEM1/2/3/4 = 270/230/288/359 V T1/T2/T3/IND = 4/4/0.1/4 kV/cm

Readout: single channel pre-amplifier + shaper + ADC, amperemeters


gain
10^4
10^3
OROC1 slope 1.84 per 100 V, gain 2000 at 4165 V
3800
4000
4200
4400
4600


Red - Anode current / Rate / Spectrum
Blue - 55Fe peak position / calibrated capacitor
GAFe55
HV R-divider, V
8000
7000
6000
5000
4000
3000
2000
1000
0
3950
4000
4050
4100
4150
4200
4250
4300
4350


OROC/1 OROC2 at nominal voltage
energy resolution: 11.6 percent
ADC counts
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700


13
12.5
12
11.5
11
10.5
10
9.5
9
3950
4000
4050
4100
4150
4200
4250
4300

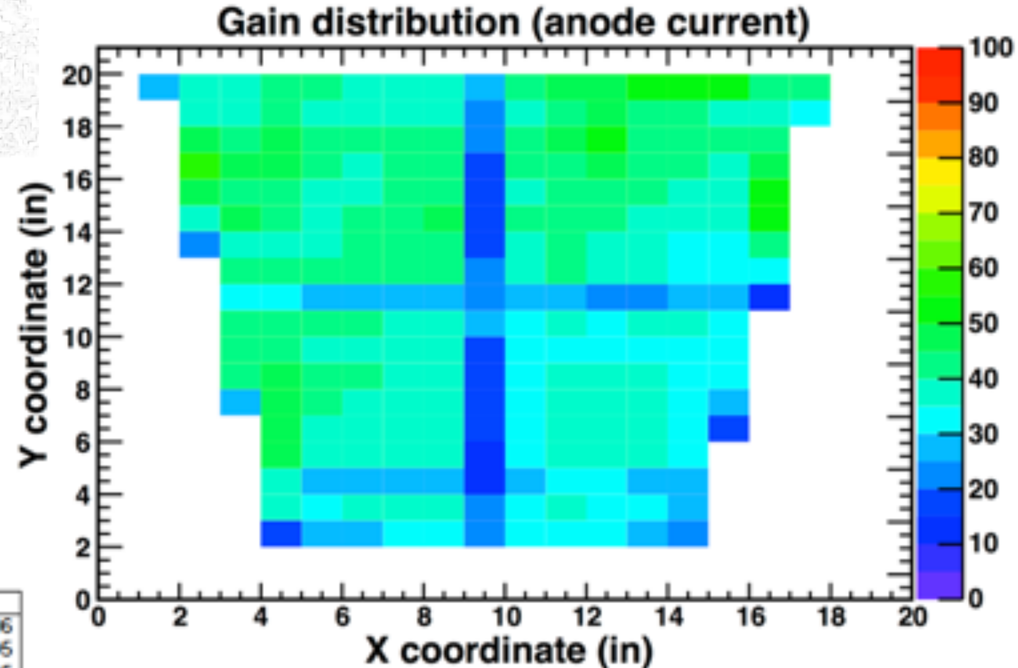
GAIN MAP

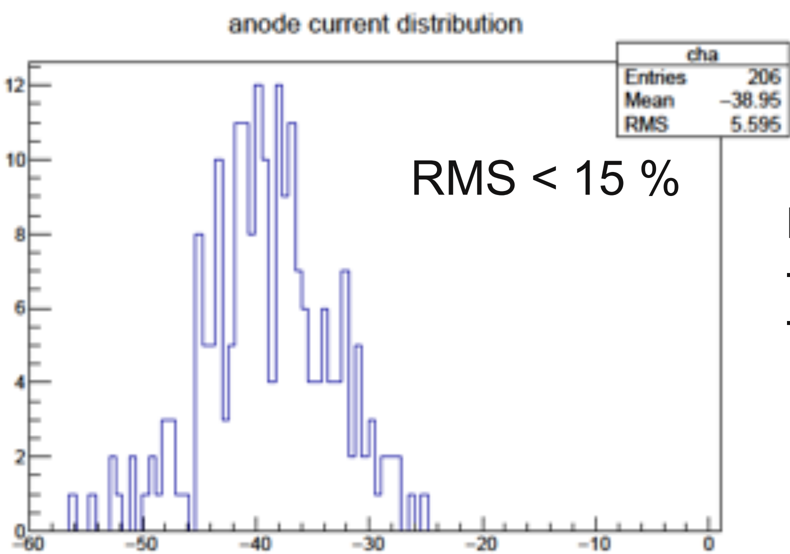
- ✓ Effective gain

  $G_{eff} = I_{anode}/(e \times N_{ion} \times R)$

- ✓ Performance within specs:
  - **gain uniformity < 20%**

- ✓ **8 IROCs within specs**

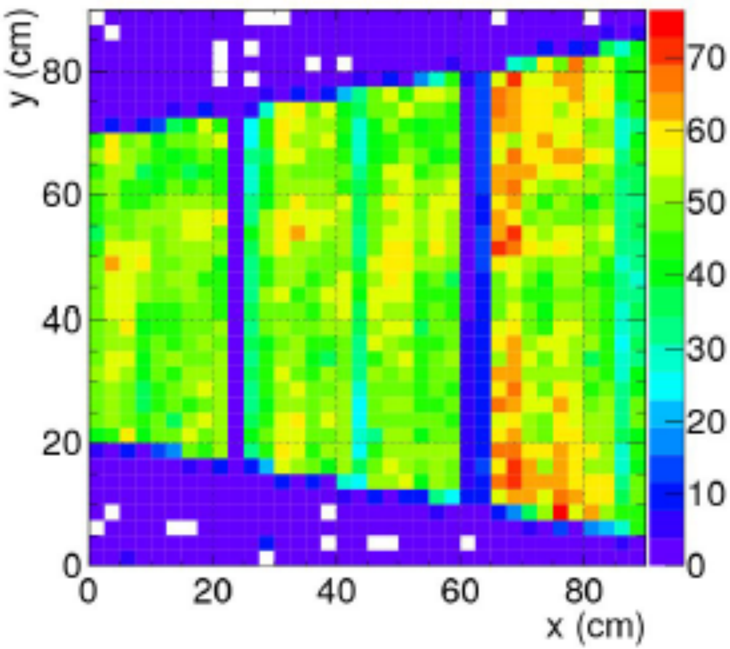


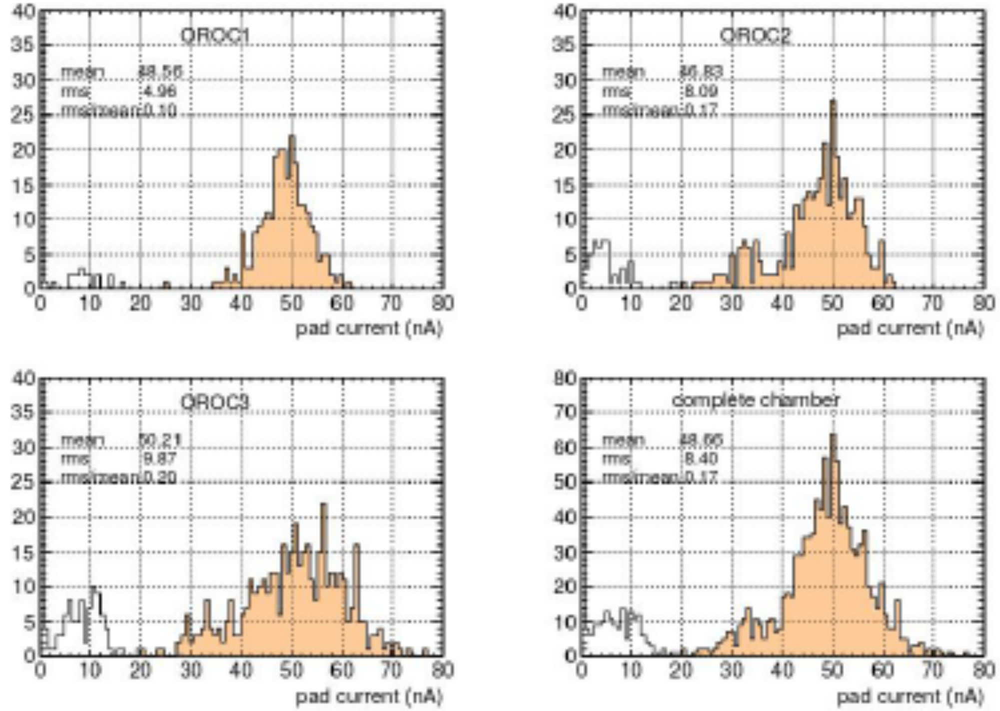


RMS < 15 %

Low-gain bins not included in 1D distribution
- spacer
- measurement edges (non-active area)

