A Large Ion Collider Experiment

ALICE

LHC-ALICE実験における GEM-TPC高度化の開発と現状

郡司　卓

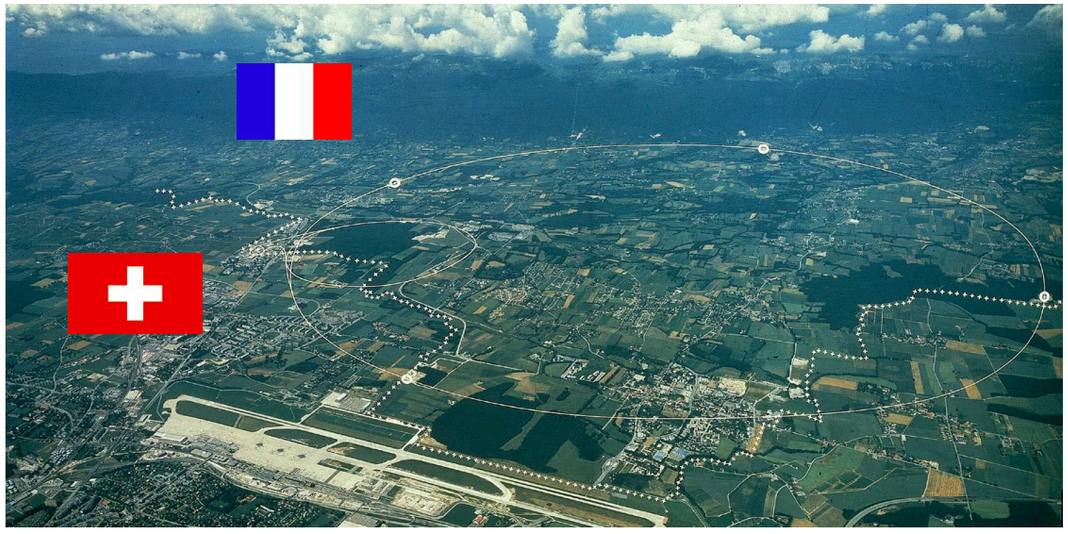
東大CNS

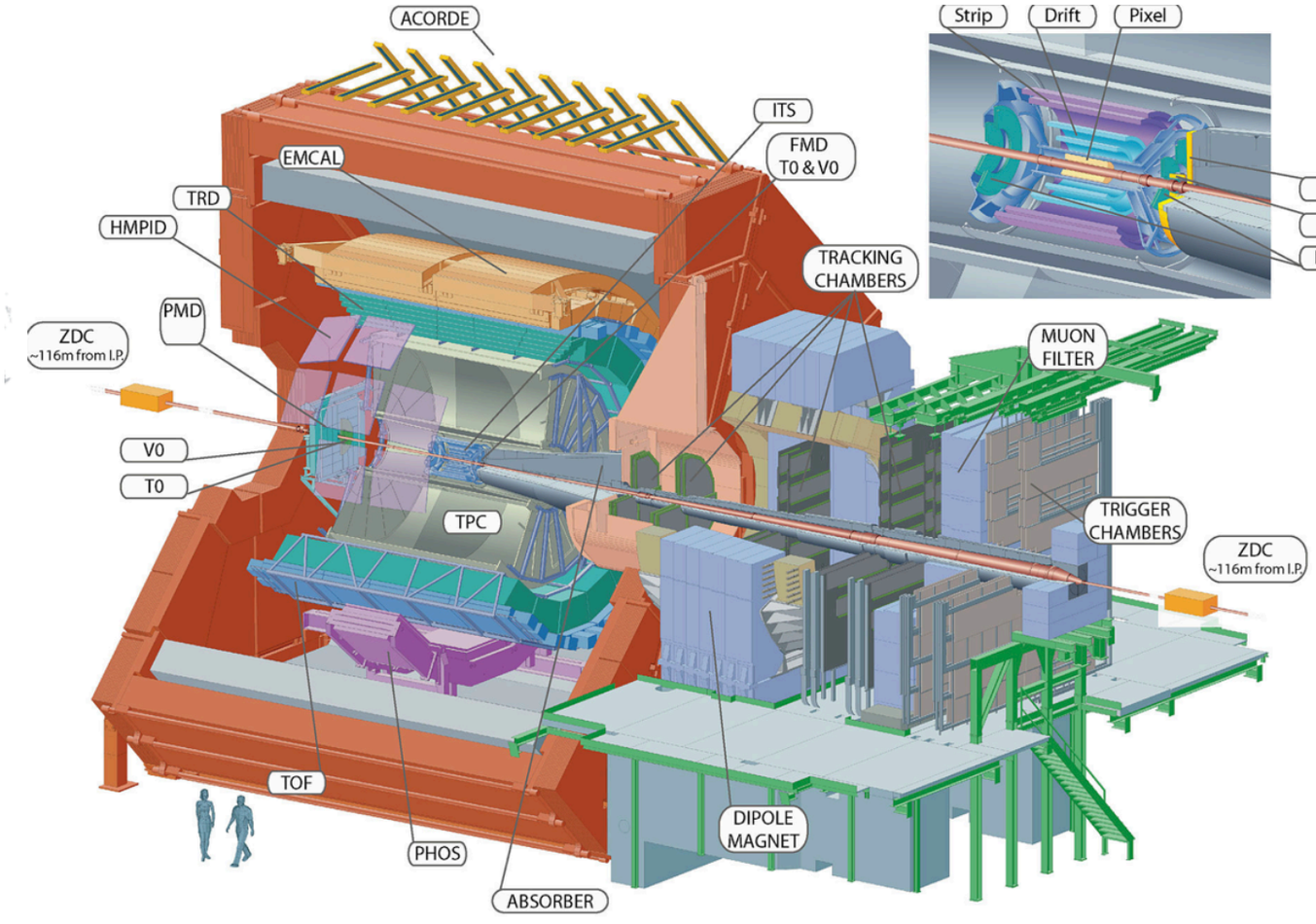
関連する過去の講演

- 第9回@長崎総合科学大学(2012)
  - 浜垣：GEM-TPC Project at LHC ALICE
- 第10回@京都大学(2013)
  - 山口：ALICE実験におけるGEM-TPC開発
  - 寺崎：Thick COBRA GEMによるイオンバックフロー抑制
- 第11回@東北大学(2014)
  - 郡司：LHC-ALICE実験MPGDを用いたTPC検出器開発の現状
  - 勇川：GEMとMICROMEGASを用いたイオンバックフローの研究
- 第12回@広島大学(2015)
  - 寺崎：LHC-ALICE実験TPC高度化の為の研究開発と量産準備状況

LHC-ALICE実験

- Large Hadron Collider (CERN) ：最高エネルギーの衝突型ハドロン加速器
- ALICE実験：高エネルギー重イオン衝突により、「クォーク・グルーオンプラズマの物性研究」を進める





40カ国、175機関、1975人の研究者

筑波大学、東京大学、広島大学、奈良女子大学、長崎総合科学大学

ALICE実験の測定器高度化(2019-2020)

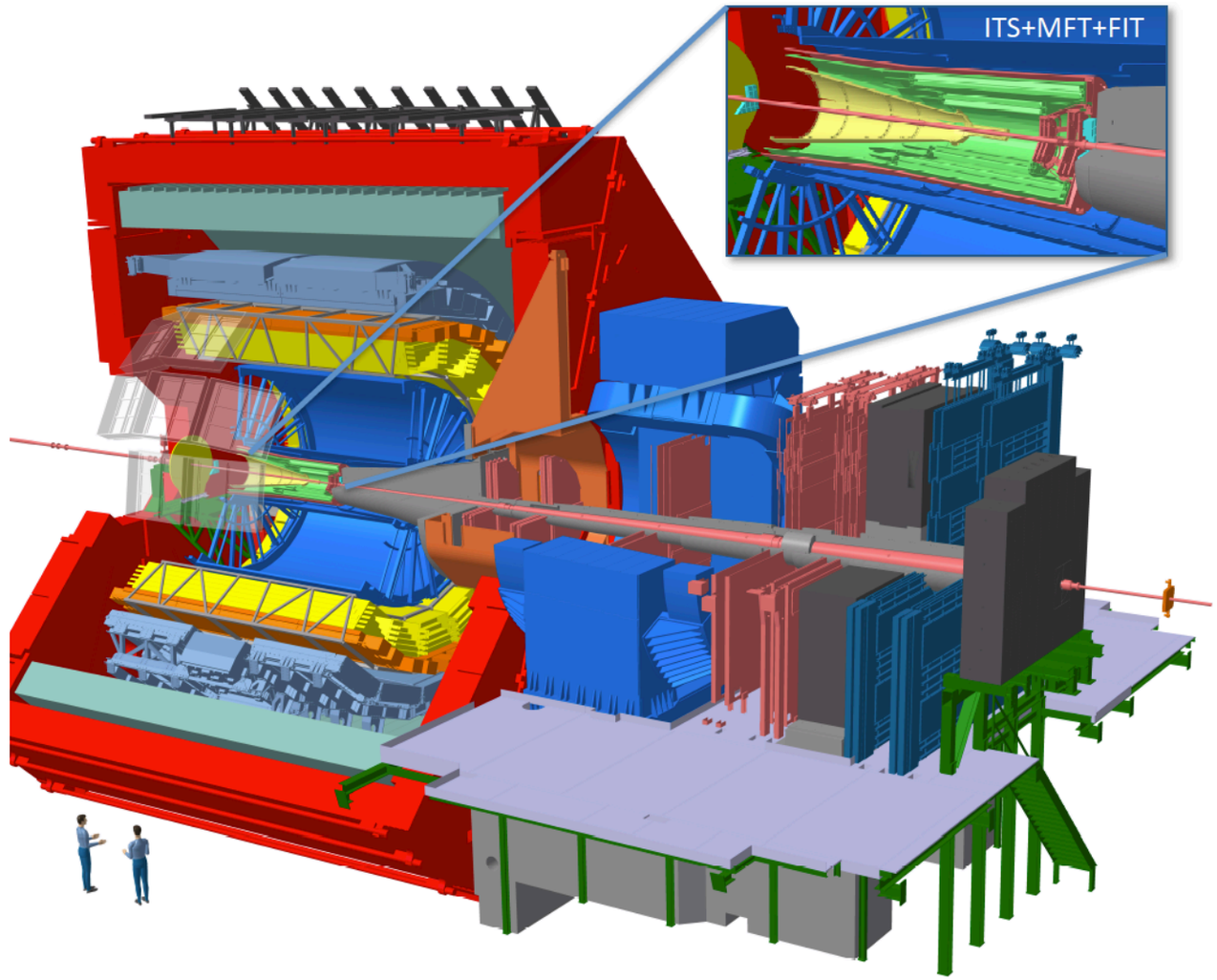
2021年以降のLHC Run3+Run4において、50kHzのPb-Pb衝突事象の全てを記録
→これまでのx100のデータを取得

中央シリコンピクセル検出器(ITS)
- ７層. MAPS技術を採用

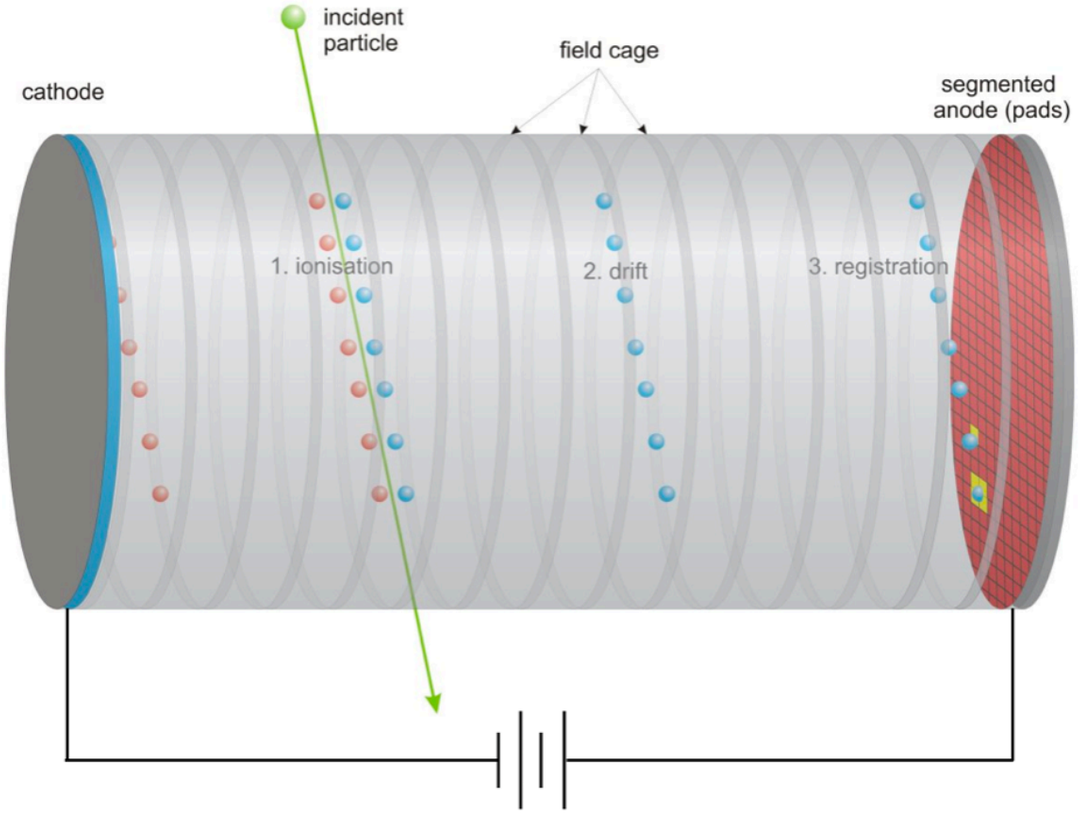
前方シリコンピクセル検出器(MFT)
- 5層. ITSと同じピクセルを採用

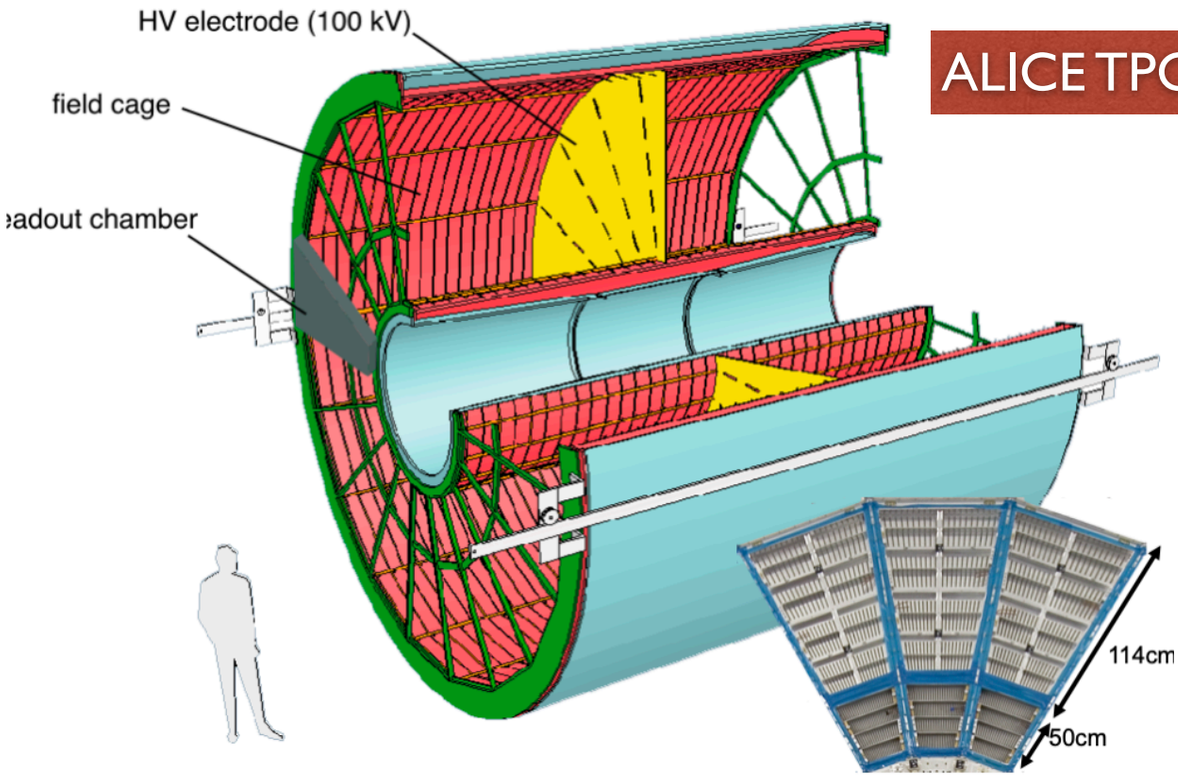
タイムプロジェクションチェンバー(TPC)
- wire増幅+gating grid → 3kHzが限界
- wire増幅からGEM増幅へ高度化
- GGなしの連続読み出し. 読出系も刷新

DAQ
- 50kHzのPb-Pbの全てを記録
- 生データ3.5 TB/sをオンラインで物理情報に再構成し圧縮する(100GB/s)