GAIN MAP

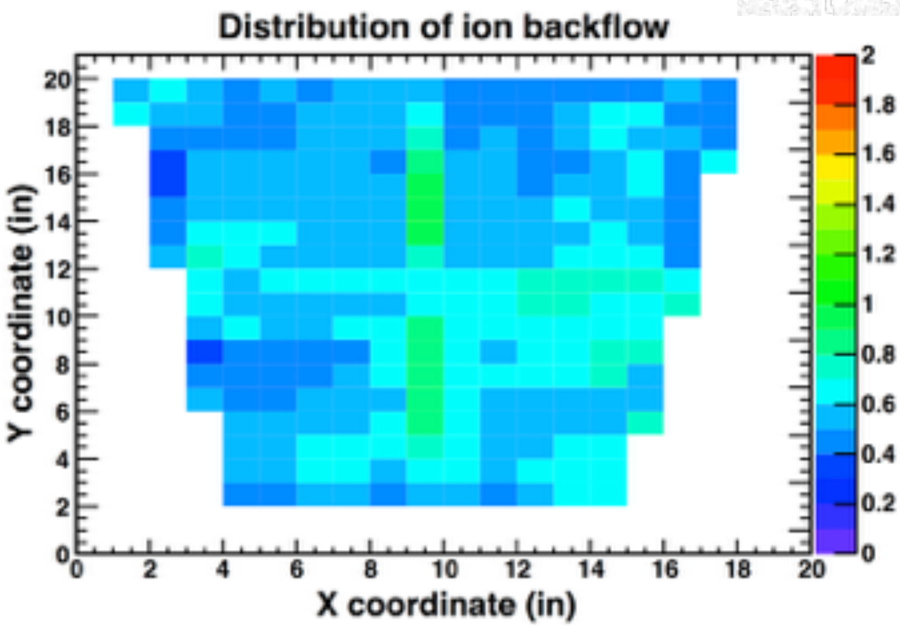


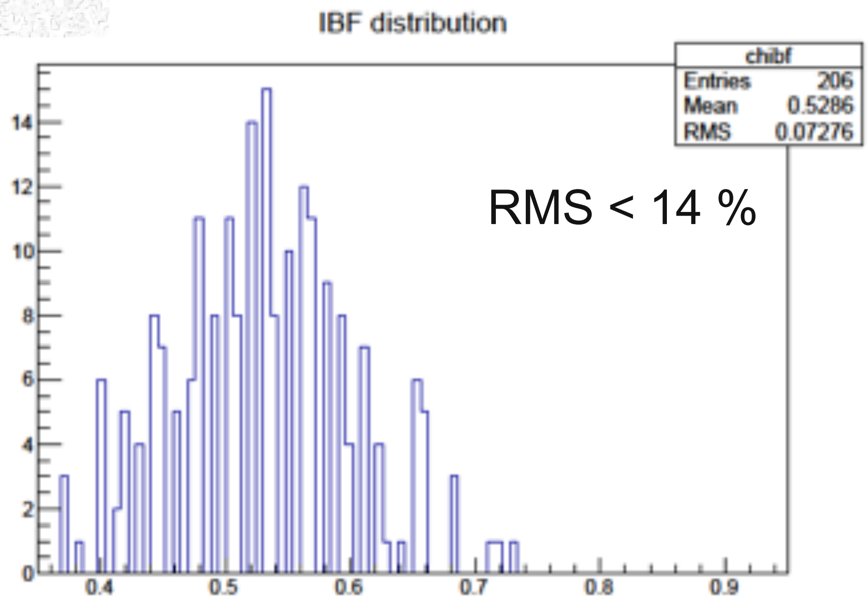


- Gain uniformity RMS ≤ 20%, within the specs
- OROC3 non-uniformity correlates with a single foil hole-size distribution – investigation ongoing
- More OROCs assembled and tested in the next few weeks

ION BACKFLOW

IROC





- ✓ Ion Backflow

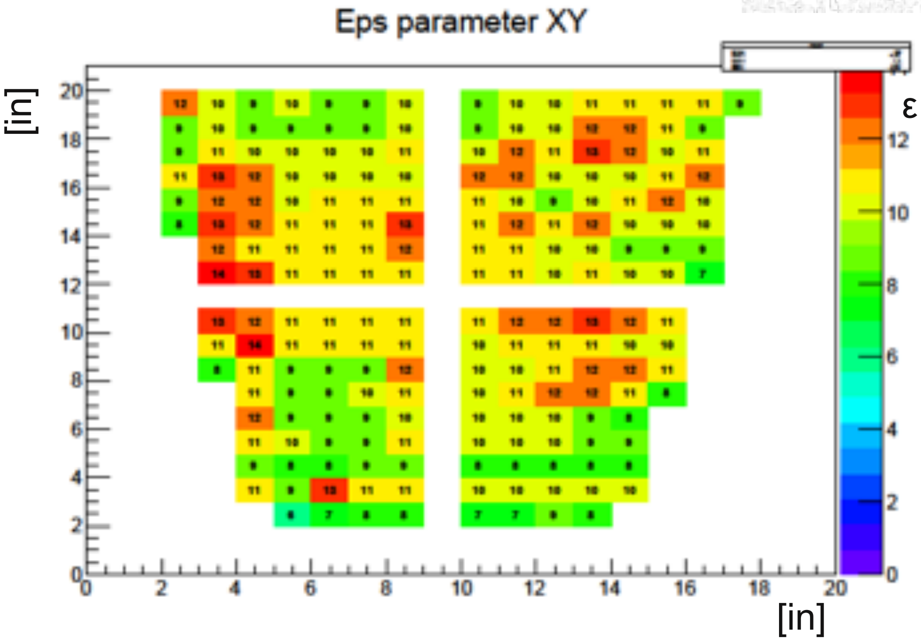
$$G_{eff} = I_{anode}/(e \times N_{ion} \times R)$$

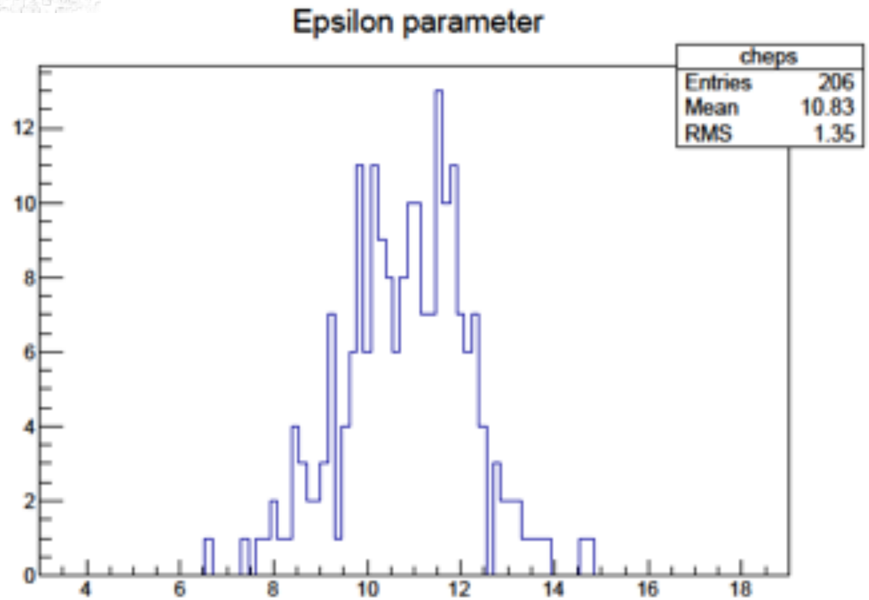
$$IB = I_{cathode}/I_{anode} = (1+\varepsilon)/G_{eff}$$

- ✓ Performance within specs. *IB* < 1 %
- ✓ Mean value in agreement with IBF < 0.7% measured with 10x10 cm^2 GEMs at G_{eff} = 2000
- ✓ **For the final TPC performance (space charge distortions) → epsilon uniformity!**

IROC

EPSILON MAP





✓ Epsilon proportional to the cathode current:

$$G_{eff} = I_{anode}/(e\times N_{ion}\times R)$$

$$IB = I_{cathode}/I_{anode} = (1+\varepsilon)/G_{eff}$$

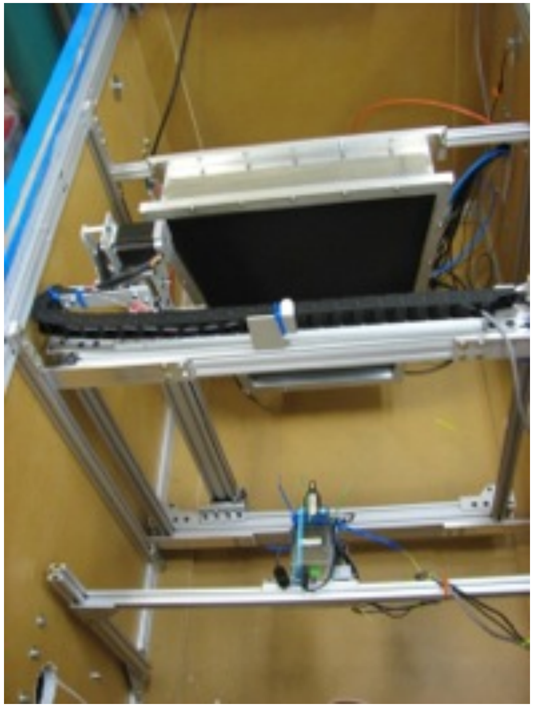
$$\boldsymbol{\varepsilon = I_{cathode}/(e\times N_{ion}\times R) - 1}$$

✓ Performance within specs:

- **gain uniformity RMS < 20%; epsilon RMS < 20%**

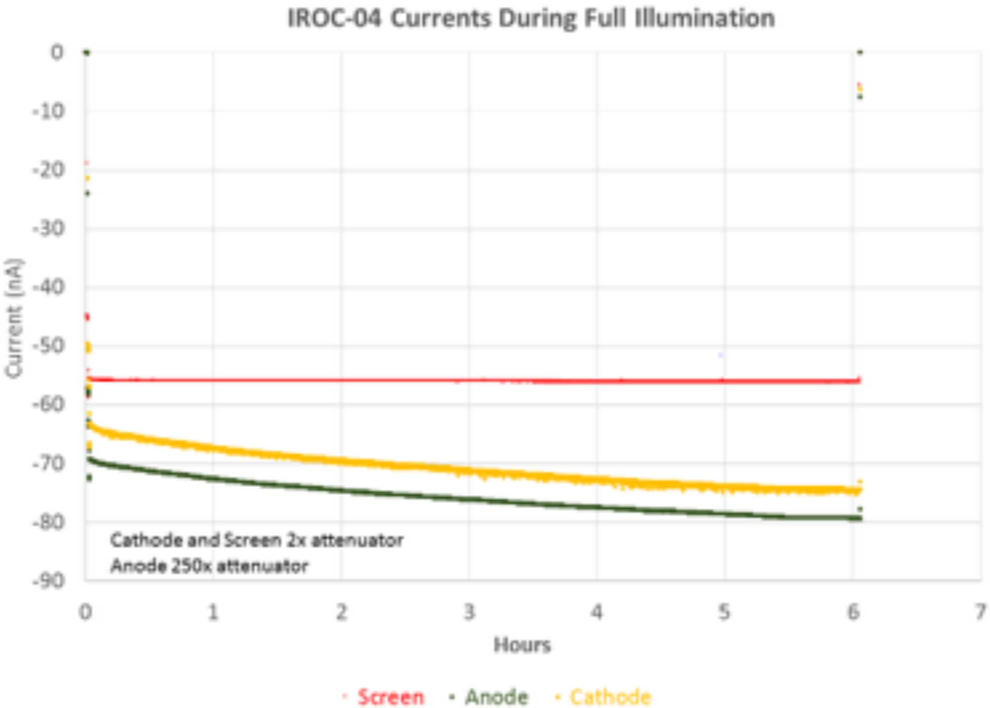
- **The calibration procedure has been demonstrated to work for effective non-uniformities of ε ~25%**

FULL IRRADIATION WITH X-RAYS



- Induce 10 nA/cm^2 current (expected in Run 3) at the pad plane after amplification G = 2000 for 6h
- Cathode/Anode current read with pA-meter

- Cathode/anode currents go directly to zero after X-ray off
- No energy resolution deterioration after the test
- Leakage current of all foils <0.5 nA after the test
- **no discharge recorded**



COMMISSIONING PROCEDURE

- Well established acceptance criteria
- Similar setups in all three assembly sites (Uni Yale, GSI Darmstadt, HPD Bucharest)
- Possible to assemble and commission 2-3 IROCs/month and 4 OROCs/month

- Acceptance criteria upon arrival at CERN:
    - Capacitance, resistance measurements
    - Leakage current at 350 V in dry gas
    - Full voltage in dry gas
    - Part of the chambers will be tested at LHC

SUMMARY AND OUTLOOK

ALICE TPC will be upgraded for RUN 3 to operate at 50 kHz rate in Pb-Pb collisions

No gating and continuous readout with GEMs

Extensive R&D leads to the 4-GEM configuration, fulfilling all requirements:

- Low Ion backflow
- Good energy resolution
- Low discharge rate
- Gain stability and uniformity

EDR to PRR Phase: I hope I could show you a bit of the challenges we had during this phase

Full production started. 25% ROCs produced until January 2018

ROC production/qualification on schedule, until Q3.2018

OROC at LHC running stable. More chambers to be tested in the upcoming months

LHC Long Shutdown 2 in 2019-2020: chamber and FEE installation, commissioning

Backup

00:00 → 00:20 1. Chamber body assembly ⏱20m
body assembly 27...

00:20 → 00:40 2a. HV cables and HV plugs assembly ⏱20m
Feedthroughs 27.0...

00:40 → 01:00 2b. Padplane test ⏱20m
padplane 2702201...

01:00 → 01:20 3. Working with GEMs
Savoir Vivre 27.08.2...

01:20 → 01:40 4. Optiguard frame installation
optiguard 27.08.20...

01:40 → 02:00 5. GEM packing/unpacking
Packing-Unpacking ...

02:00 → 02:20 6. Coarse optical check
coarse optical chec...

02:20 → 02:40 7. HV test
GEM HV test 23.10...

02:40 → 03:00 7a. HV test in the PCB wokrshop
GEM HV test in PC...

03:00 → 03:20 8. Optical scanning
GEM_OSS_test_v1...

03:20 → 03:40 9. GEM frame assembly
frame assembly 27...

03:40 → 04:00 10. GEM framing
gem framing 27.08...

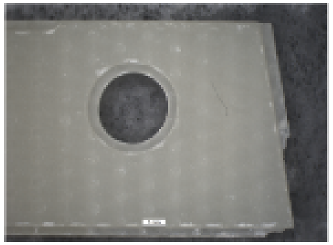
04:00 → 04:20 11. ROC assembly
ROC assembly 23.1...

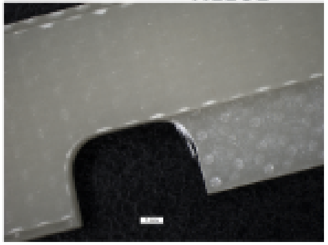
04:20 → 04:40 12. ROC commissioning ⏱20m
ROC commissionin...

04:40 → 05:00 13. ROC acceptance ⏱20m
ROC acceptance 28...

FRAME ASSEMBLY

FRAME LEDGES CLEANING

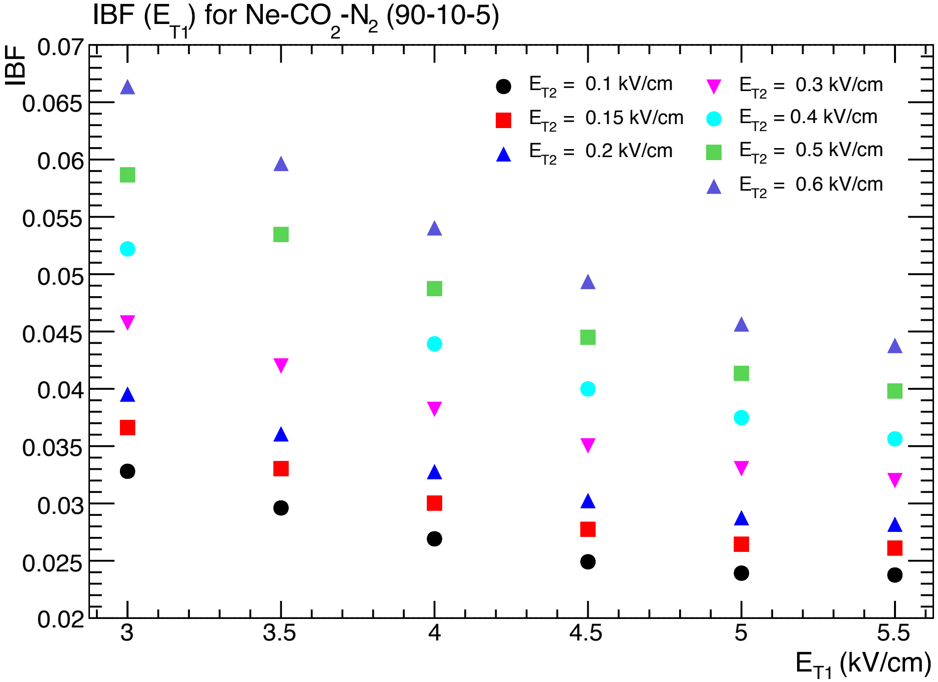


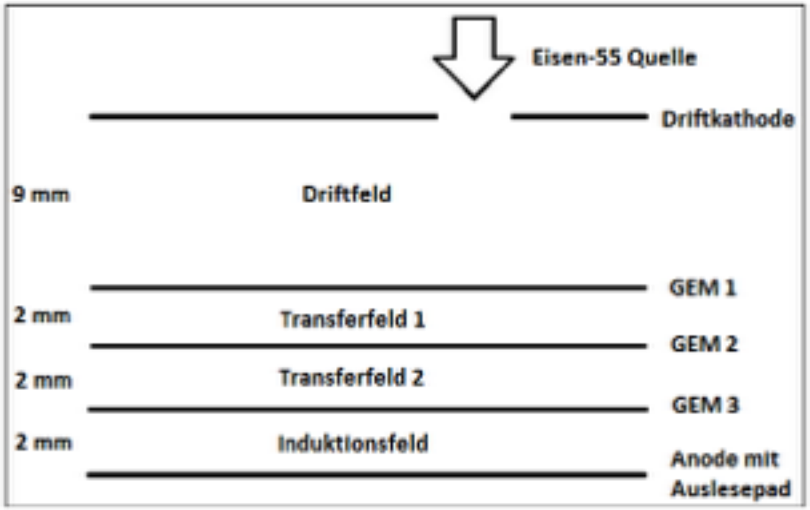


1. Check ledges under the microscope
2. Document possible damages
3. Remove overhanging glass fibers with sand paper (see picture)
4. Clean in an ultrasonic bath for at least 5 minutes. For example:
    - Bath 1 with isopropanol for pre-cleaning – 5' (or pre-clean with iso-propanol manually)
    - Bath 2 with isopropanol for final cleaning – 3'-5' and let isopropanol drain
    - Bath 3 with distilled water – 3' and let water drain
5. Blow dry with nitrogen
6. Check ledges again under the microscope
7. Put ledges into the dry cabinet. Leave them (at least) over night for drying before the final assembly.