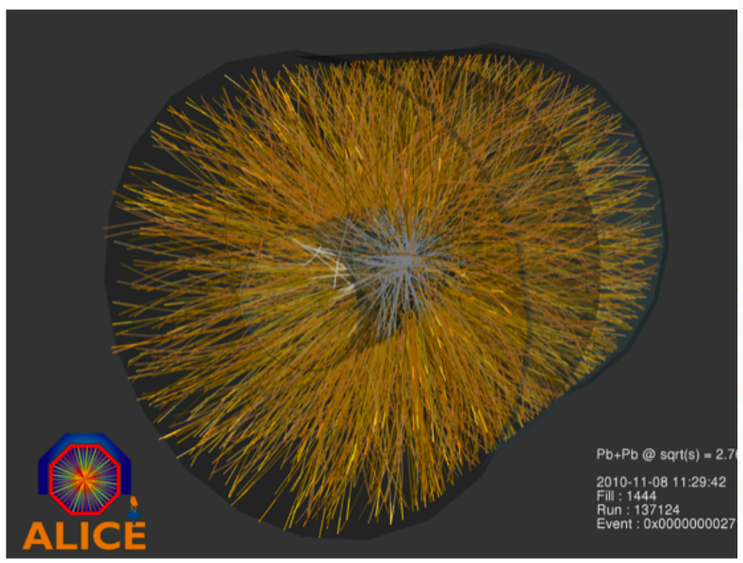


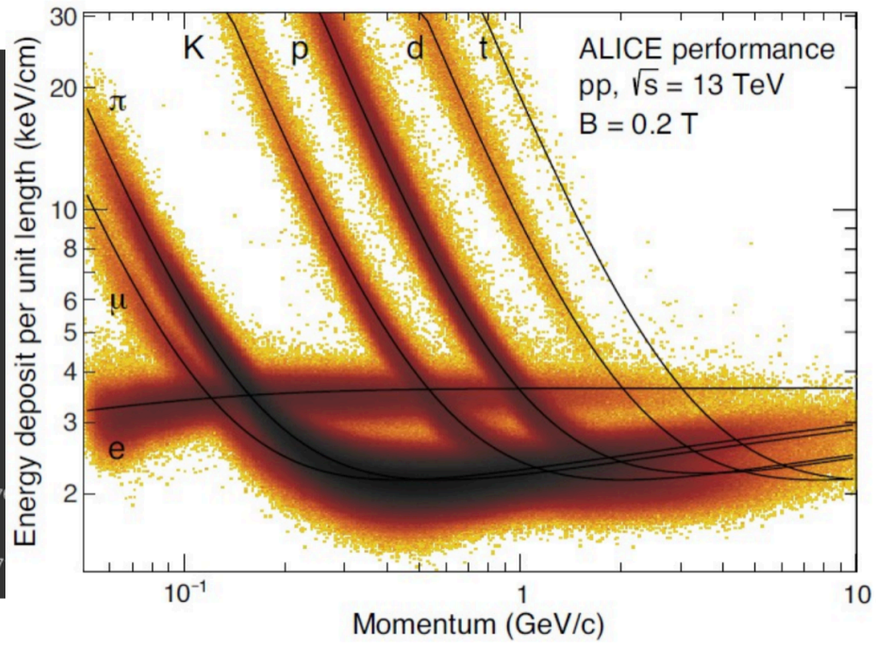
ALICE Time Projection Chamber





ALICE TPC



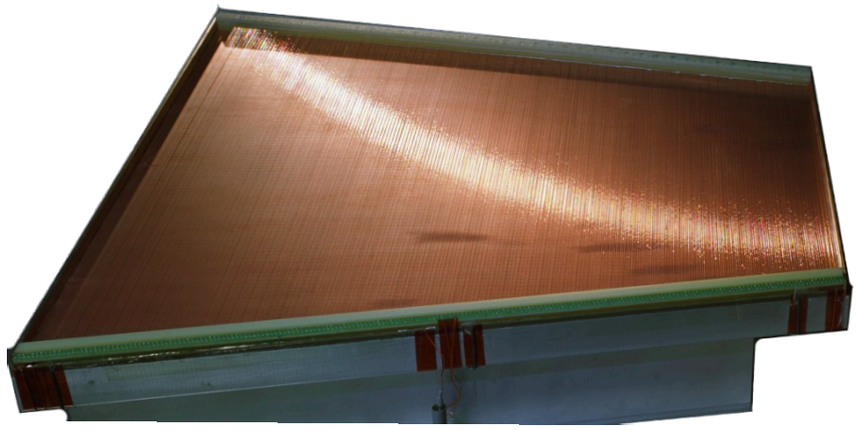


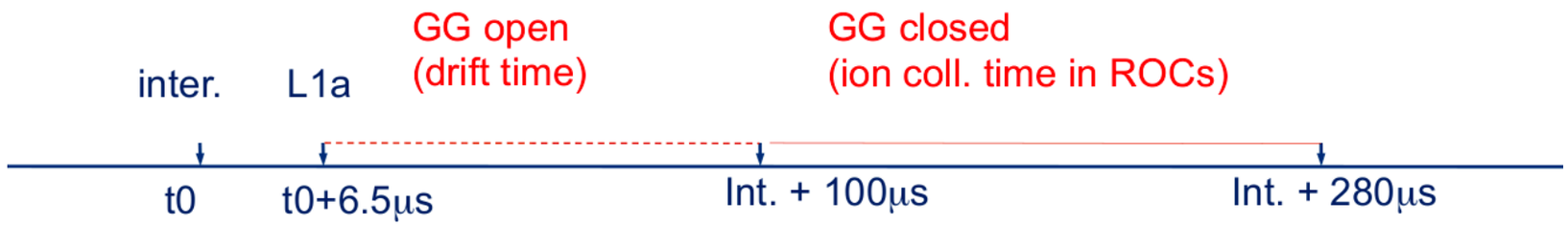
- Diameter = 5.6m, length=5.2m
- Gas = Ne-CO_2(-N_2), Ar-CO_2
- Drift field = 0.4 kV/cm
  - e diffusion ~ 0.2mm/1cm (in Ne)
  - e drift velocity ~ 2.6 cm/μs (in Ne)
- 72 MWPC readout chambers
  - Pad size : total 560k pads
    - Inner: 4×7.5 mm²
    - Outer: 6×10 mm²

M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001, Fig. 34.15

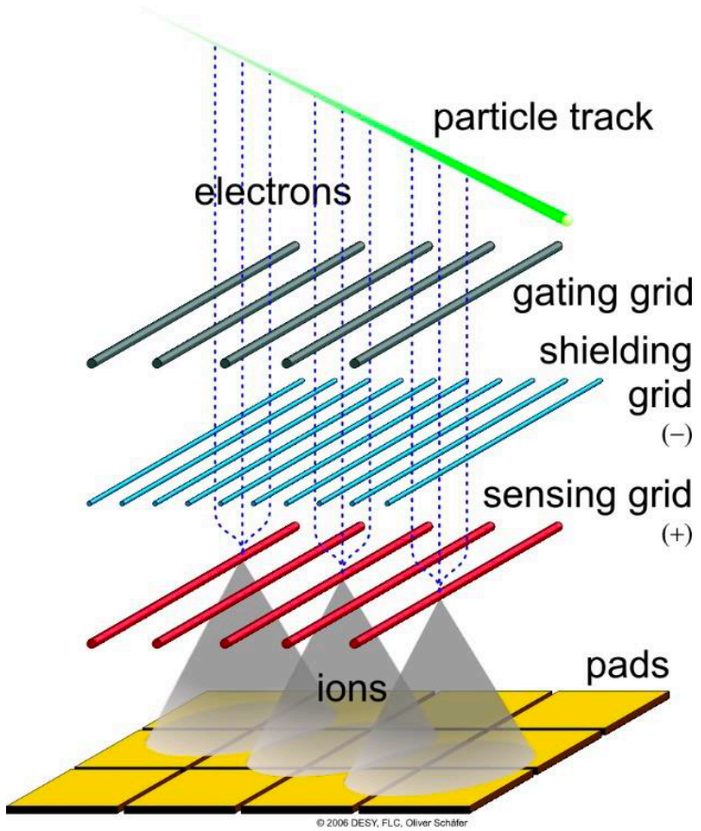
Operation of Gating Grid

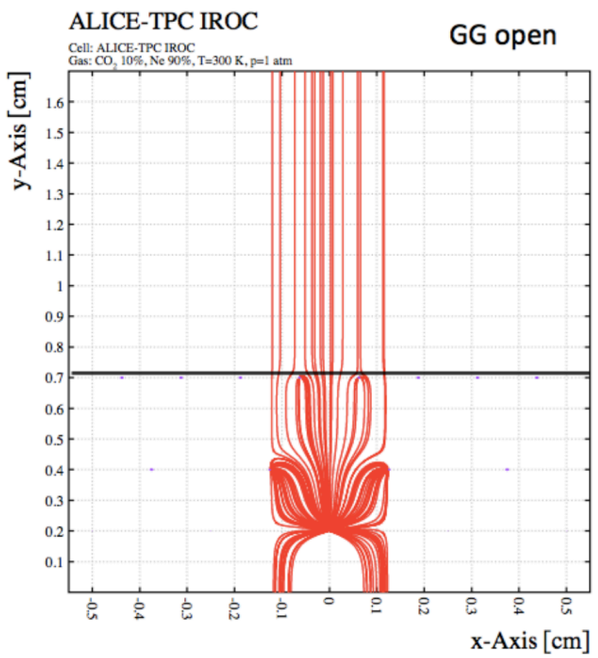
GG is employed to prevent ions from escaping into drift space (="ion backflow")

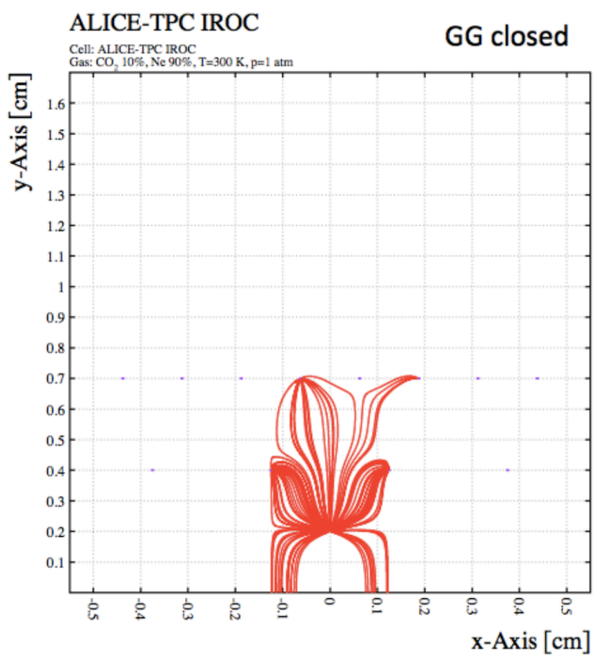




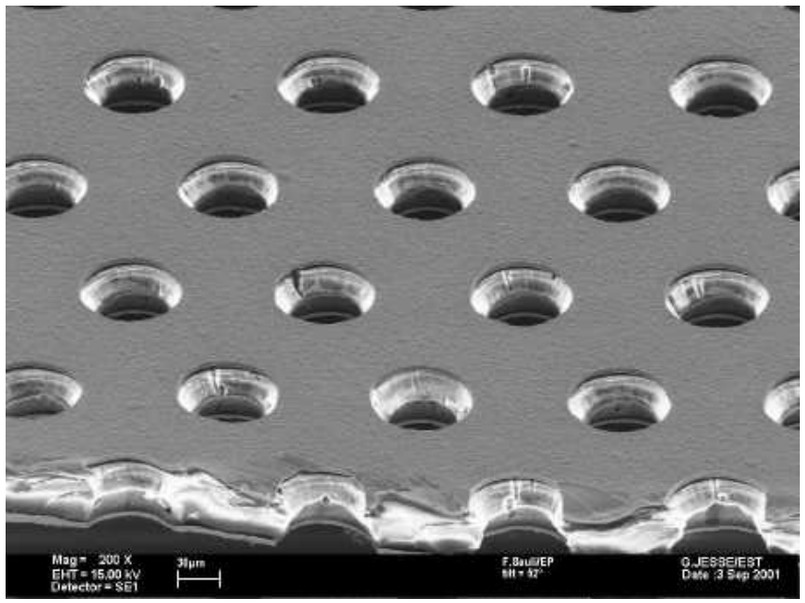
After 100us of electron drift time, the gating grid needs to be kept closed for 200 us to prevent back-drift ions into the drift space (= dead time for TPC) → total time ~ 300 used limits maximum readout rate to 3 kHz

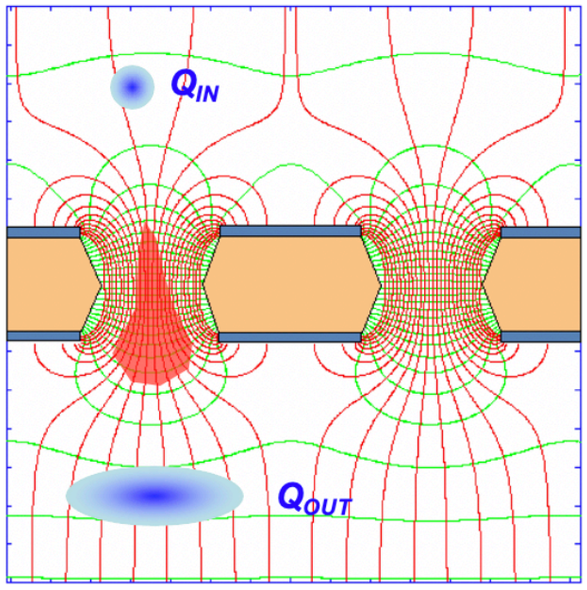






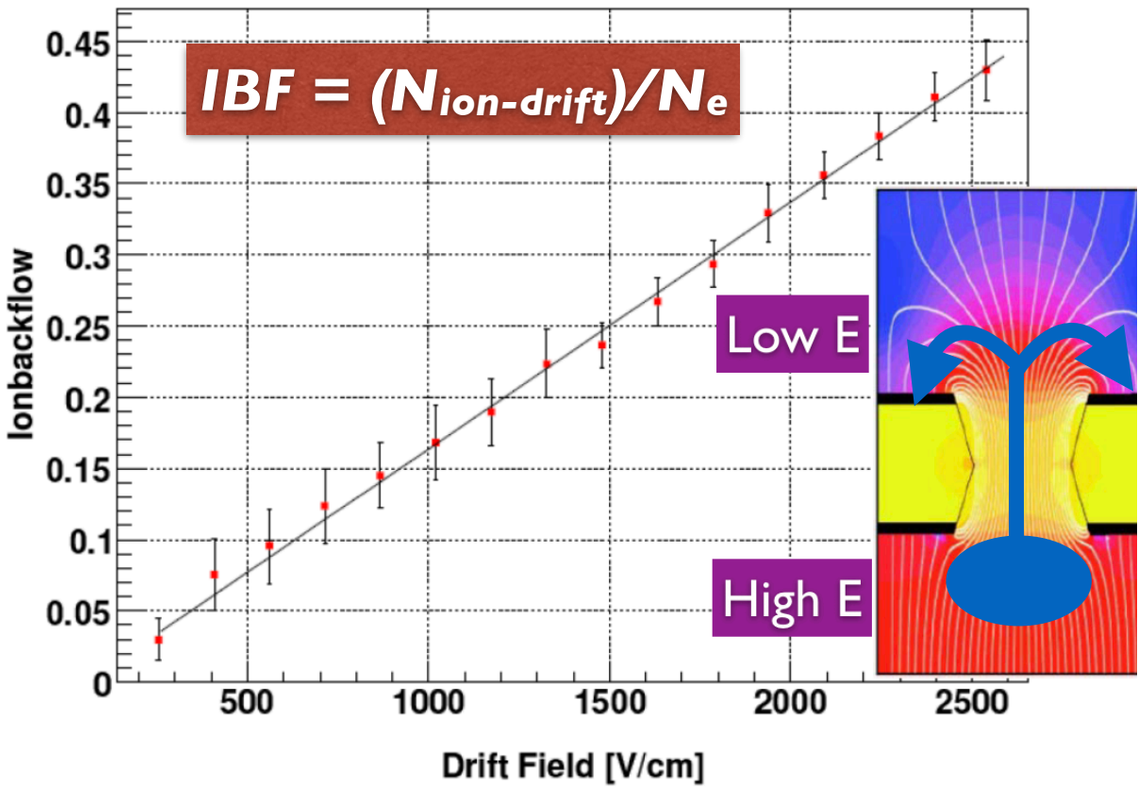
Gas Electron Multiplier (GEM)

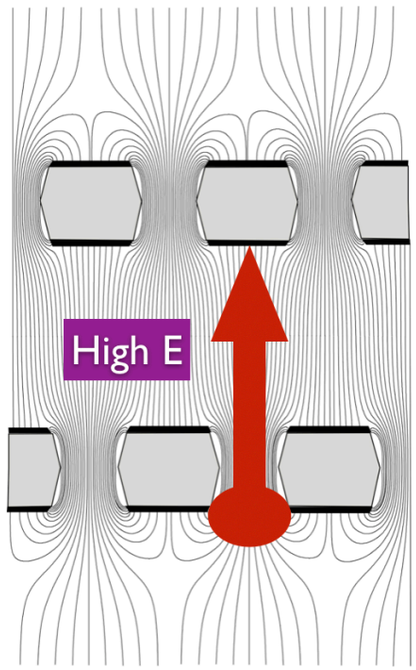




- high rate capability (< 1 MHz/mm^2)
- ion backflow suppression
- fast signal
- safer operation by stacking GEMs
- Less ExB effect
- …

Standard GEM : 50um insulator (Kapton)+5um copper layers on both sides, φ~70um, pitch~140um





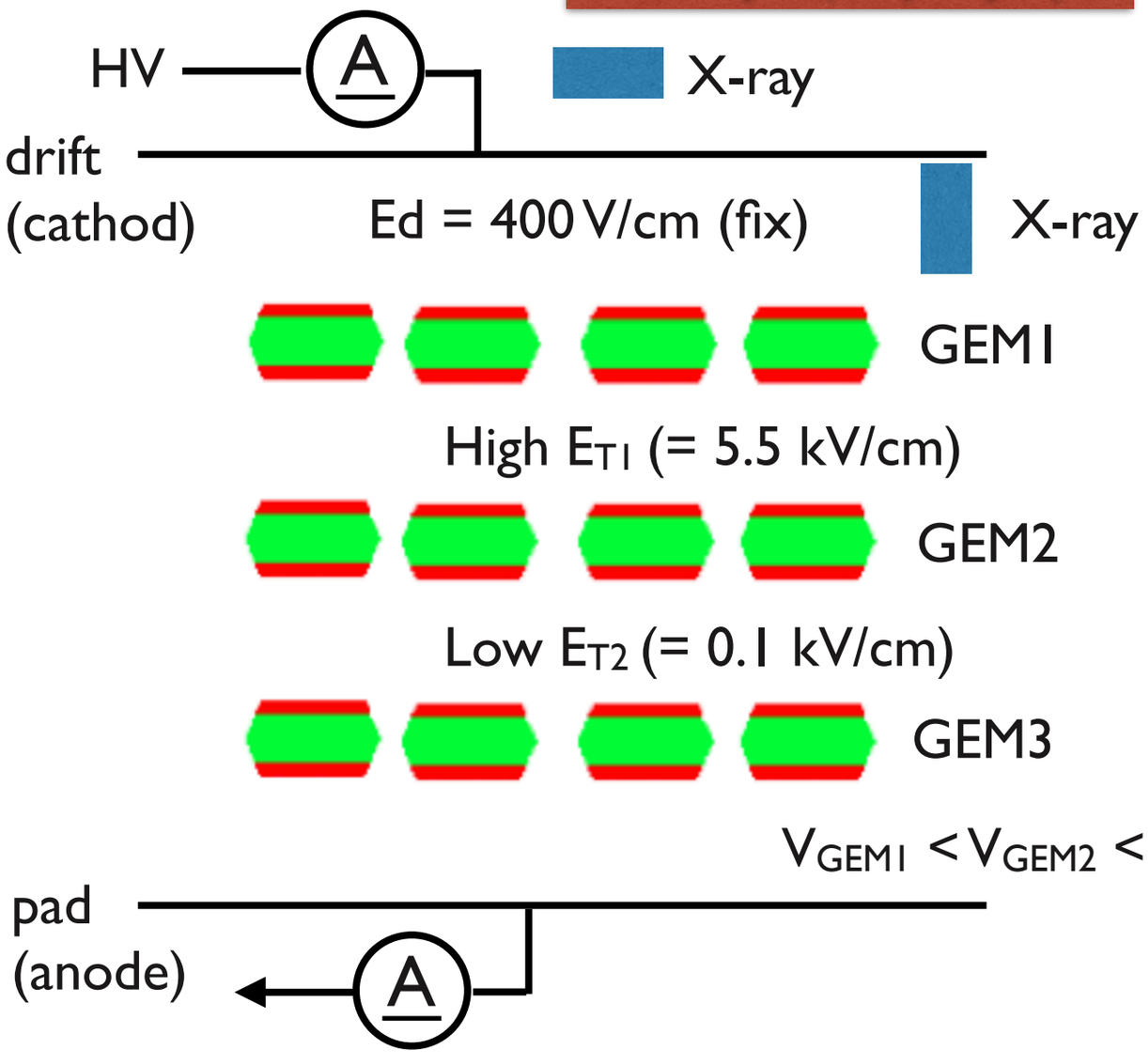
If IBF is good under 50 kHz Pb-Pb, TPC can run continuously without any gating.