Limit of a triple GEM setup

CERN-LHCC-2013-020





Limitations of a triple GEM setup

Asymmetric field configuration can be repeated in a GEM stack !

$E_{drift} < E_{T1}, E_{T2} < E_{ind}, \Delta U_{G1} < \Delta U_{G2} < \Delta U_{G3}$

- Ion Backflow was measured with triple GEM stack. Best value achieves was around 2.5 % at a gain of 2000 $\rightarrow \epsilon \sim 50$
- Asymmetric field configuration separates Gain of GEM_3 from Gain of GEM_1 + GEM_2 $\rightarrow$ higher discharge probability

Ion trapping with GEMs

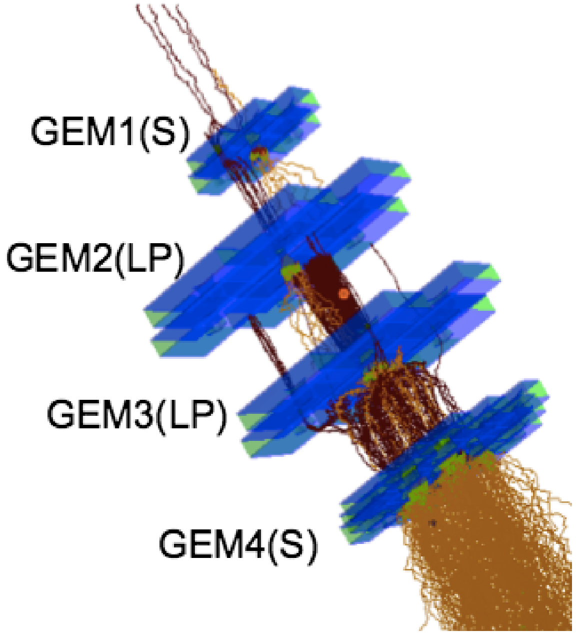
Electron transport properties for IB optimised HV settings

ε_{coll} = collection efficiency

ε_{extr} = extraction efficiency

M = gas multiplication factor

$G_{eff} = \varepsilon_{coll} \times M \times \varepsilon_{extr}$ = effective gain



	ε_{coll}	$n_{e,in}$	M	n_{e-ion}	ε_{extr}	$n_{e,out}$	G	$n_{ion,back}$	fraction of total IBF (sim.)	fraction of total IBF (meas.)
GEM1 (S)	1	1	14	13	0.65	9.1	9.1	3.6 (28%)	40%	31%
GEM2 (LP)	0.2	1.8	8	12.7	0.55	8	0.88	3.3 (26%)	37%	34%
GEM3 (LP)	0.25	2	53	104	0.12	12.7	1.6	1.3 (1.3%)	14%	11%
GEM4 (S)	1	12.7	240	3053	0.6	1830	144	0.84 (0.03%)	9%	24%
Total				3183		1830	1830	9 (0.28%)		

Ion trapping with GEMs

ALICE universitätbonn

Electron transport properties for IB optimised HV settings

ε_{coll} = collection efficiency

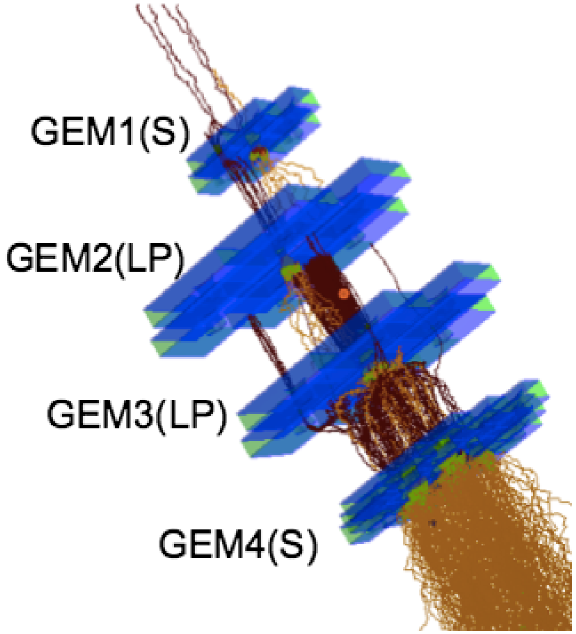
ε_{extr} = extraction efficiency

M = gas multiplication factor

$G_{eff} = \varepsilon_{coll} \times M \times \varepsilon_{extr}$ = effective gain

$n_{e\text{-}ion}$ = number of produced e-ions pairs

$n_{ion,back}$ = number of ions drifting back into the drift volume (ε)



$$IB = (1+\varepsilon)/G_{eff}$$

	ε_{coll}	$n_{e,in}$	M	n_{e-ion}	ε_{extr}	$n_{e,out}$	G	$n_{ion,back}$	fraction of total IBF (sim.)	fraction of total IBF (meas.)
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Ion trapping with GEMs

Electron transport properties for IB optimised HV settings

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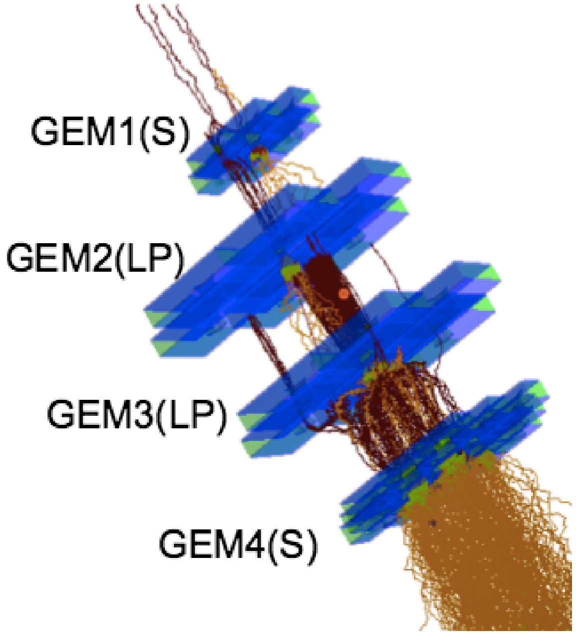
fraction of total IB: simulation vs. experiment



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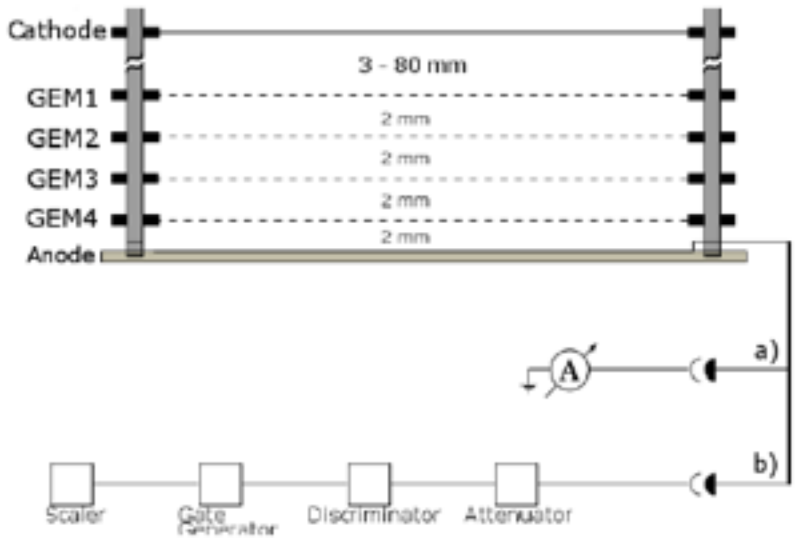
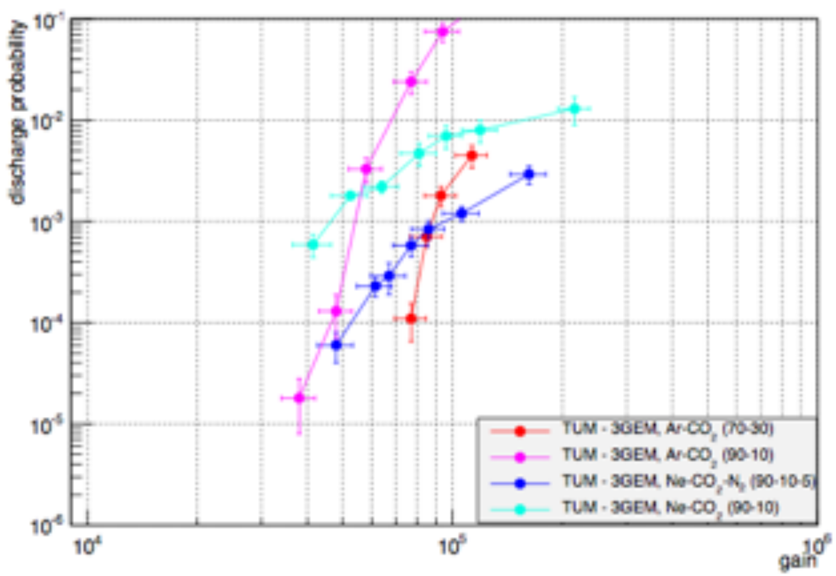
Total				3183		1830	1830	9 (0.28%)		