Goal: @Gain=2000
IBF < 1%
σ(dE/dx) <12 % for ^{55}Fe

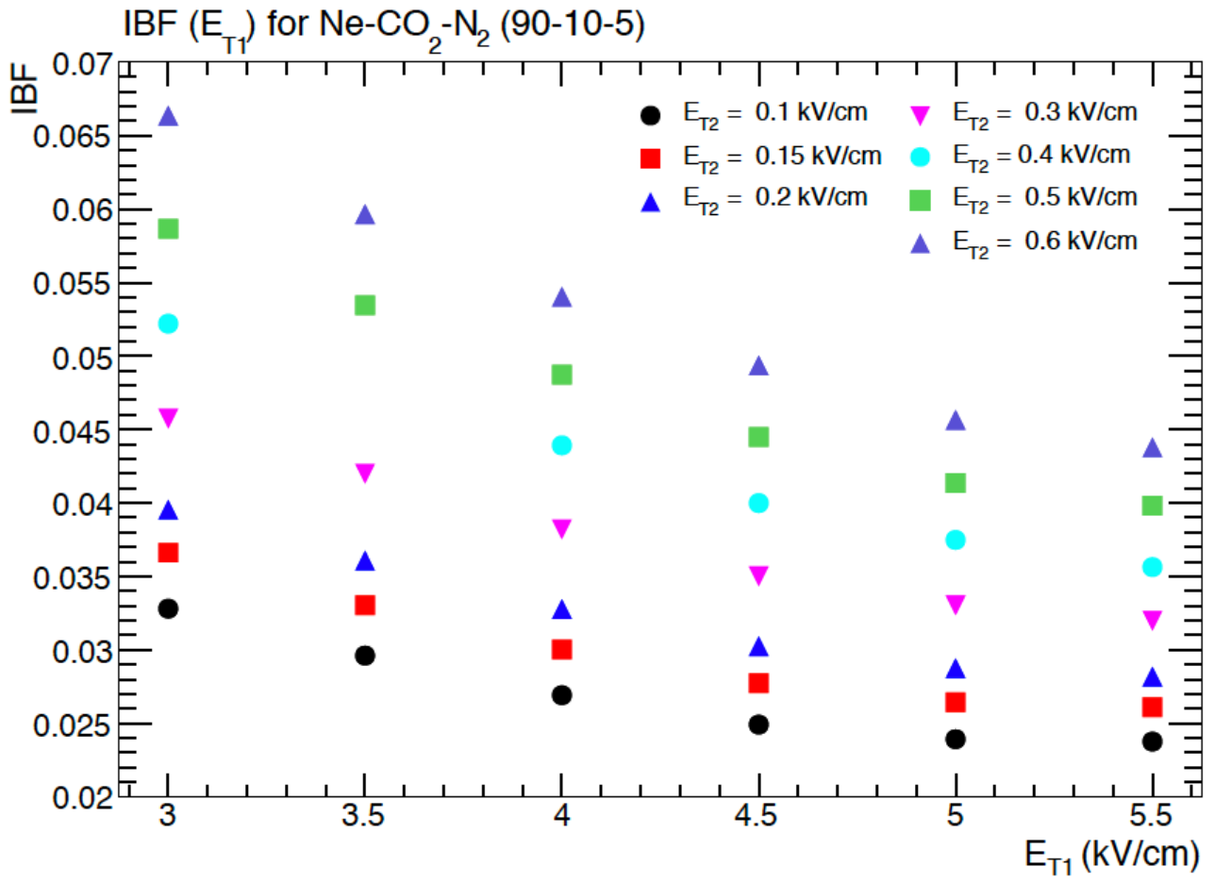
Ion backflow - 3 & 4 GEM layers

- The number of GEM layers
- V_{GEM}, E_{T1}, E_{T2}, E_{T3} scans

$$IBF = (I_{drift} - I_{prim})/I_{pad}$$



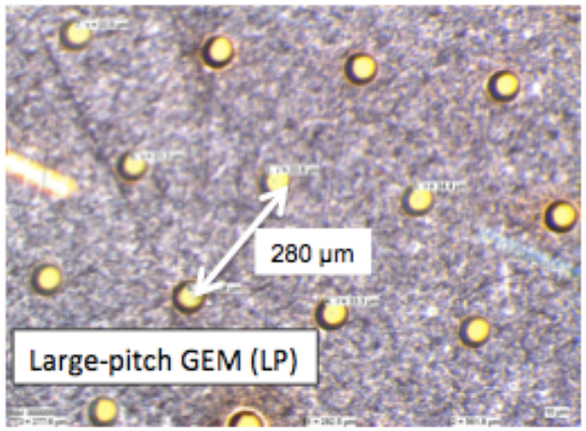
3 GEM configuration
→ minimum IBF ~ 2%



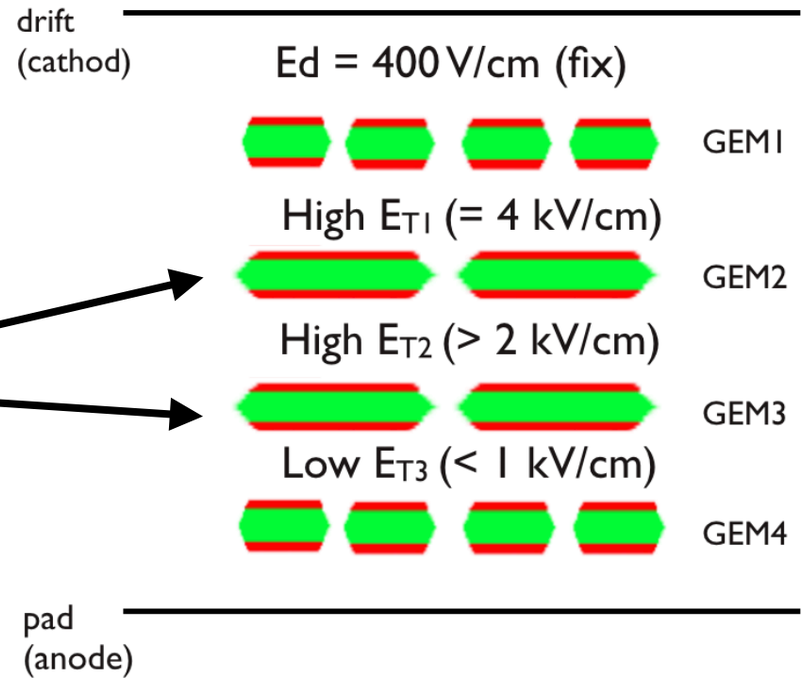
4 GEM configuration
→ minimum IBF ~ 1%

Ion backflow - “S-LP-LP-S”

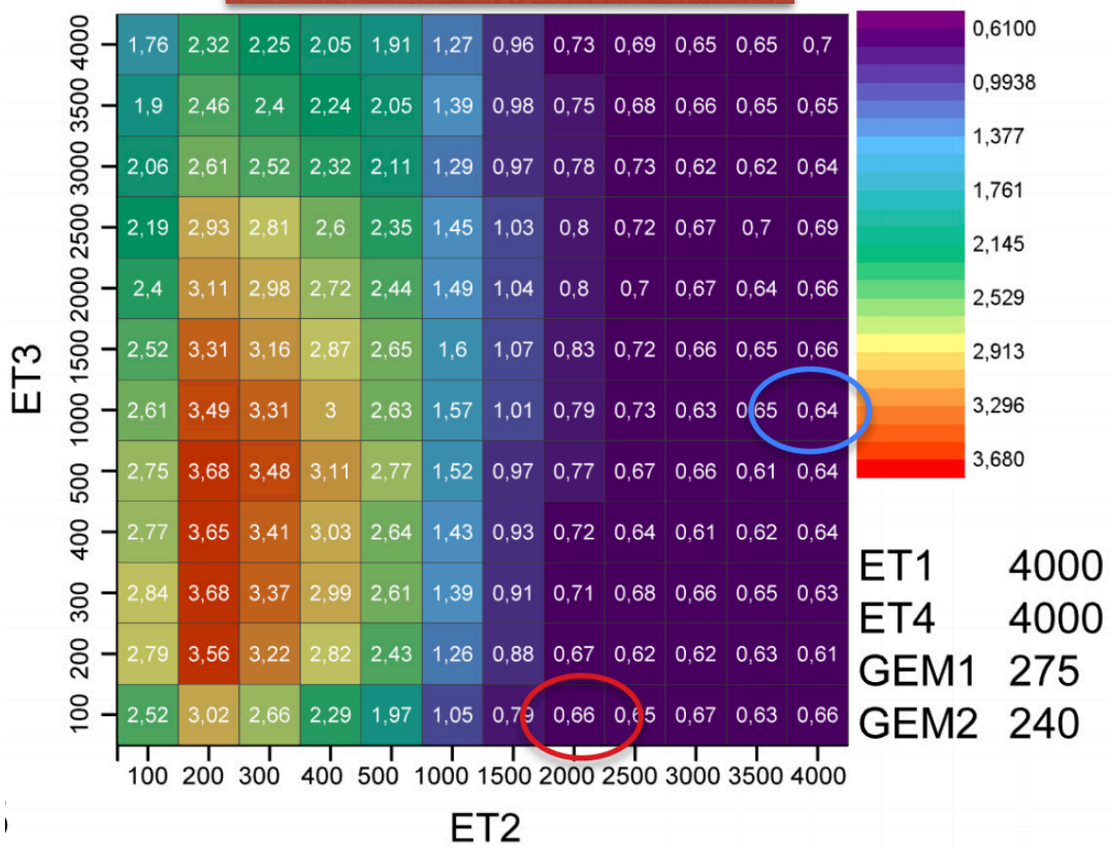
Combination of GEMs with different pitches



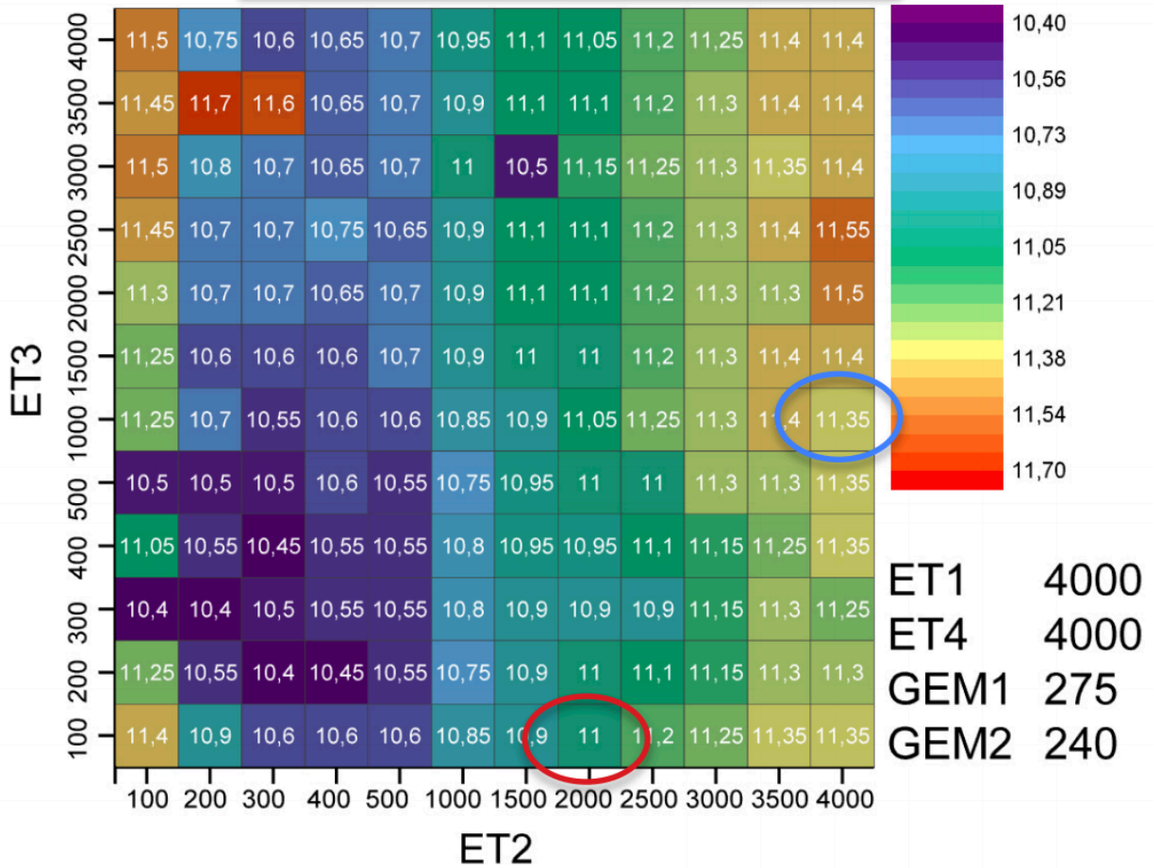
Large pitch GEM (LP)
φ = 70um,
pitch=280um



minimum IBF ~ 0.6%



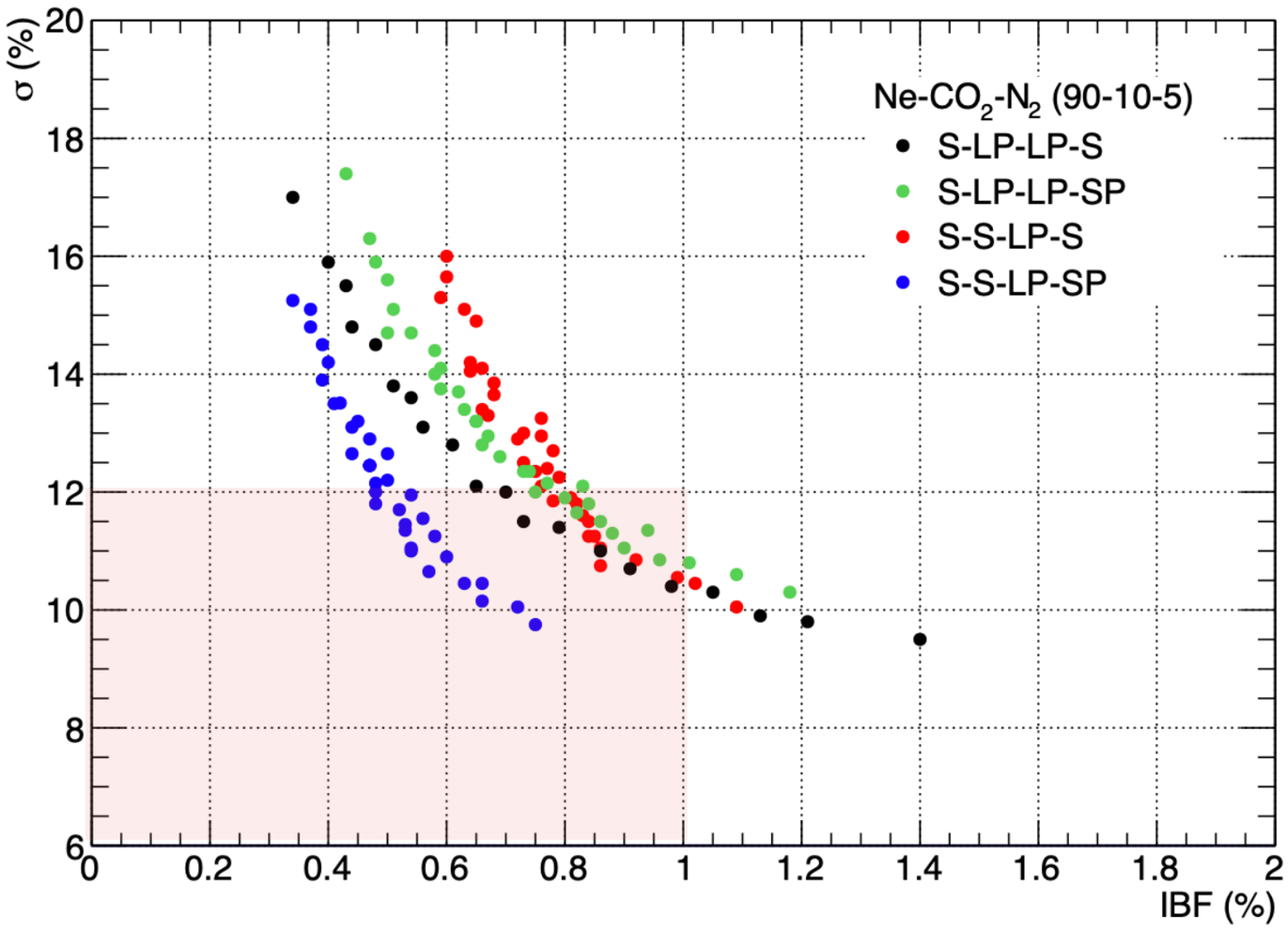
σ(dE/dx for Fe^{55}) ~ 11%



Ion backflow - more combinations

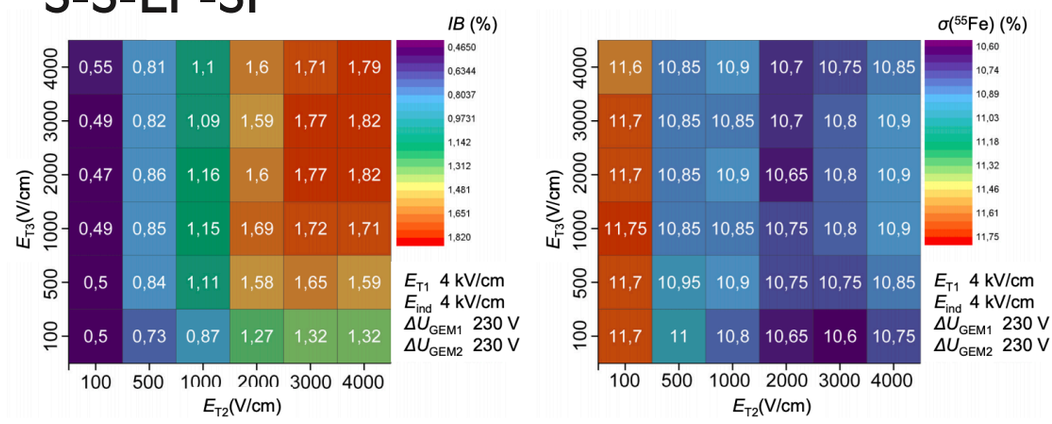
Combination of GEMs with different pitches

Scanned parameters: V_{GEM1} and V_{GEM2}



standard pitch (**S**) 140 mu
large pitch (**LP**) 280 mu
small pitch (**SP**) 90 mu
medium pitch (**MP**) 200 mu