Triple GEM discharge probability
(S-S-S)

Triple GEM stack in standard settings





Optimisation of two parameters at the same time is conflicting:

- ^{220}Rn source, randomly distributed in the detector
- Measurement for TPC gas mixtures: Ar-CO_2 (90-10), Ne-CO_2 (90-10), Ne-CO_2-N_2 (90-10-5)
- Different slopes for Ar- and Ne-based gas mixture
- Clear influence of additional quencher

Goals of the QA

- **QA of the CERN workshop:**
  - Deliver GEM foils within specification agreed upon in collaboration document
- **Basic QA (CERN):**
  - Reject malfunctioning GEM foils at the earliest possible stage
  - Give fast feedback to the producer (CERN)
  - First reference (to identify e.g. defects coming from transport)
- **Advanced QA:**
  - Additional quality selection (hole size distributions, defect classification, gain uniformity prediction, long term stability)
  - Provide additional criteria to select the best foils
  - Provide additional information for the producer to improve/optimise the production process
- **Basic QA (Framing-, Assembly sites)**
  - Continuous quality monitoring
  - Shows if the basic HV stability is kept after each additional production step

Extended Traffic Light System

- **Red Light:**
  - GEM did not pass Basic QA (most important HV stability) → Reprocessed
  - Not (necessarily) permanent
- Orange Light
  - Basic QA passed → HV stability ok
  - Hole size distributions: both inner or outer holes show an asymmetry
  - Target design values for hole (inner outer deviate more than 10 μm)
- **Yellow Light:**
  - Basic QA passed → HV stability ok
  - Hole size distributions: either inner or outer holes show an asymmetry
  - Predicted gain spread larger than 10 % (RMS), long term HV stability acceptable
- **Green Light**
  - Passed all basic and advanced QA criteria
  - Basic HV stability is kept after all processing steps

Advanced QA consists of:

- High definition optical scan including the determination of 1-dim and 2-dim hole size distributions and map of optical defects
- Gain uniformity measurements of statistically significant sample of GEM foils
- Correlation of gain uniformity and hole size distribution is used to predict the gain uniformity of each GEM foil
- $I_{leakage}$ measurements for at least five hours, data is stored in a leakage current file with common data format
- Determination and classification of defects (in preparation)

10	QA-B	I_leak histo data	01_O2-G1-001_N2_corrected.txt	evaluate	2	2017-08-11 16:22:15	no comment | avg all segments 10.7, sparks: 0 ok	Viktor	file
12	12	hole size distribution	O2-G1-001_1D.txt	evaluate 1D		2017-06-09 11:44:02	no comment | avg all segments 10.7, sparks: 0	Marton	file txt
13	13	hole size data 2D	O2-G1-001_2D.txt	evaluate 2D		2017-06-09 11:44:43	no comment | avg all segments 10.7, sparks: 0	Marton	file txt
15	QA-A	long term leakage current data	O2-G1-001-20170504-15-42_sectors.txt	evaluate	2	2017-06-29 14:11:17	no comment | avg all segments 3.4, sparks: 0 sticky rolled after shorted sector, looks better although many sparks	Marton	file txt
20	20	frame glueing comment if not perfect (wrinkels?)							eq
25	25	quality	B		2	2017-06-10 23:01:47	Also slight problems from the HV, had to sticky roll it, but came back alive.	Marton	le C
submit		darker field: mouse hover for more explanations							

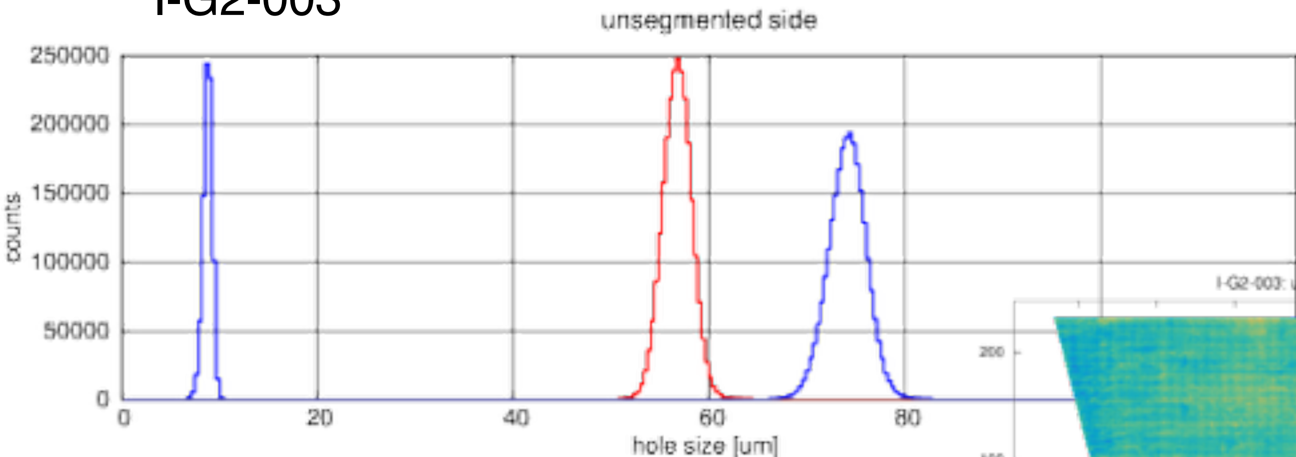
Advanced QA

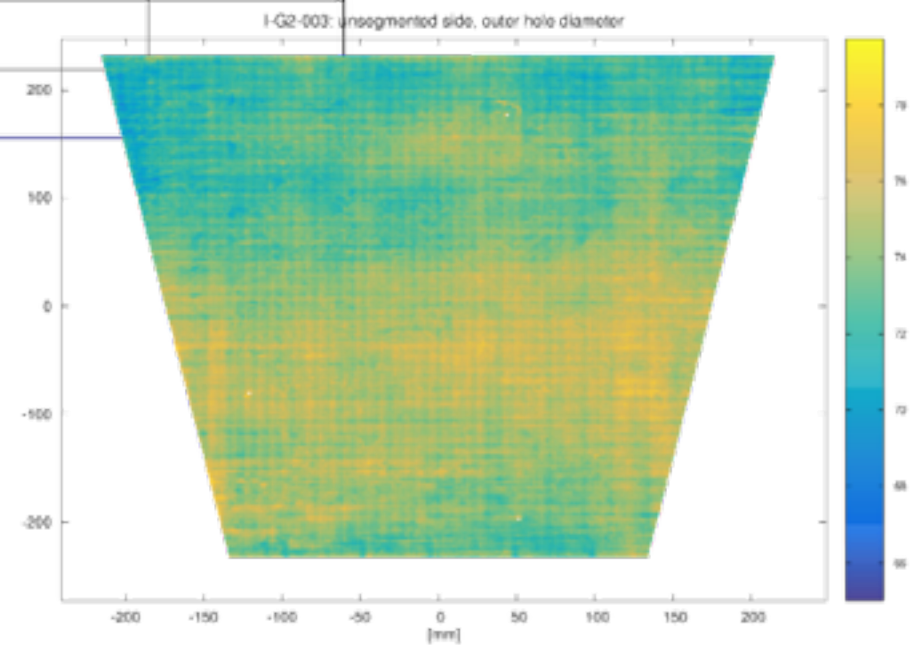
All values in µm

Green GEM foil:

Segmented Side				Unsegmented Side		
inner (RMS)	outer (RMS)	rim (RMS)		inner (RMS)	outer (RMS)	rim (RMS)
56.6 (1.54)	74.7 (1.54)	9.0 (0.58)		56.6 (1.57)	73.9 (1.94)	8.7 (1.94)

I-G2-003





- Long term I_{leak} ok
- Hole size distribution uniform
- Mean values of the inner, outer holes close to the target values