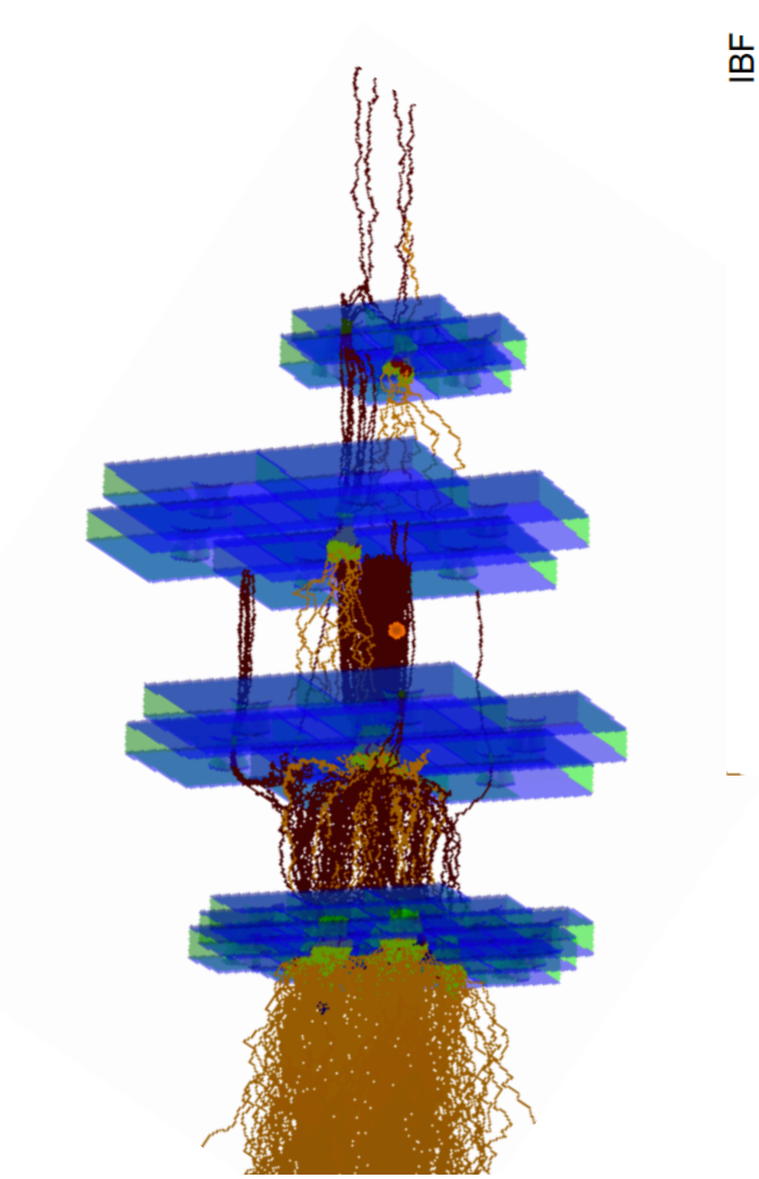
S-S-LP-SP

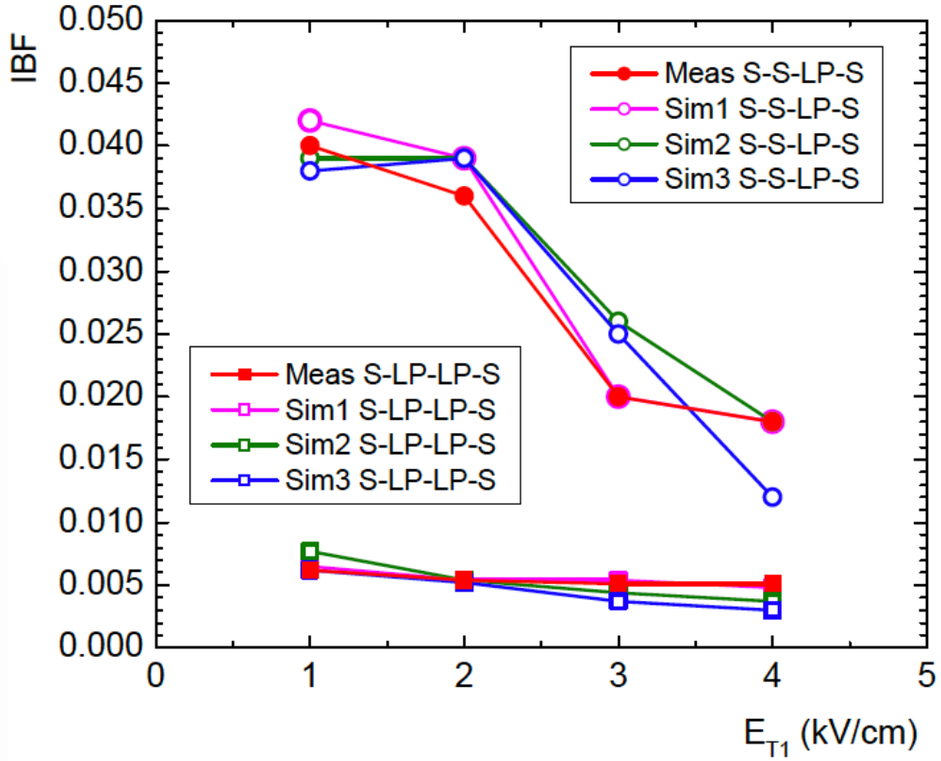


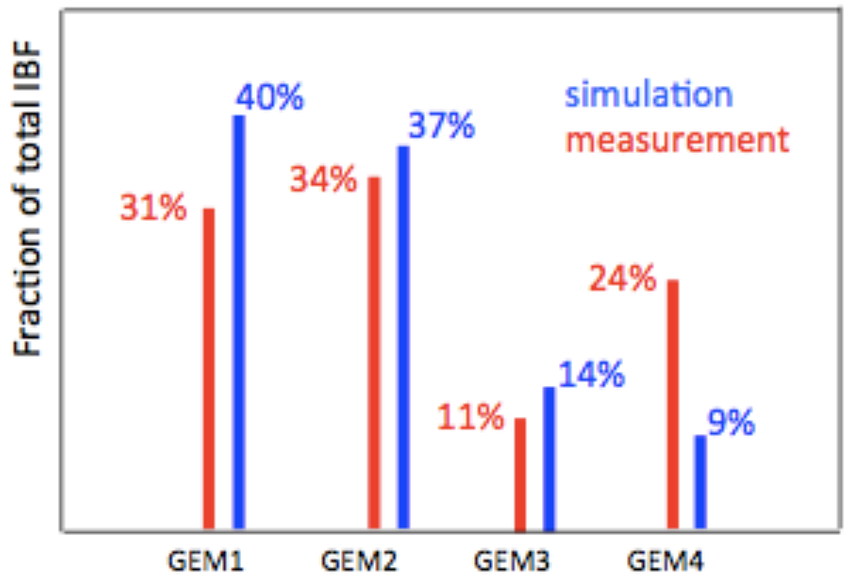
Our Baseline = S-LP-LP-S

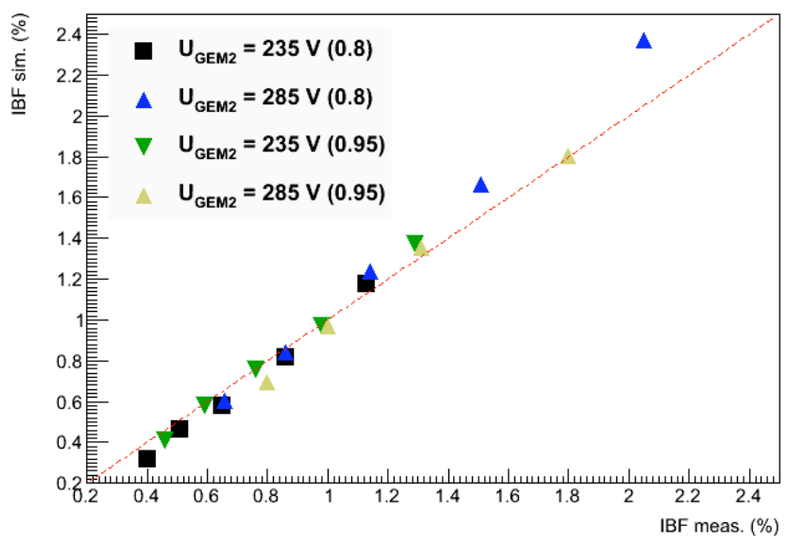
Ion backflow - Simulations

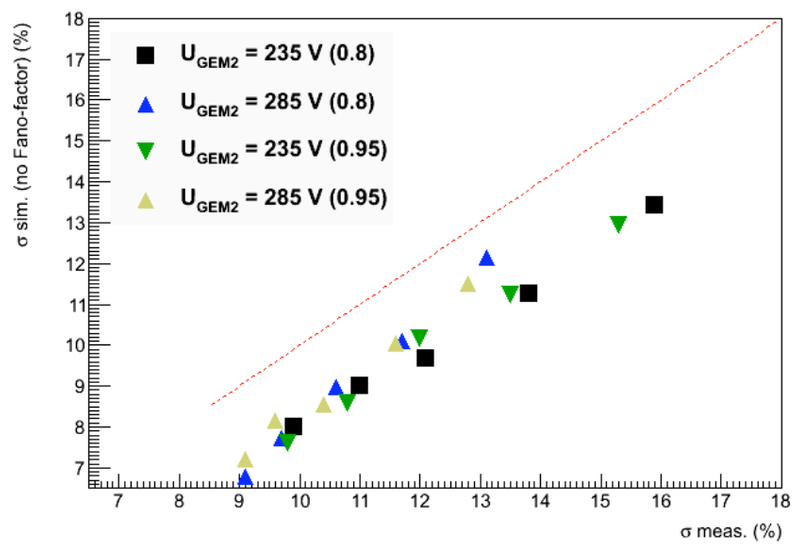
Executive Summary of IBF studies - confirmed by Garfield simulations





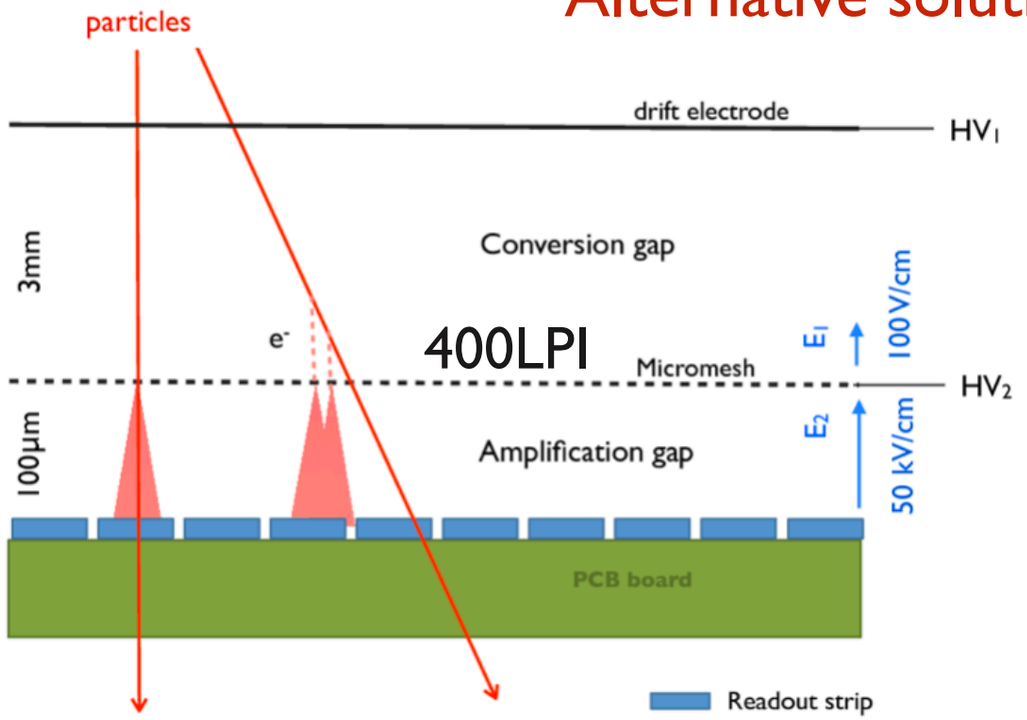


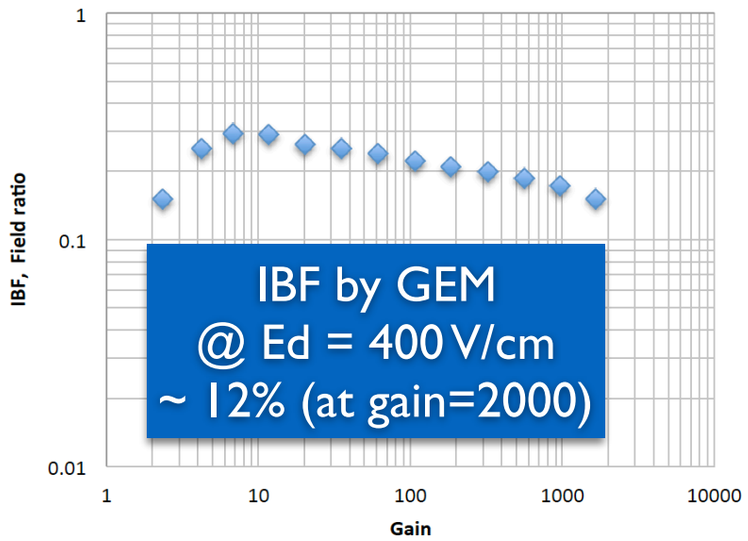


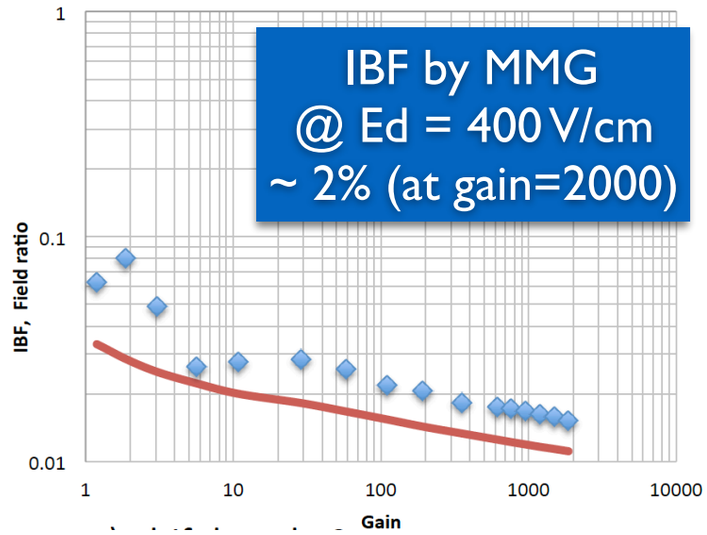


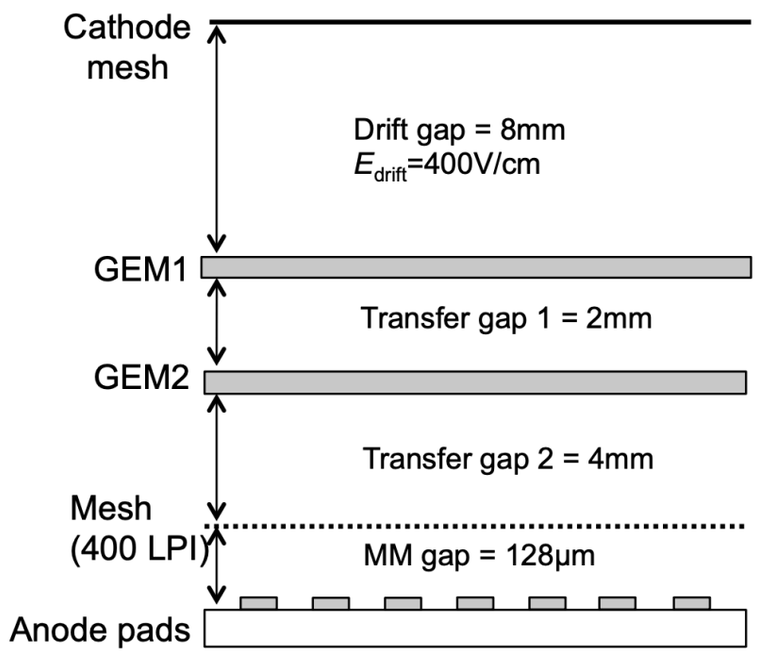
Ion backflow - 2 GEM + MMG

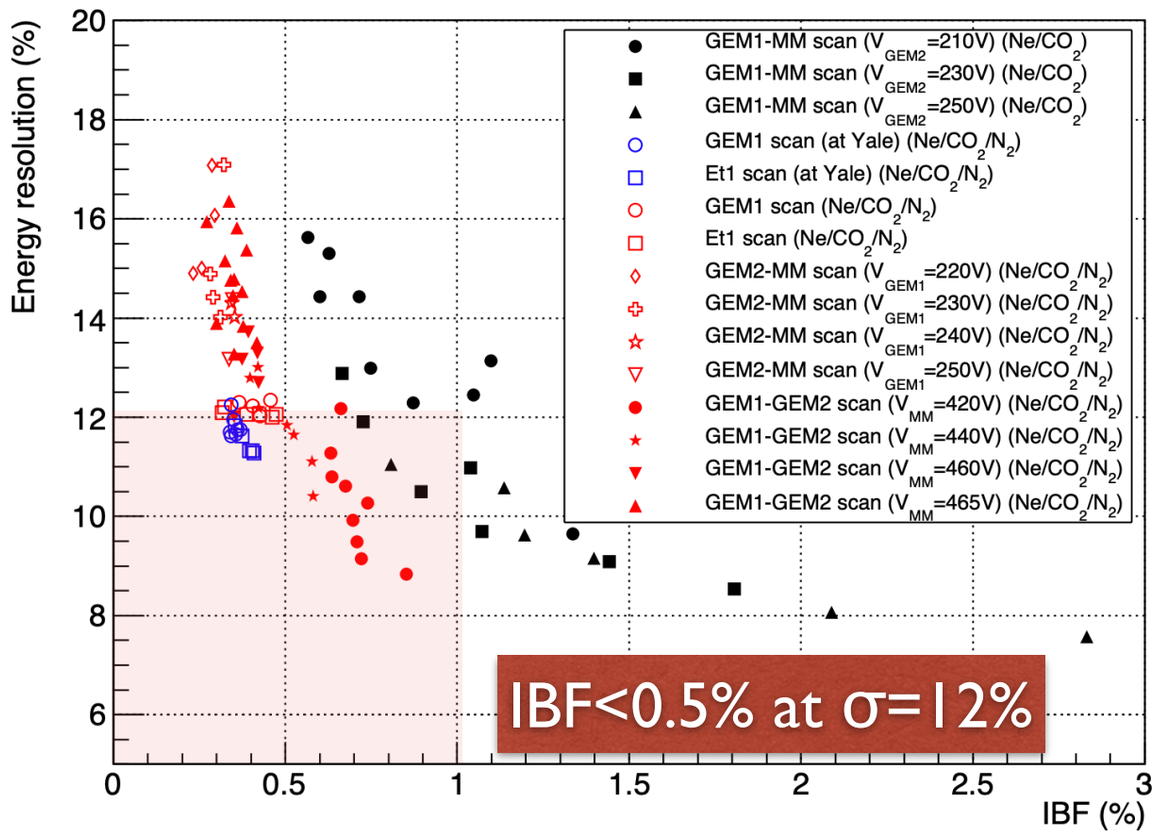
Alternative solution = (2GEM+)MicroMegas