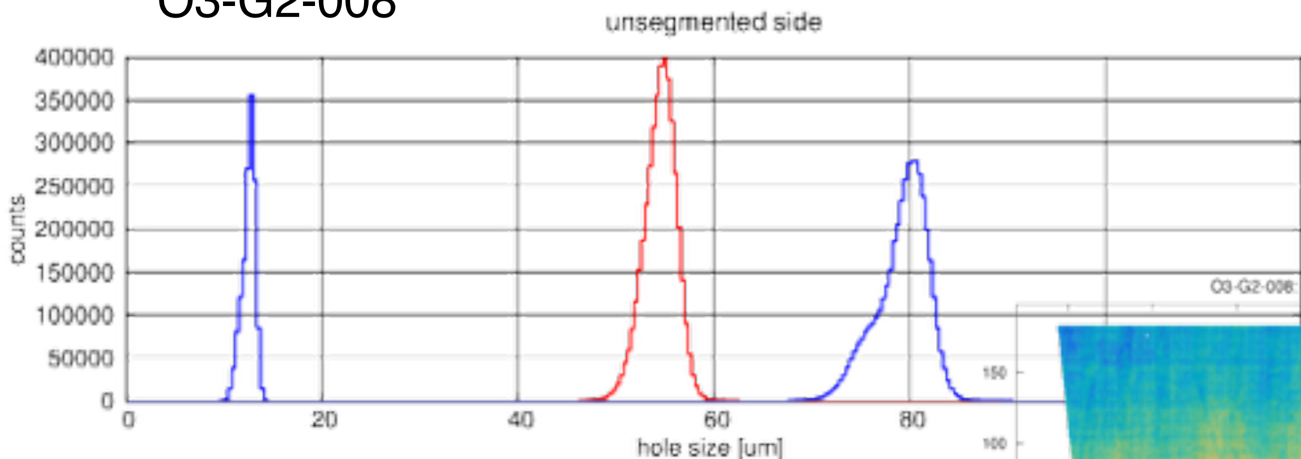
Advanced QA

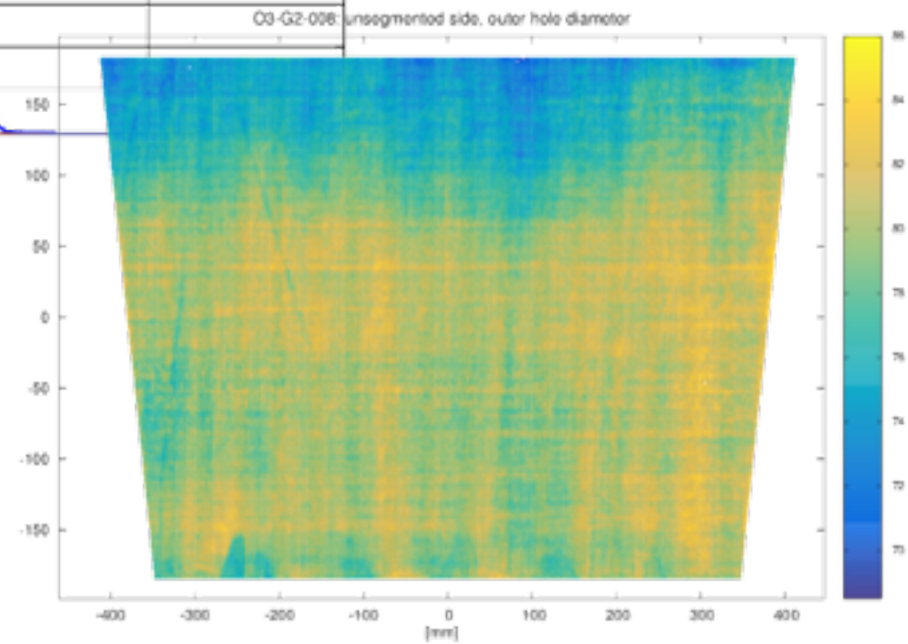
All values in µm

Yellow GEM foil:

Segmented Side				Unsegmented Side		
inner (RMS)	outer (RMS)	rim (RMS)		inner (RMS)	outer (RMS)	rim (RMS)
54.6 (1.72)	80.5 (1.57)	13.0 (0.49)		54.3 (1.67)	79.1 (2.64)	12.4 (0.68)

O3-G2-008





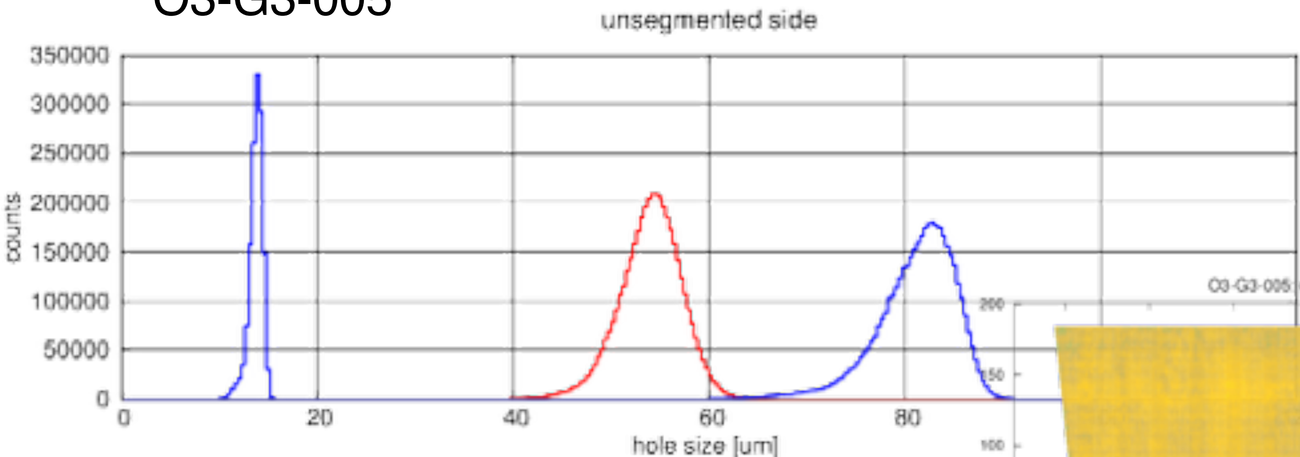
- Long term I_{leak} ok
- Hole size distribution not (always) uniform
- Mean values of the inner, outer holes within 5-10 µm of batch average

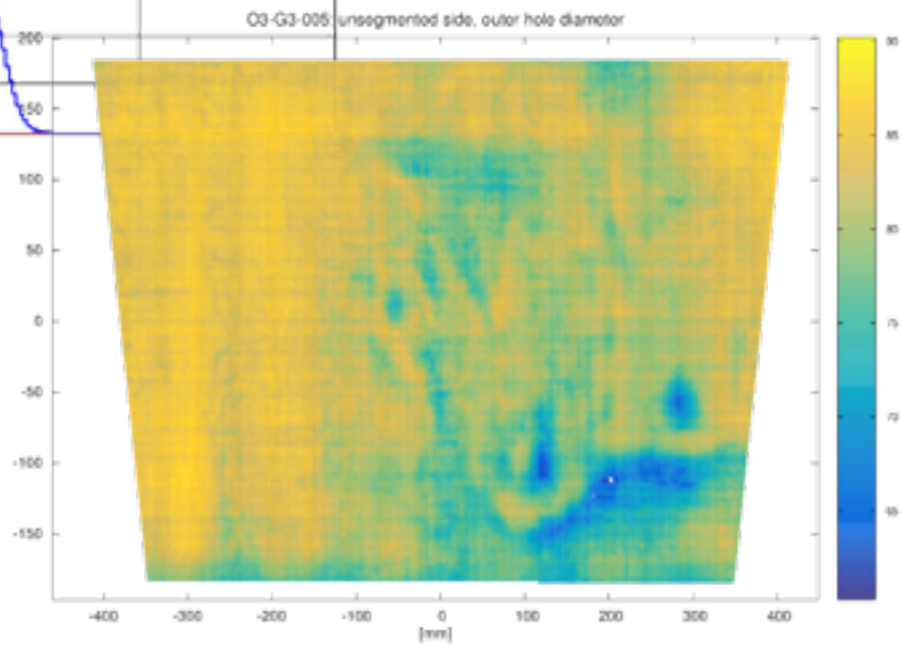
All values in µm

Orange GEM foil:

Segmented Side				Unsegmented Side		
inner (RMS)	outer (RMS)	rim (RMS)		inner (RMS)	outer (RMS)	rim (RMS)
53.9 (3.14)	77.3 (2.92)	11.7 (0.52)		53.8 (3.16)	81.0 (4.02)	13.6 (0.71)

O3-G3-005





- Long term I_{leak} ok
- Hole size distribution of segmented and unsegmented side not uniform
- Mean values of the inner, outer holes bigger than 10 µm of batch average