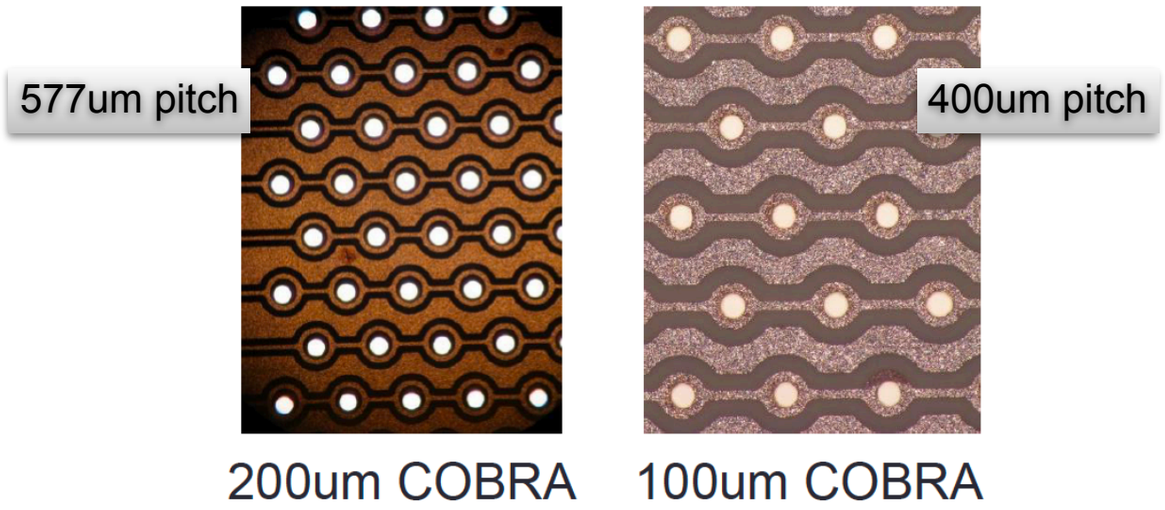


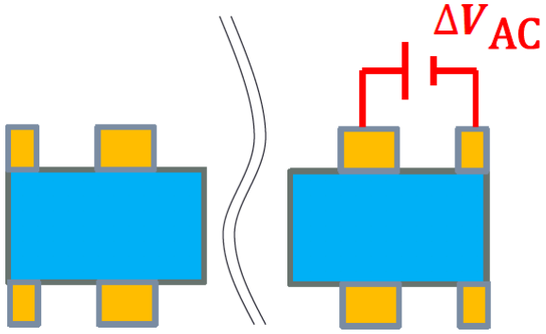




Ion backflow - “COBRA-GEM”

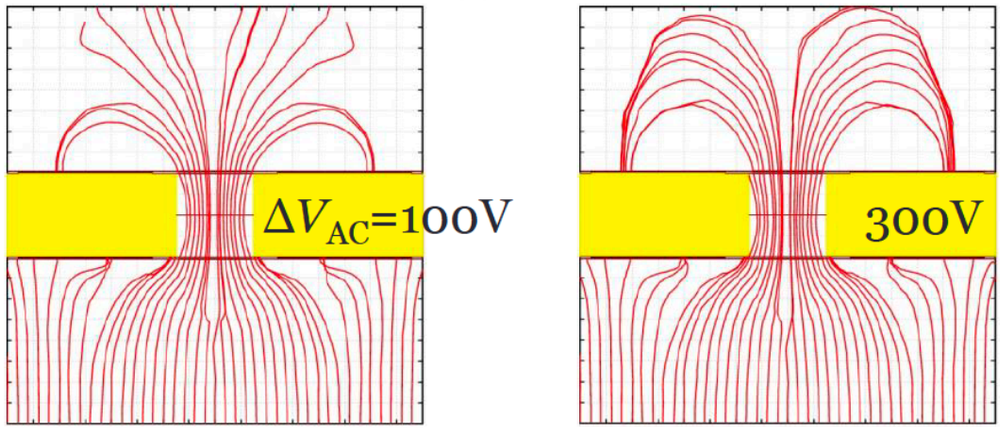
Alternative solution = COBRA-GEM



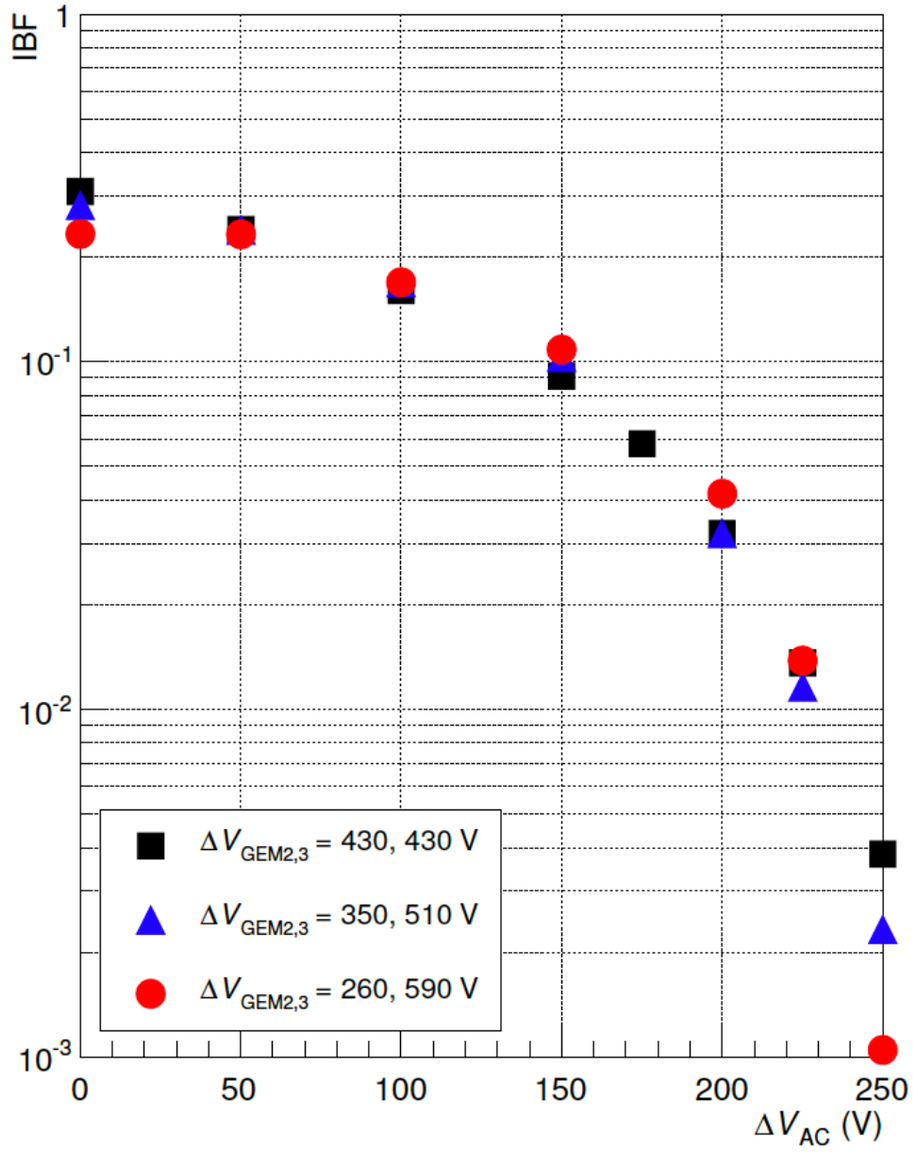


By applying ΔV_{AC}, further IB suppression can be achieved.

Originally developed by J.F.C.A.Veloso et al., NIM A639 (2011) 134-136



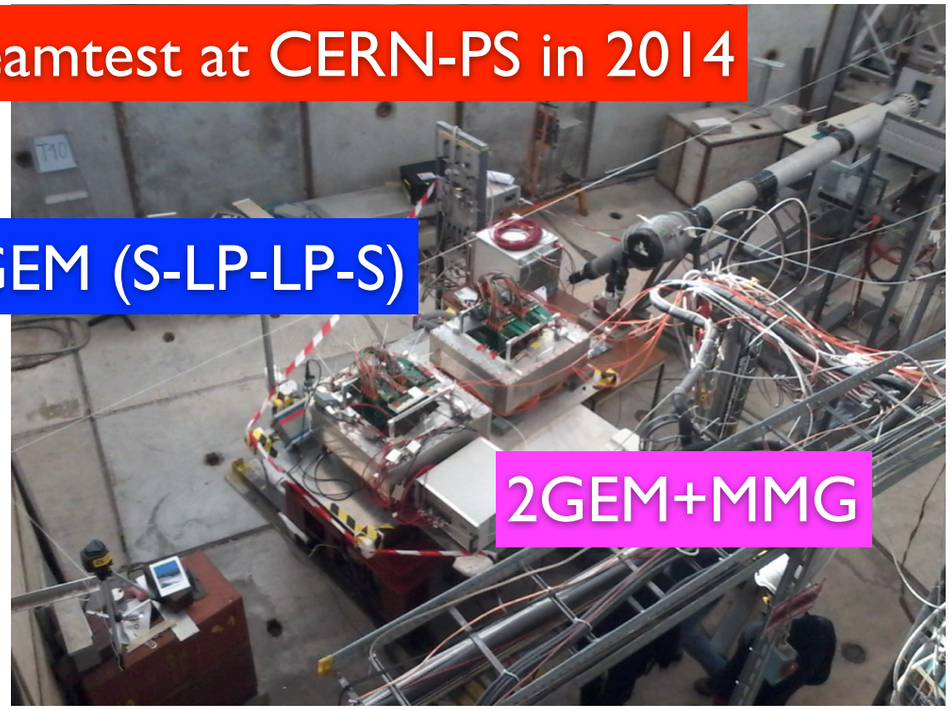
GEM-COBRA-COBRA stack

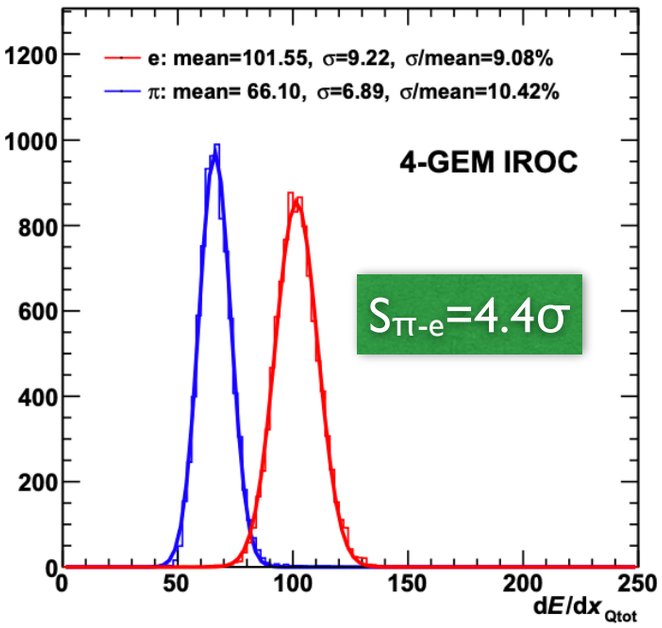


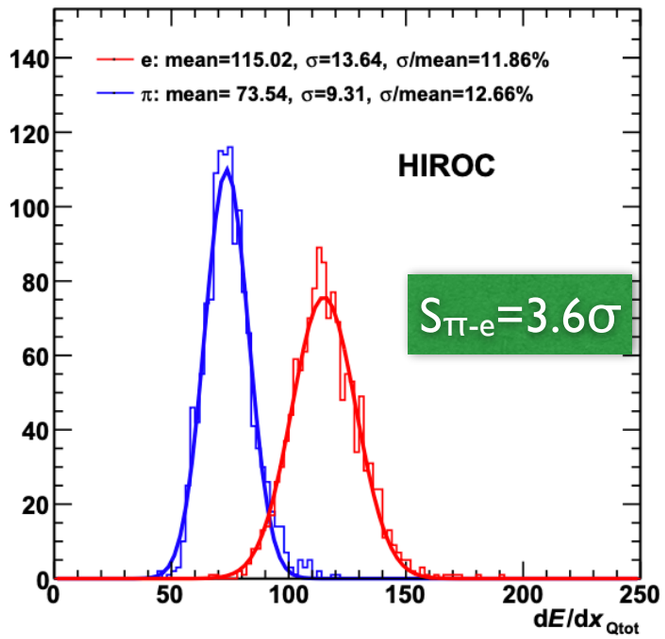
Issues: worse resolution (σ~20%), charge-up

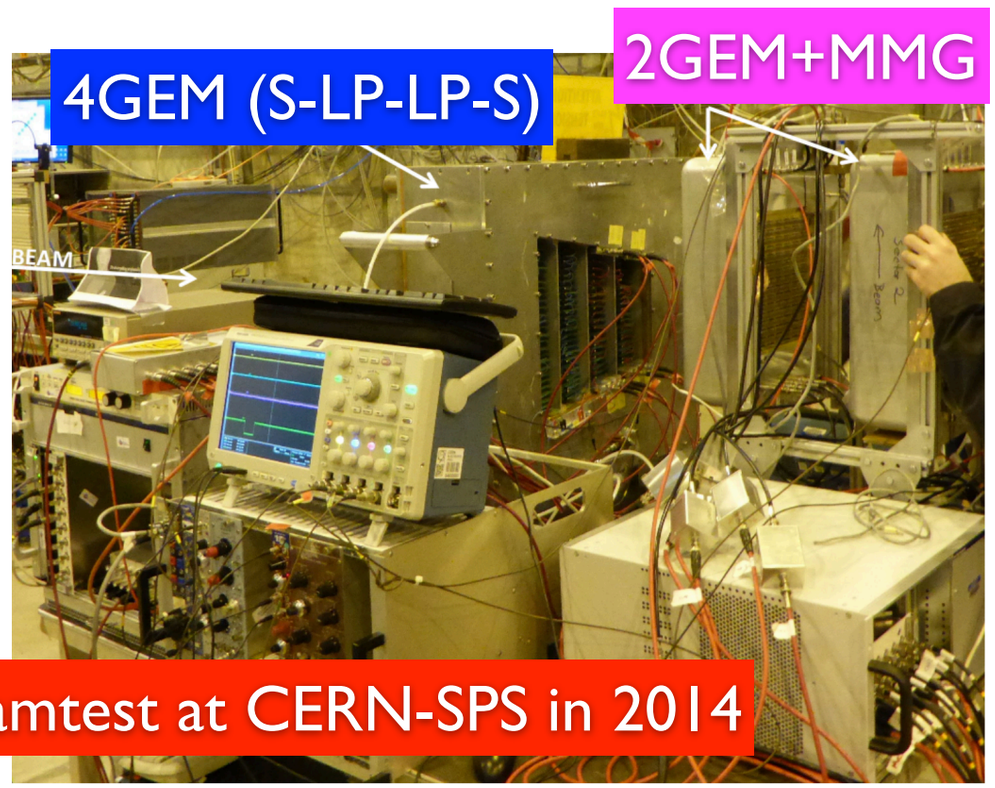
Beamtest at CERN-PS and SPS

Beamtest at CERN-PS in 2014

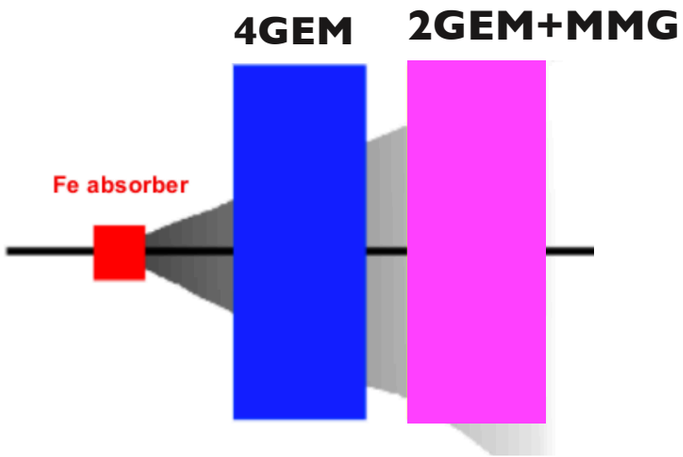


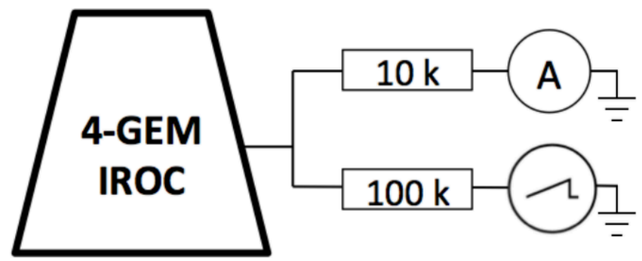






Beamtest at CERN-SPS in 2014



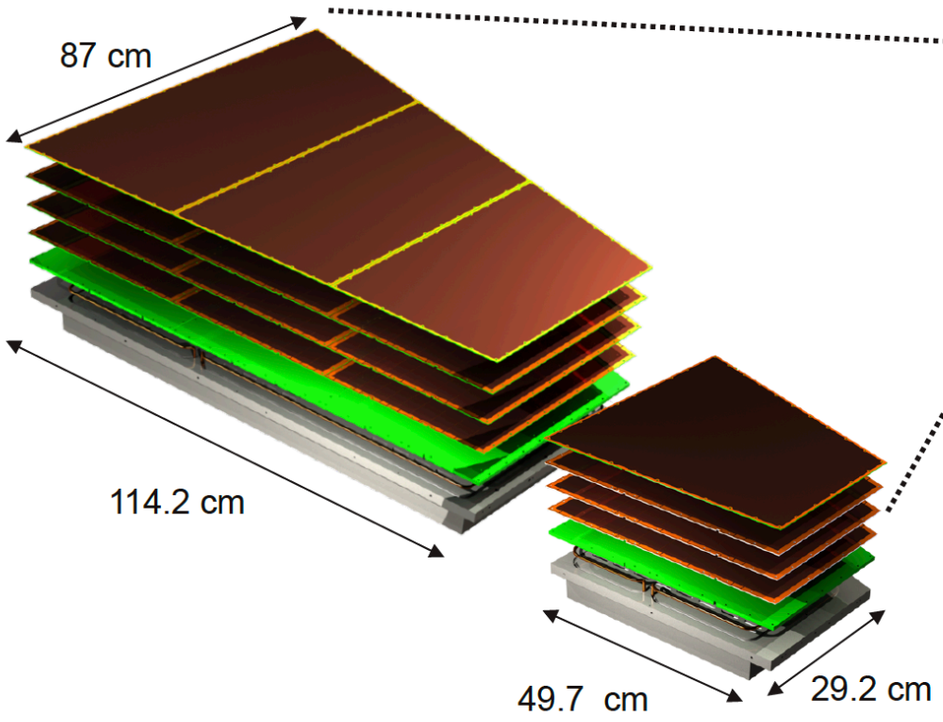


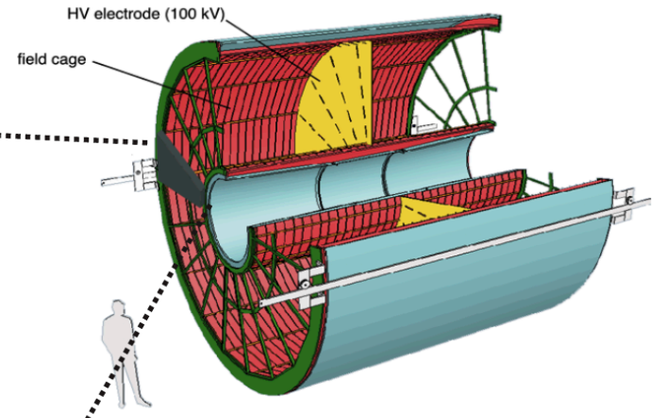
4 GEM: discharge probability (# of sparks/hadron)
= $(6.4 \pm 3.7) \times 10^{-12}$ ~500 sparks /year HI run