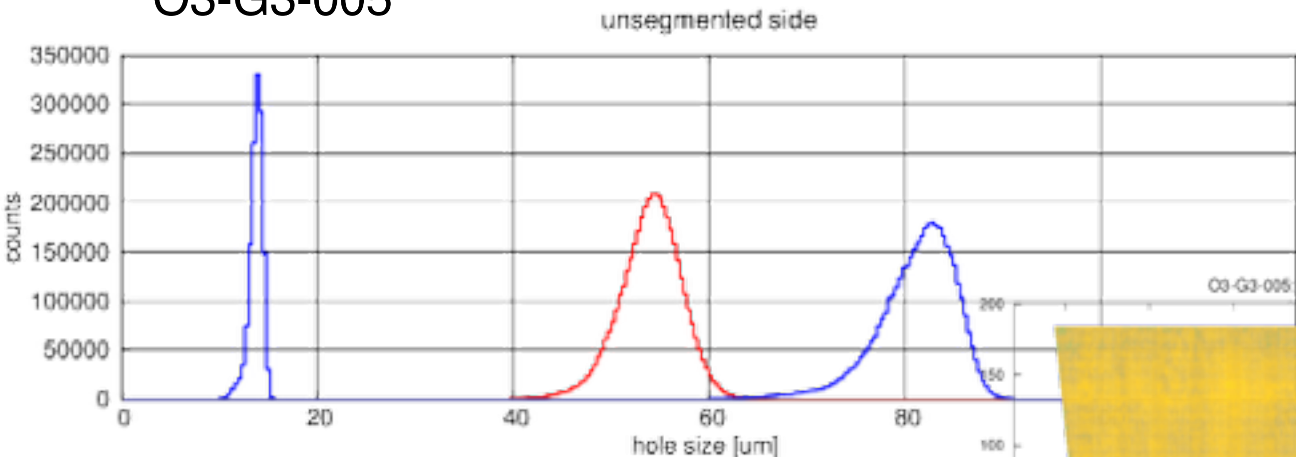
Advanced QA

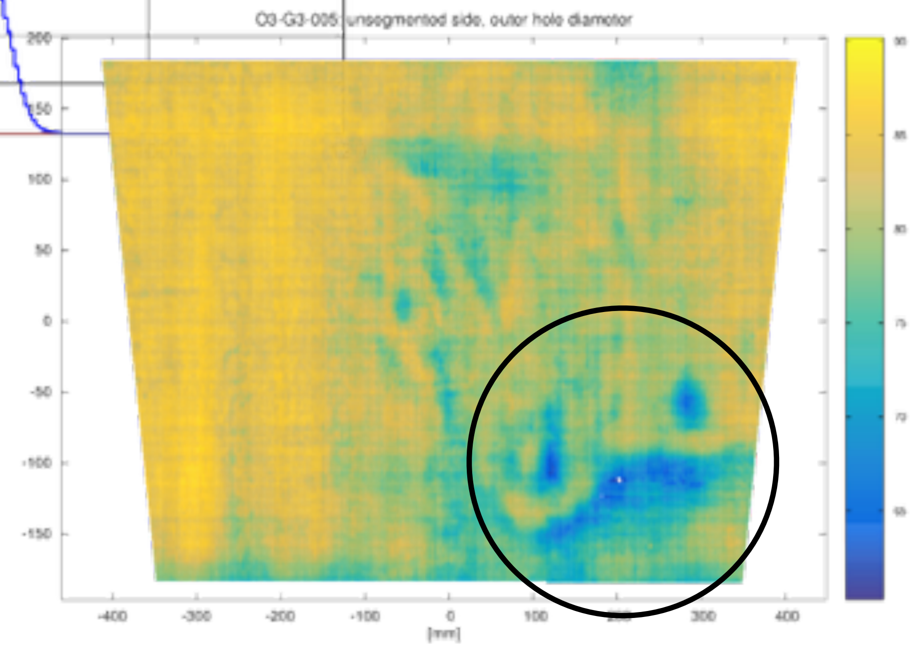
All values in µm

Orange GEM foil:

Segmented Side				Unsegmented Side		
inner (RMS)	outer (RMS)	rim (RMS)		inner (RMS)	outer (RMS)	rim (RMS)
53.9 (3.14)	77.3 (2.92)	11.7 (0.52)		53.8 (3.16)	81.0 (4.02)	13.6 (0.71)

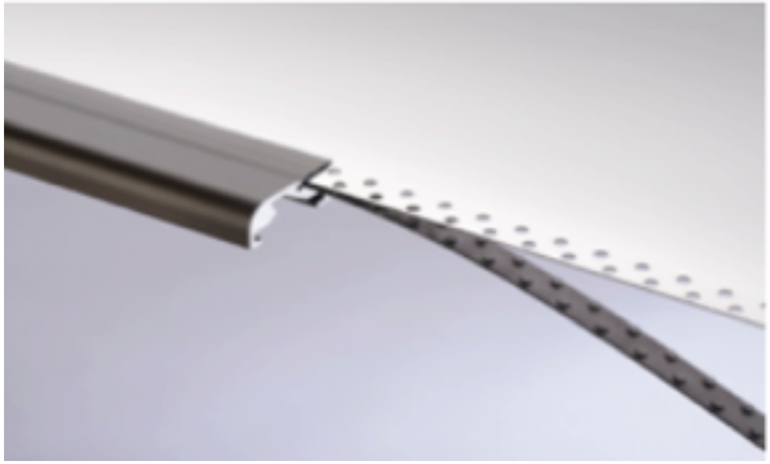
O3-G3-005



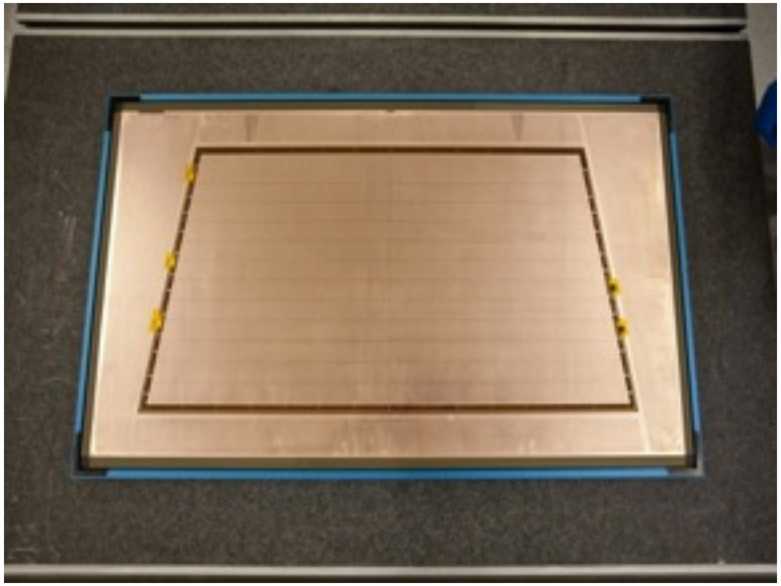


- Long term I_{leak} ok
- Hole size distribution of segmented and unsegmented side not uniform
- Mean values of the inner, outer holes bigger than 10 µm of batch average

GEM Framing



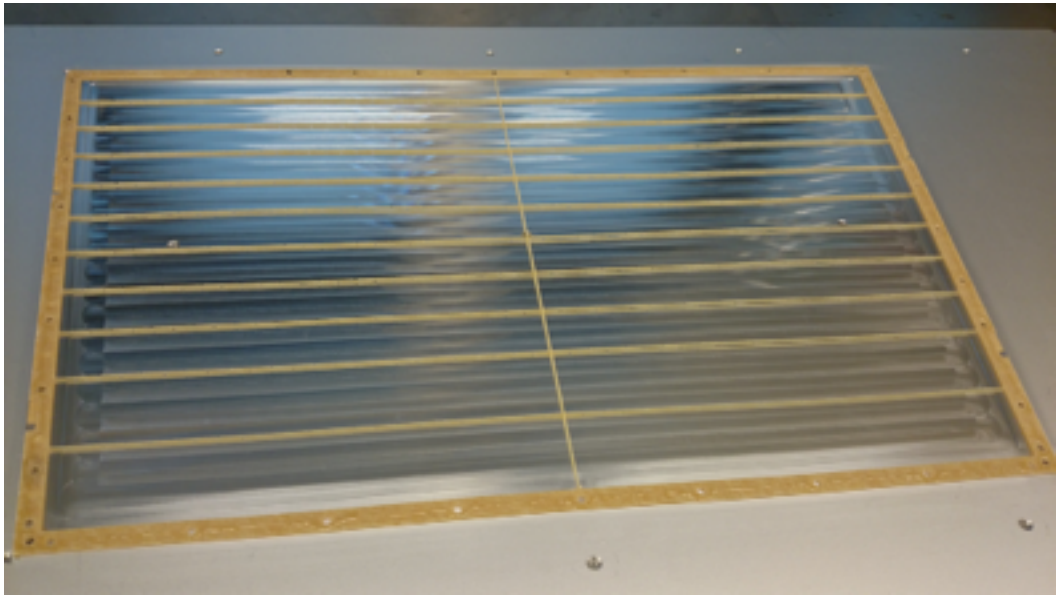
Optiguard® profile



Blue DEK frame with a stretched GEM

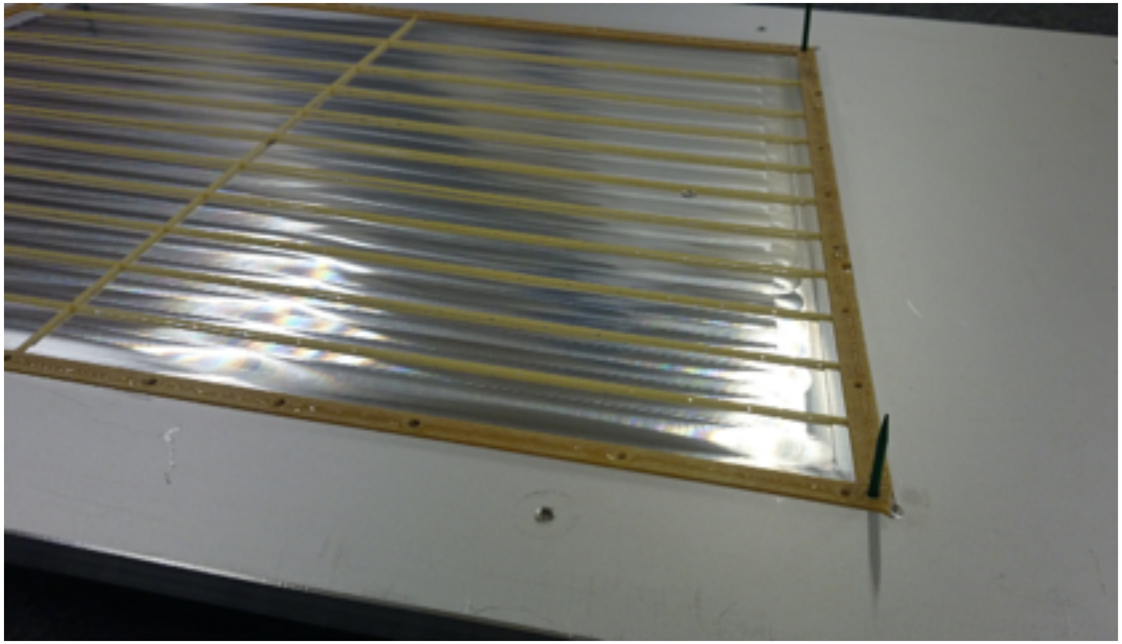
- Foil stretching by pneumatic DEK (Vectorguard®) frame produced by ASM Assembly.
- Foils equipped in aluminium profiles (Optiguard®)
- Foil in a profile is installed in the DEK frame
- By applying 0.5 MPa pressure DEK claws open allowing foil to be installed
- Releasing pressure closes DEK claws which stretch GEM
- DEK frame stretching force: **10 N/cm**