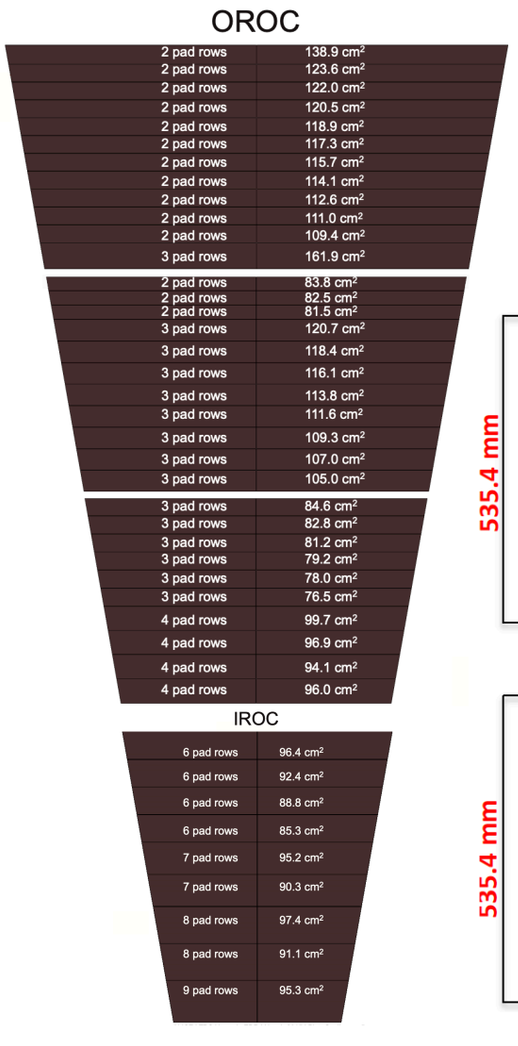
2 GEM + MMG: discharge probability
= 10^{-9} - 10^{-11}

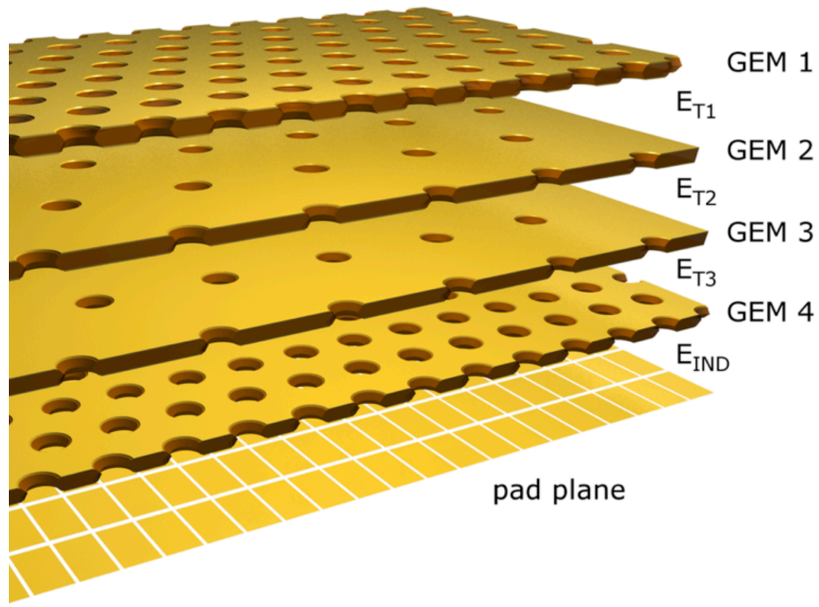
GEM mass production

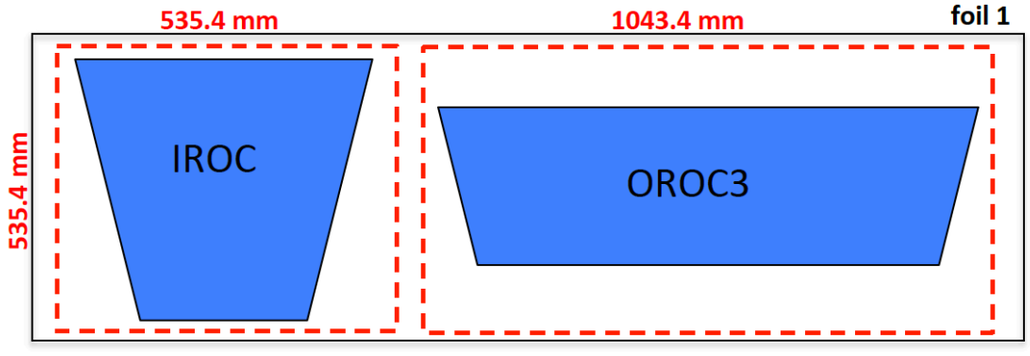
2 x 18 **O**uter **R**ead **O**ut **C**hambers

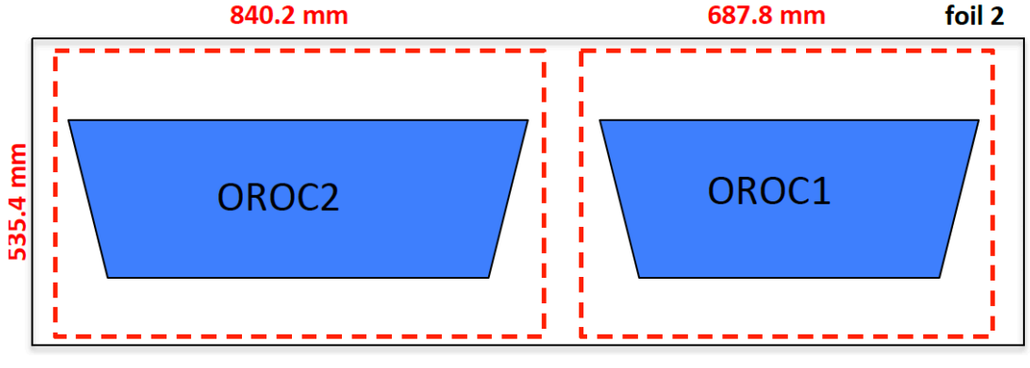








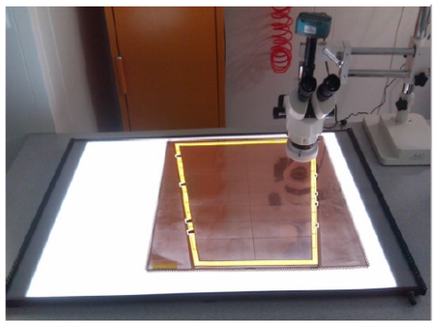


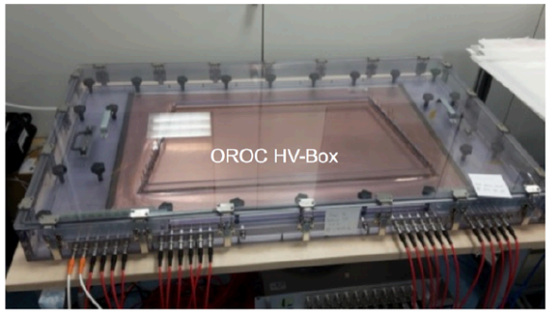


- 40xIROC, 40xOROC
- 640x GEMs + 10 % spares
- GEM foil production at CERN PCB workshop
- GEMs are produced on sheets containing 2 GEMs of different size
- GEMs are segmented in one side.

GEM mass production - GEM-QA

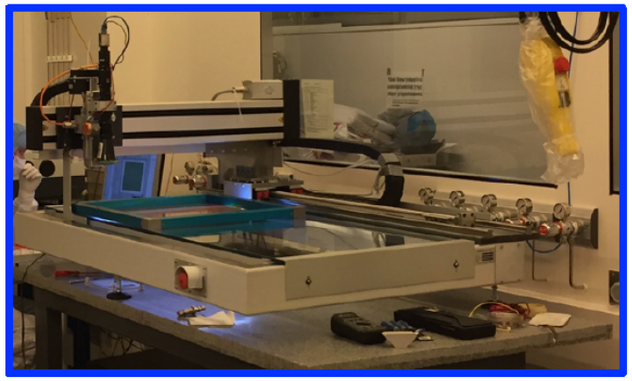
QA at CERN





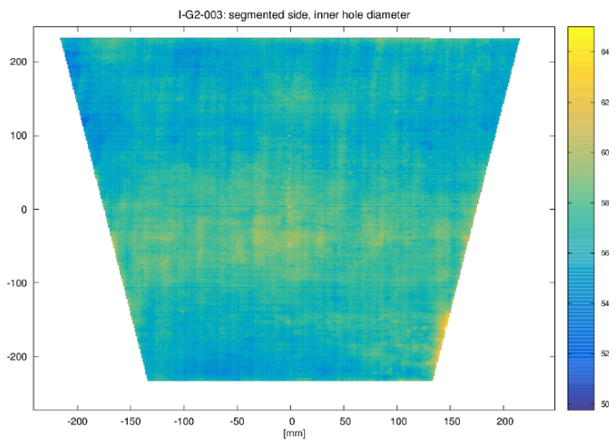
- Coarse optical check
  - Search for mechanical defects
- HV test
  - apply 500 V for 15' in dry N2
  - Ileak < 0.5 nA/segment, no repeated sparking
  - all segments tested independently using multi-channel pA-meters

Advanced QA at Helsinki/Budapest

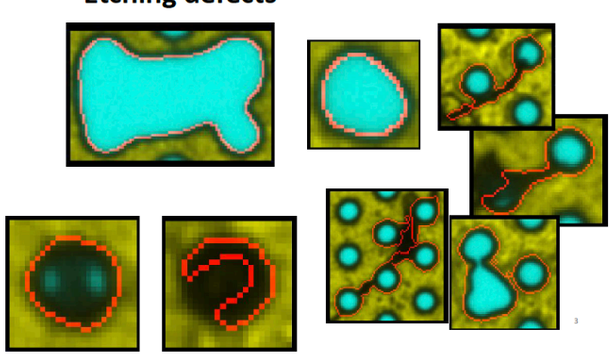


- High definition scanning
  - Measure outer/inner hole diameter
- Gain uniformity test
  - Measure one foil from a batch
- Long term HV test (6h or more)

Hole size distributions

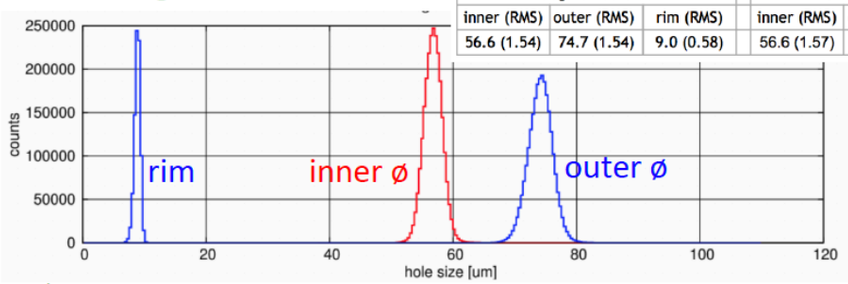


Etching defects



I-G2-003 green

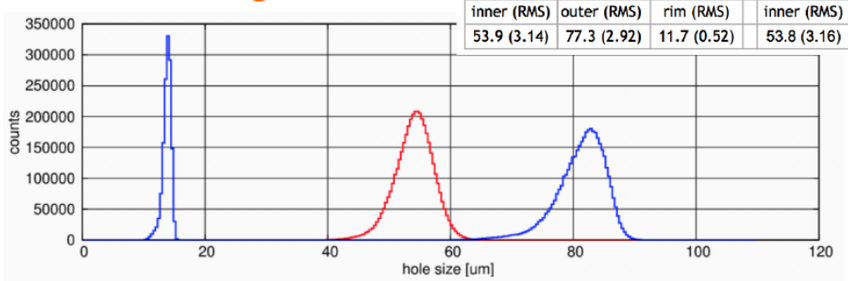
Segmented Side			Unsegmented Side		
inner (RMS)	outer (RMS)	rim (RMS)	inner (RMS)	outer (RMS)	rim (RMS)
56.6 (1.54)	74.7 (1.54)	9.0 (0.58)	56.6 (1.57)	73.9 (1.94)	8.7 (1.94)



- ✓ Mean diameter < 5 µm from the batch average
- ✓ All RMS < 4 µm
- ✓ PTP variations (10 < P ≤ 90) < 5 µm

O3-G3-005 orange

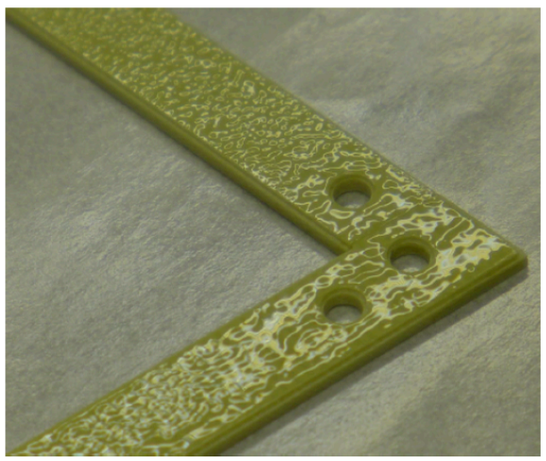
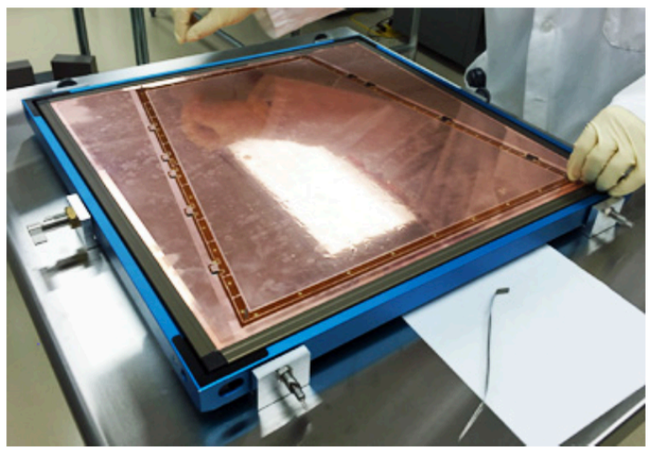
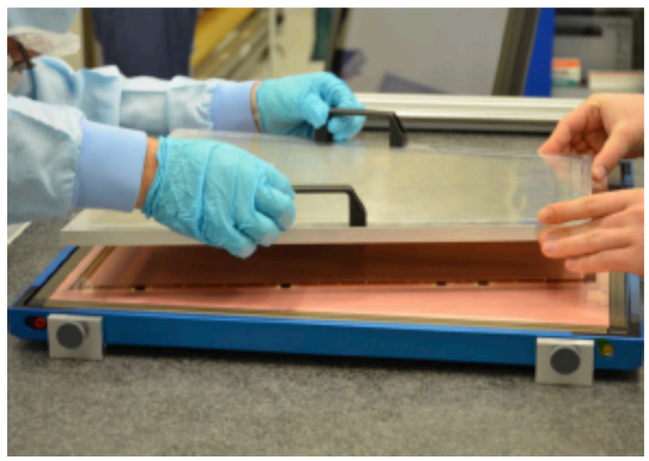
Segmented Side			Unsegmented Side		
inner (RMS)	outer (RMS)	rim (RMS)	inner (RMS)	outer (RMS)	rim (RMS)
53.9 (3.14)	77.3 (2.92)	11.7 (0.52)	53.8 (3.16)	81.0 (4.02)	13.6 (0.71



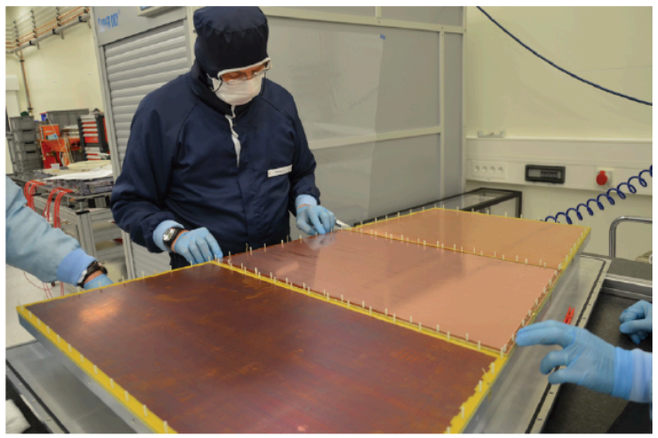
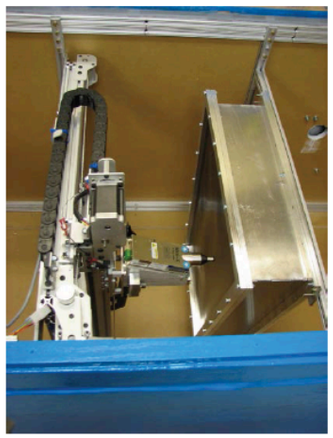
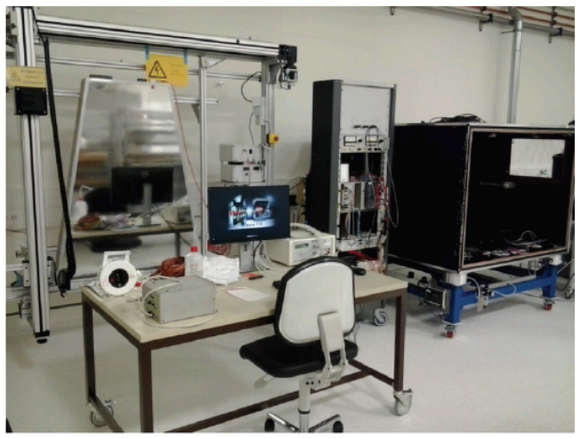
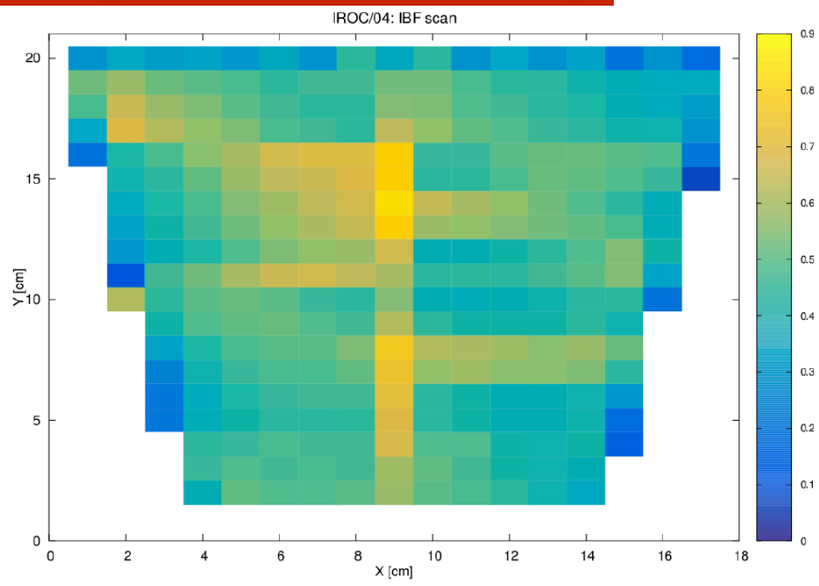
- ✓ Mean diameter >10 µm from the batch average
- ✓ Any RMS > 4 µm
- ✓ PTP variations (10 < P ≤ 90) > 10 µm

GEM processing and Chamber production

GEM framing

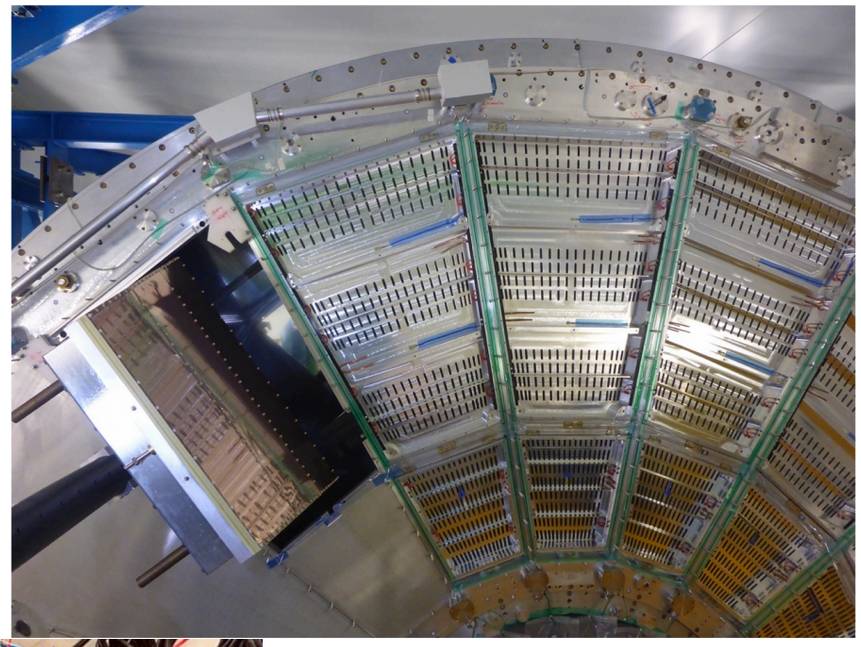
ROC assembly and commissioning (gas tightness, gain/IBF uniformity, irradiation tests)

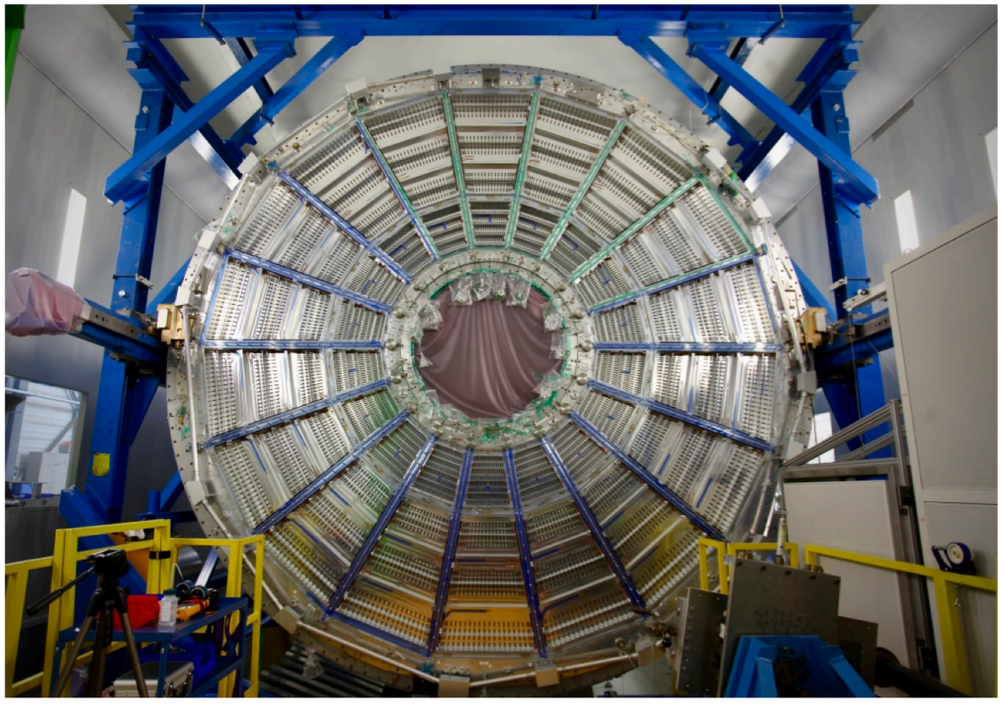





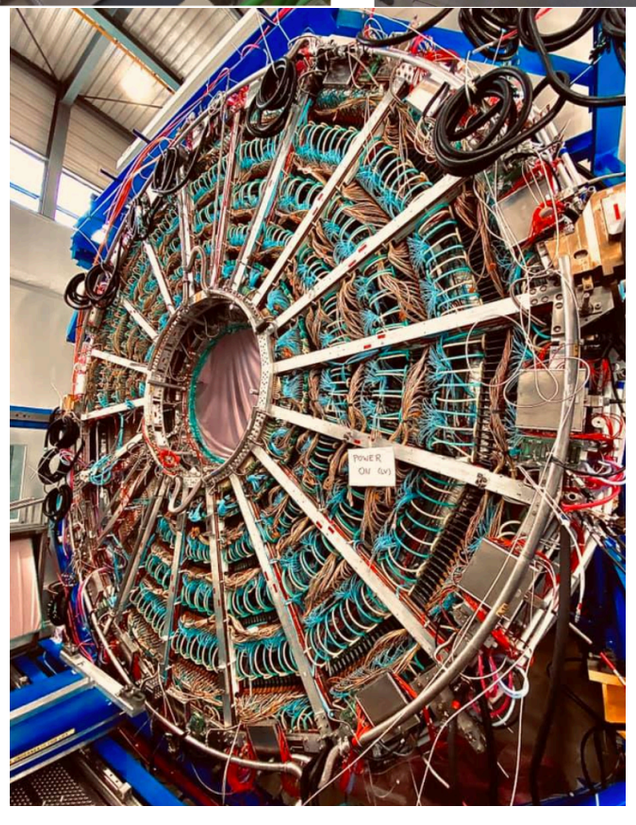
Uniformity of IBF
(IBF ~ 0.4-0.9)

GEM chamber installation in 2019

ROC stored at CERN

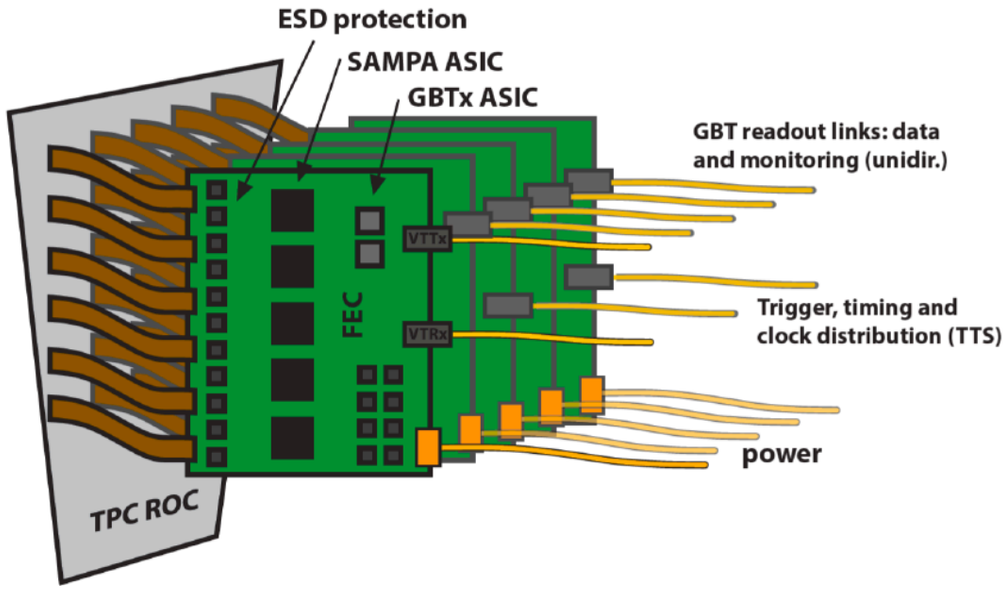


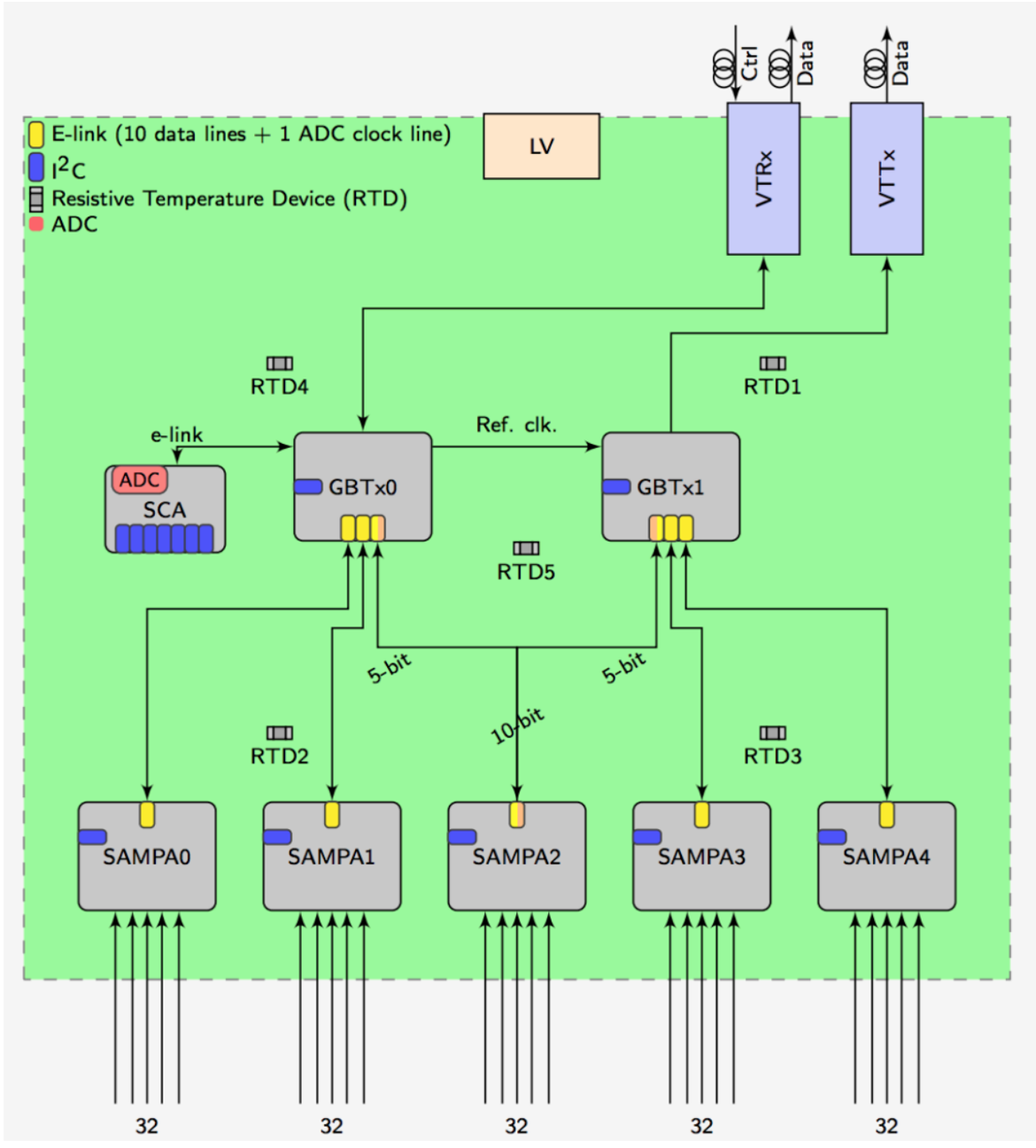


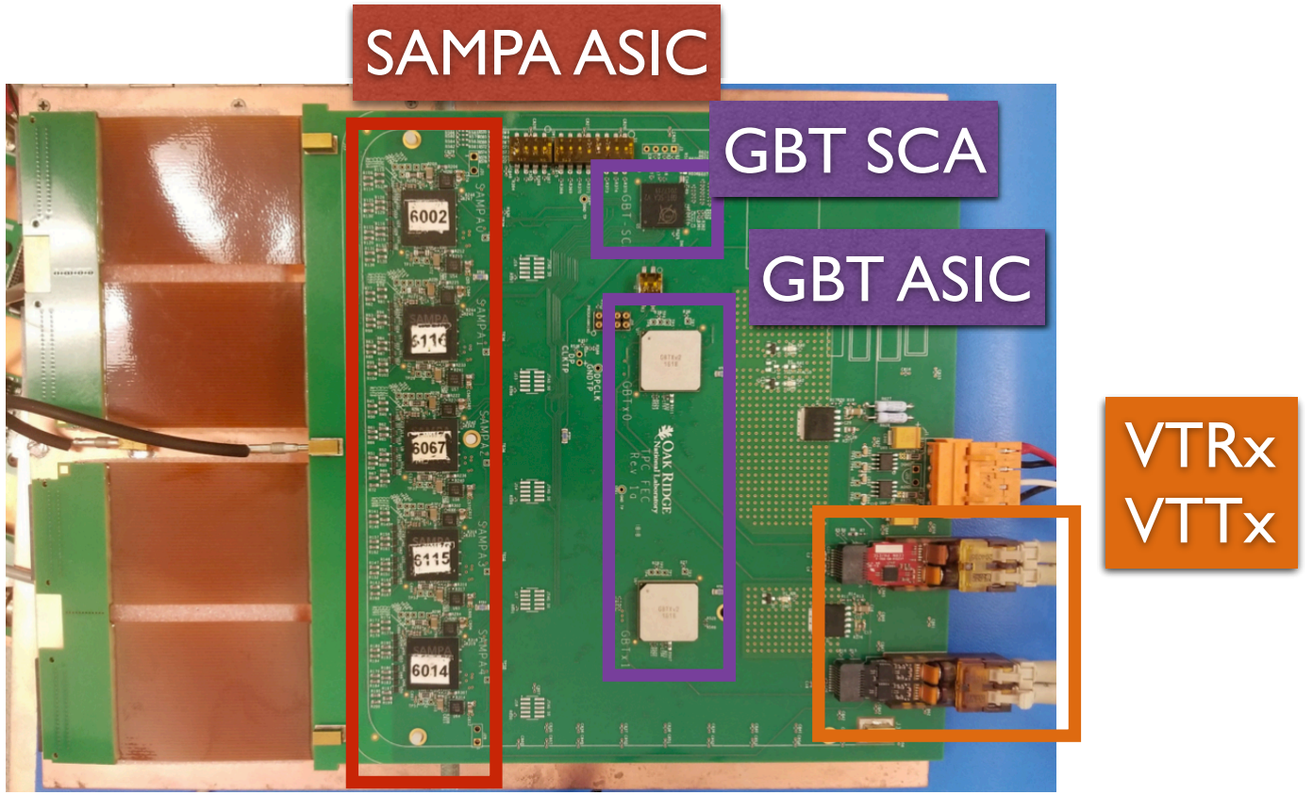


Completion of GEM and FEC installation in 2019

Front End Electronics







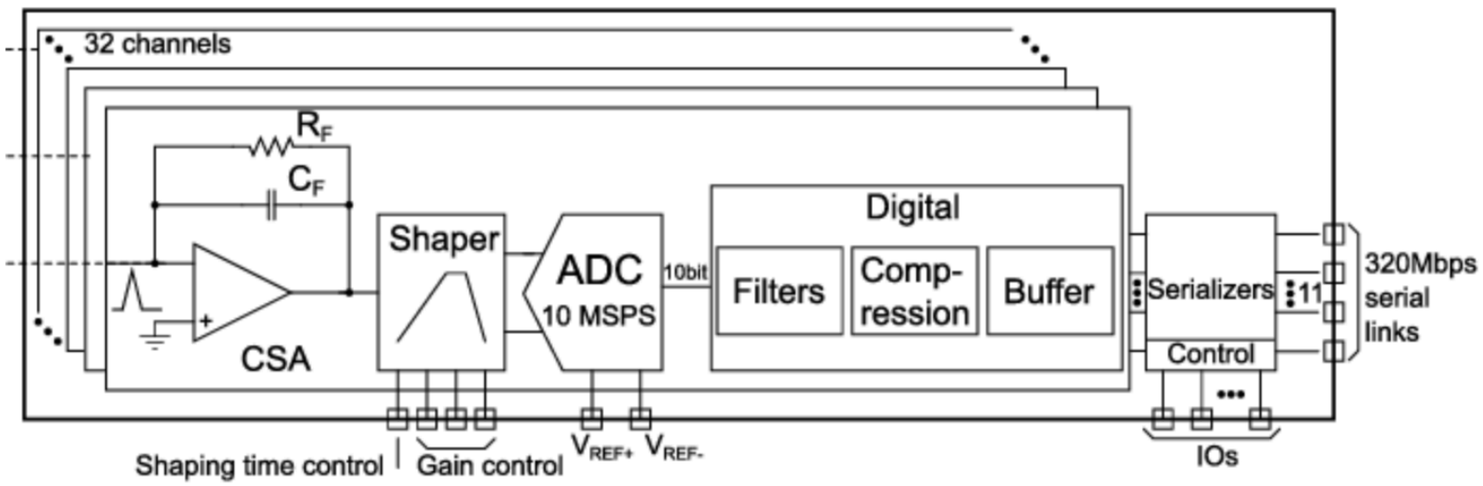
SAMPA and GBT

J. Adolfsson et al 2017 JINST 12 C04008

SAMPA ASIC

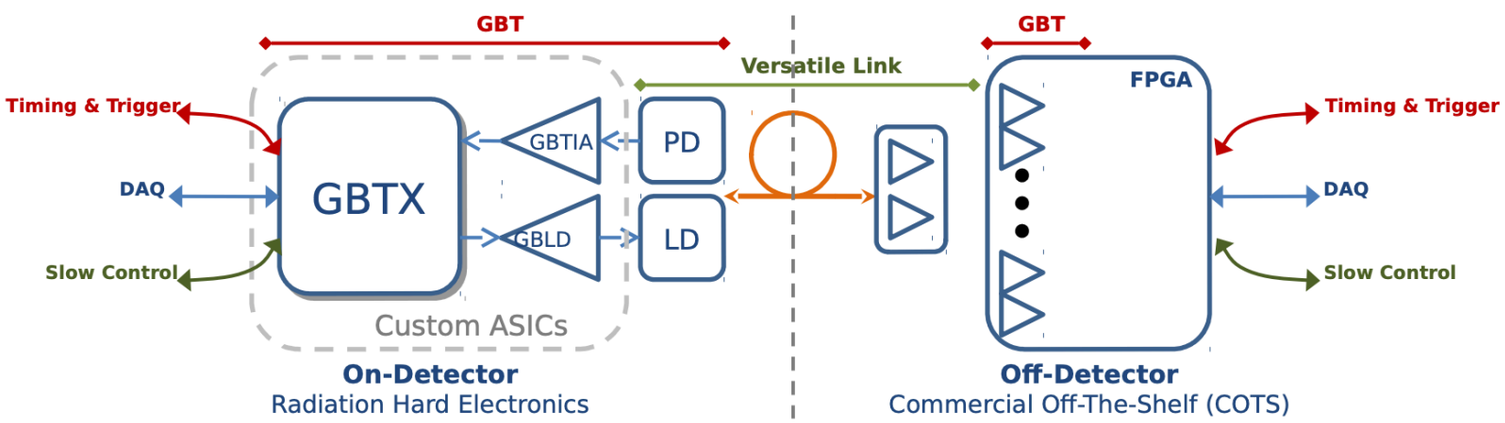
Developed by Sao Paolo team

- 130 nm TSMC CMOS
- PASA+ADC+DSP(BC, ZS, TC, HC,etc)
- 32 channel/chip
- Both polarities
- **Continuous** or triggered mode
- PA gain: 4, **20**, 30 mV/fC
- SA peaking time : 80, **160**, 300 ns
- Sampling rate: **5**, 10, 20 MHz
- 2Vpp, 10 bit ADC
- output: 320 Mbps x 10 serial links
- 15 - 30 mW/channel