GEM Framing



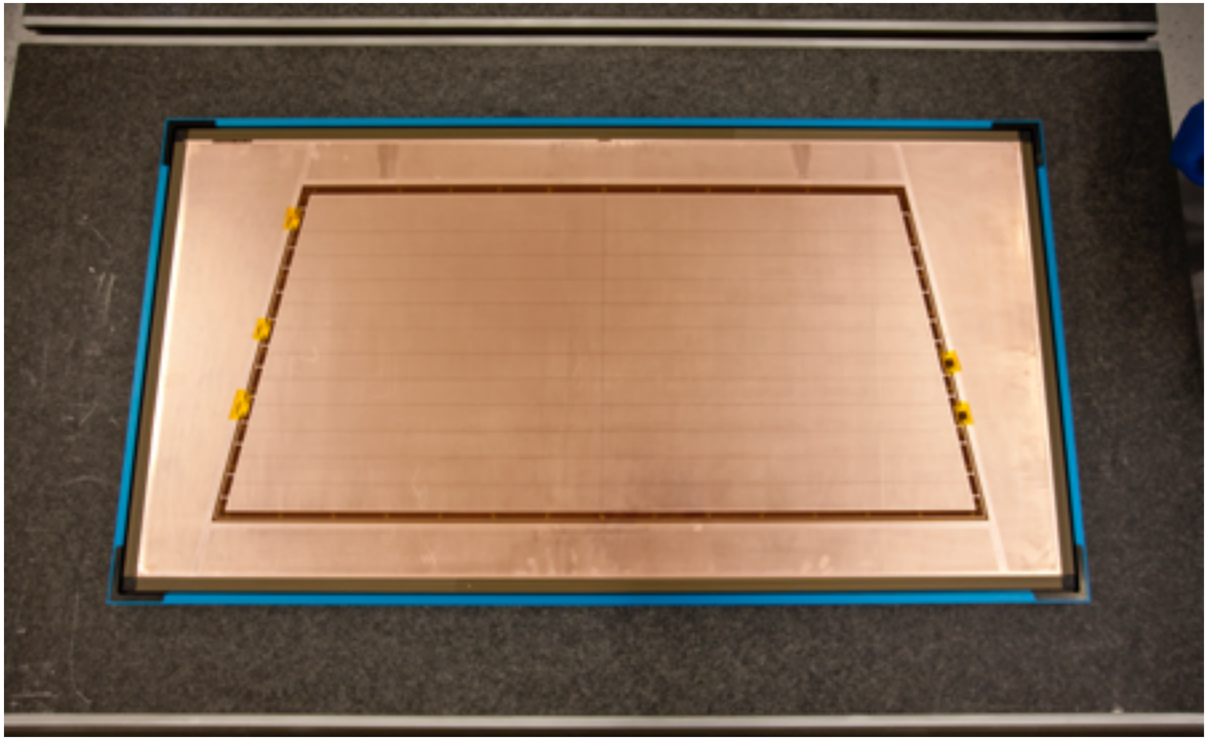
- Aluminum jig (platen) to precisely position a GEM frame.
- Glue is dispensed on a frame installed in its jig

GEM Framing



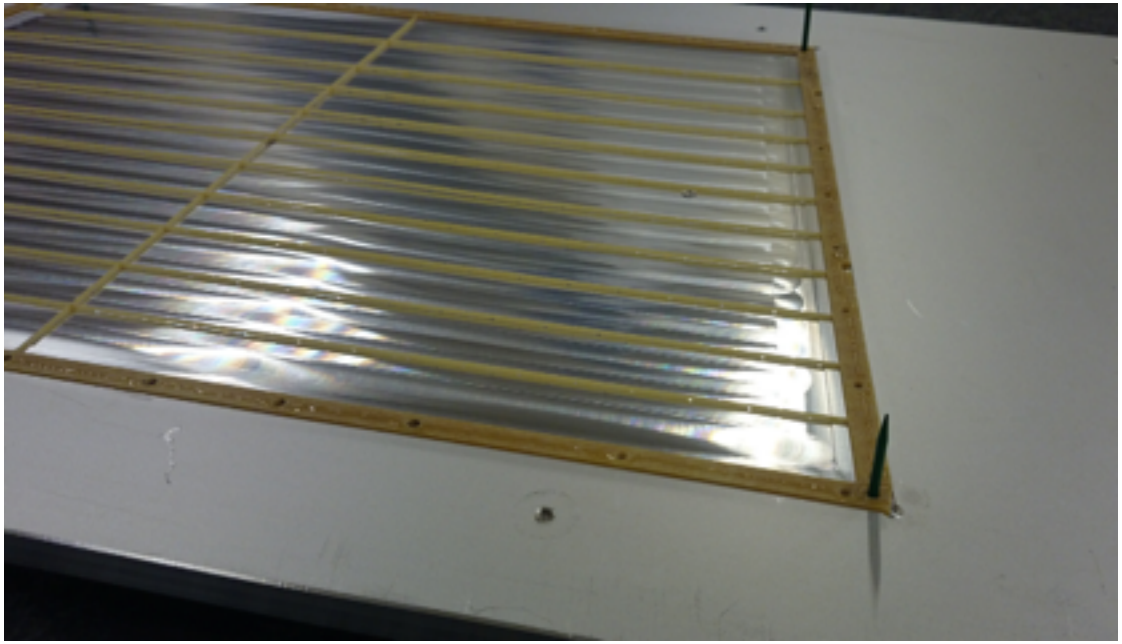
- Glue dispensed in a form of a thin line
- Groove in a middle of a frame to guide the tip
- Manual corrections possible “in-situ”
- Glue: ARALDITE 2011
- Install corner alignment pins

GEM Framing



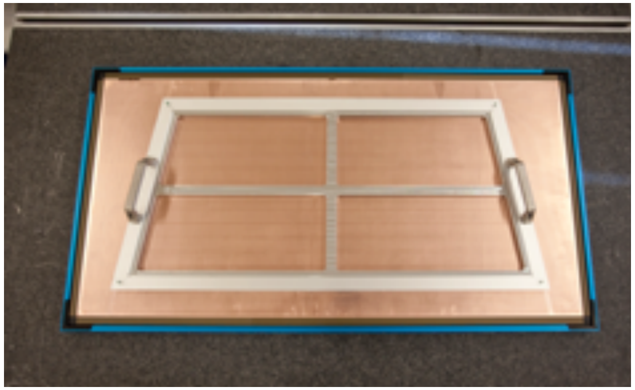
- Stretch a GEM foil and cover all mounting holes (HV flap cutouts) with a Kapton® tap

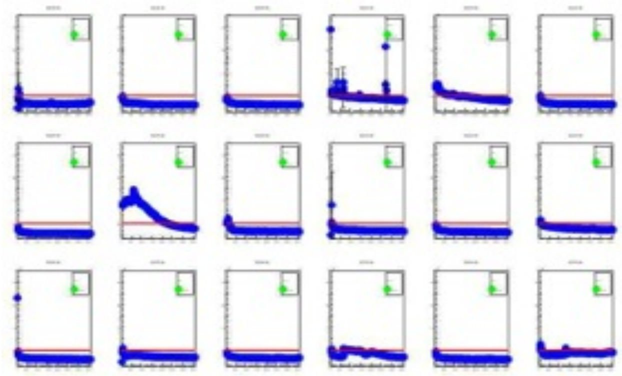
GEM Framing

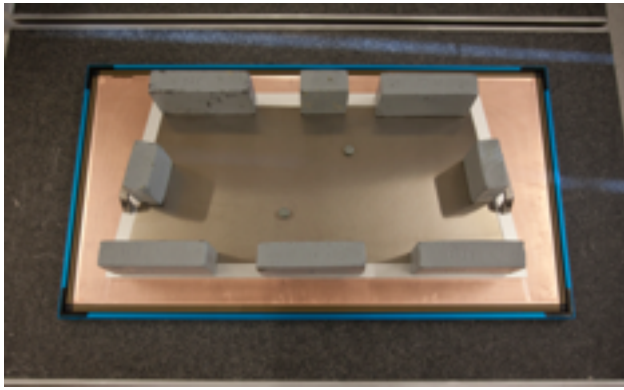


- Stretch a GEM foil and cover all mounting holes (HV flap cutouts) with a Kapton® tap
- Place GEM frame in its jig and apply glue
- Place a stretched foil on a GEM frame (alignment with corner pins)

GEM Framing







- Stretch a GEM foil and cover all mounting holes (HV flap cutouts) with a Kapton® tap
- Place GEM frame in its jig and apply glue
- Place a stretched foil on a GEM frame (alignment with corner pins)
- Put a top plate and press with weight