GBT ASIC

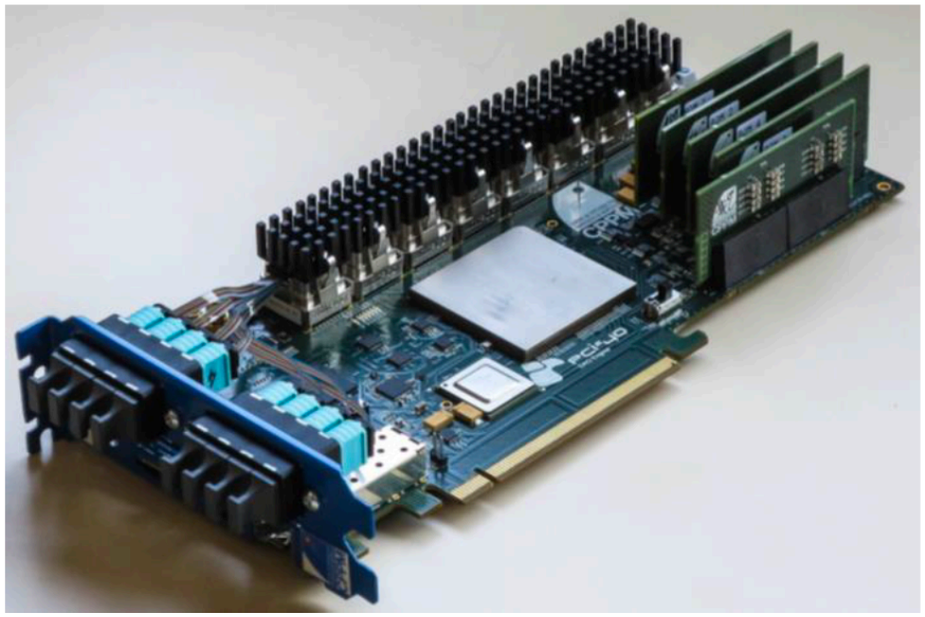
Developed by CERN and LHC experiments



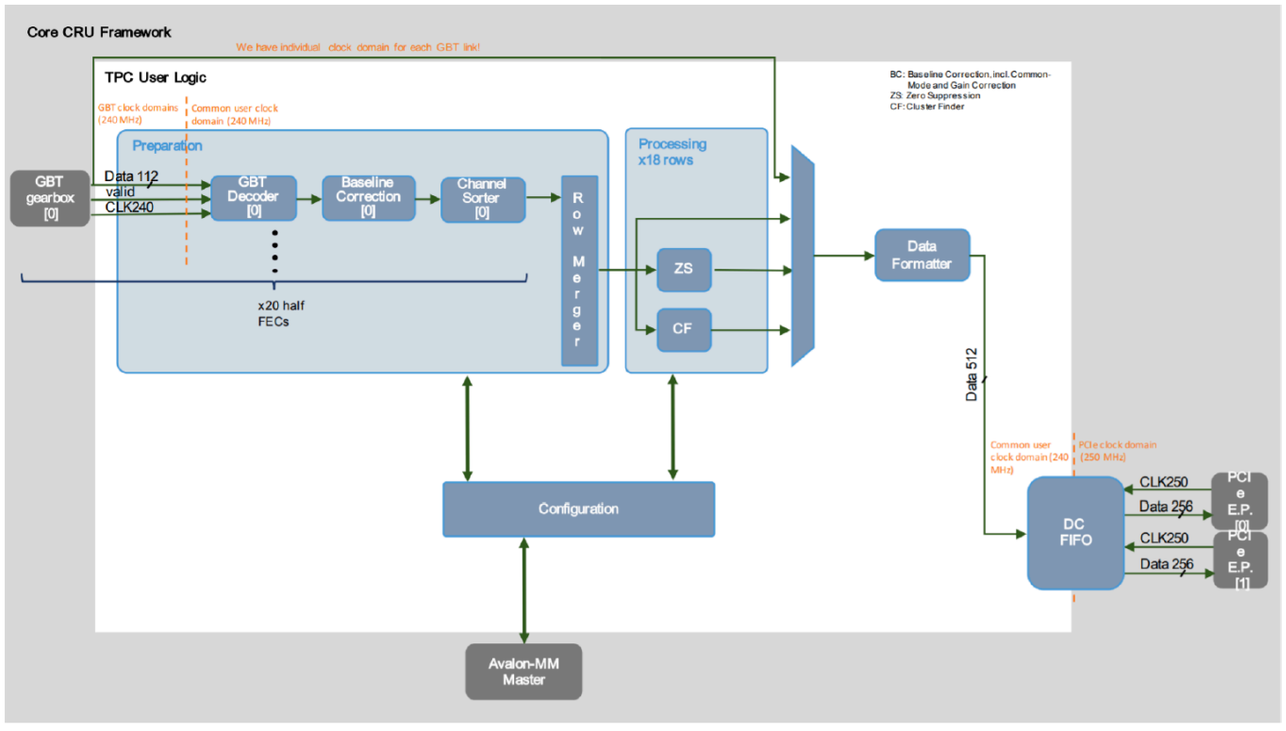
- Timing & Trigger & Data transmission
- Maximum BW : 4.8 Gbps data
  - **TPC: 4 Gbps/GBT link**
- Radiation hardness (~ 100Mrad)
- FPGA IP core library available
- Slow control via GBT-SCA through I^2C

Backend module = Common Readout Unit

- Common project between LHCb and ALICE
- PCI Express Gen3 card (installed in FLP-PC)
  - Maximum output BW : 128 Gbps (~90 Gbps)
- Receive data from GBT
  - Maximum 48 optical in/out (215 Gbps)
  - For TPC: 20 GBTs are connected to 1 CRU (80Gbps)
  - ~350 cards are needed for TPC



- Intel/Altera Arria 10 FPGA
  - Online data processing in FPGA
    - Base line correction
    - Common mode filtering
    - Channel sorting
    - (Cluster Finder)
  - 1150k LE, 427k ALMs, 1518 DSP blocks
  - 96 x 17.4 Gbps SERDES

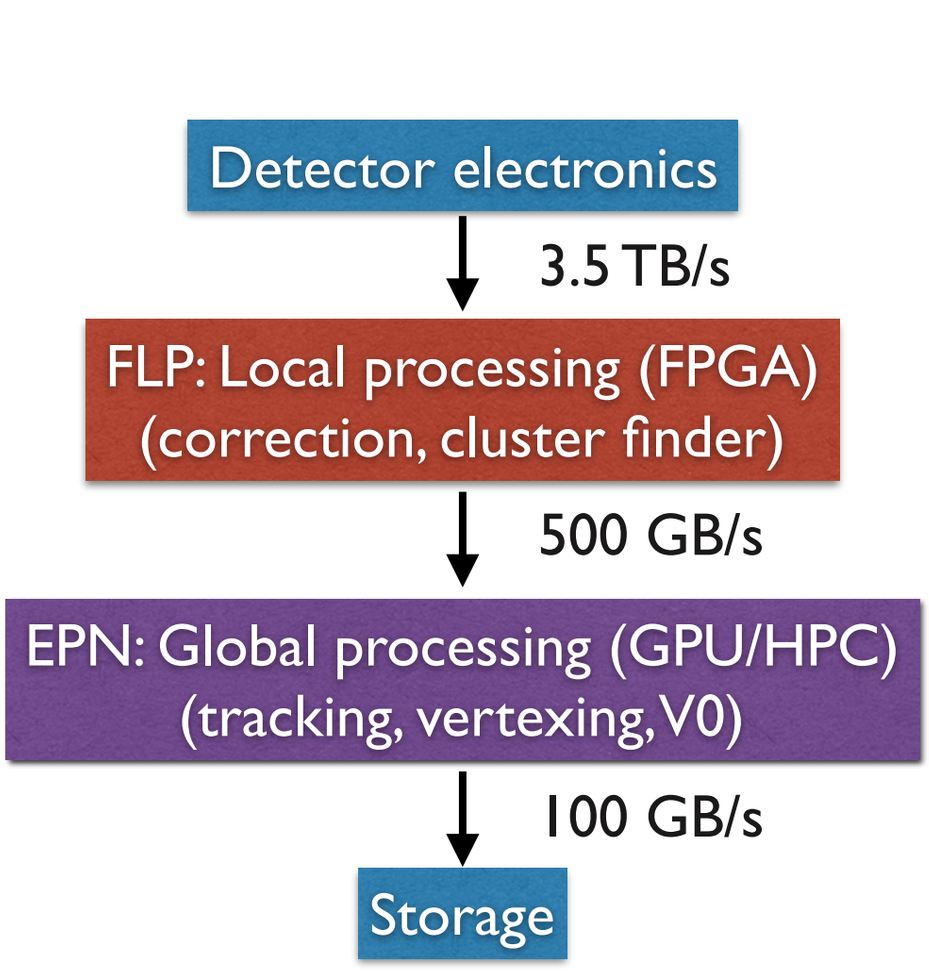


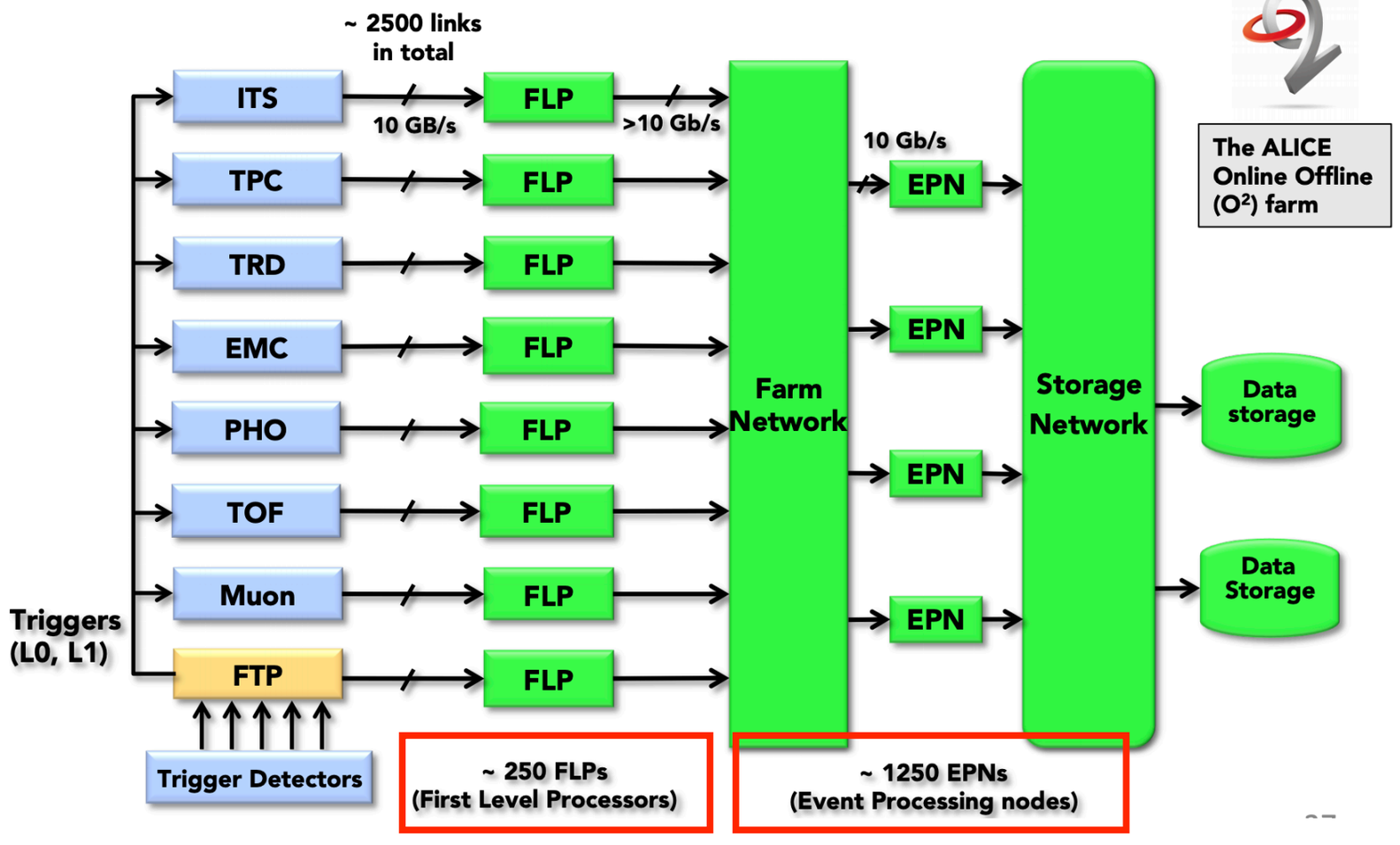
new DAQ system

Continuous readout of the TPC

→ Data volume = 3.5 TB/s. Impossible to write all data in the storage!

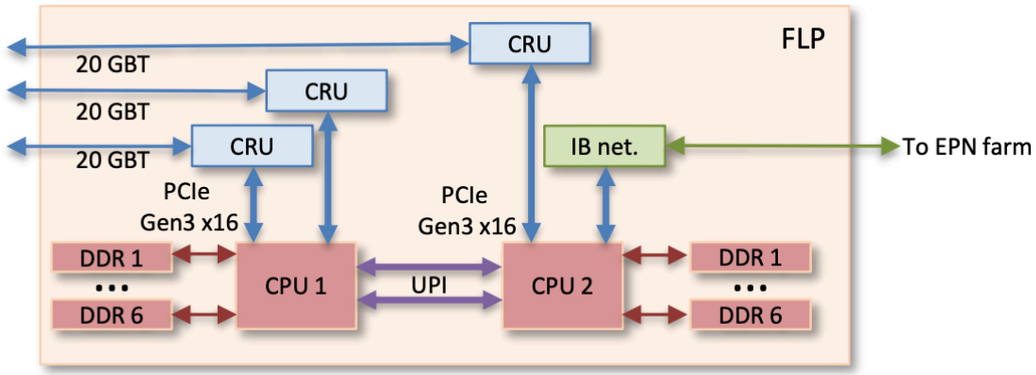
→ **Continuous data processing and online data reconstruction**

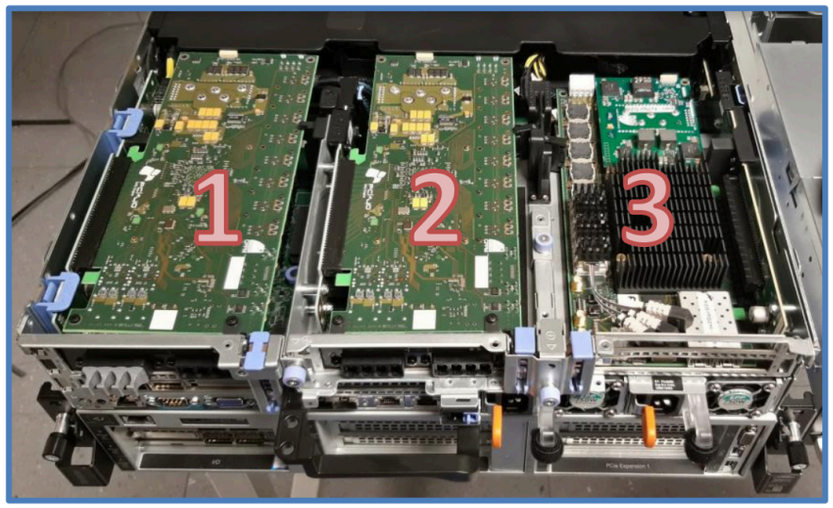




FLP and EPN

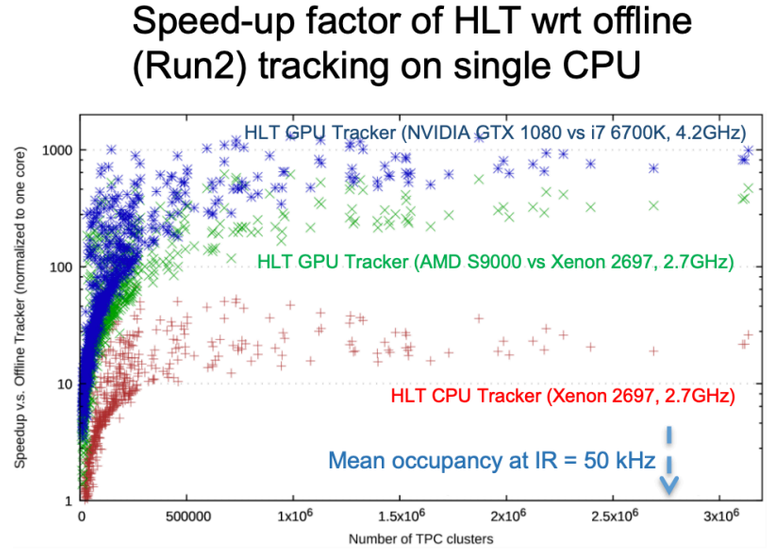
FLP (server (ASUS, Dell, SM) still under evaluation)





144 nodes are needed for TPC.
Data corrections and online clustering
→ data compression by x7.
Output to EPN farm: up to 100 Gb/s/FLP

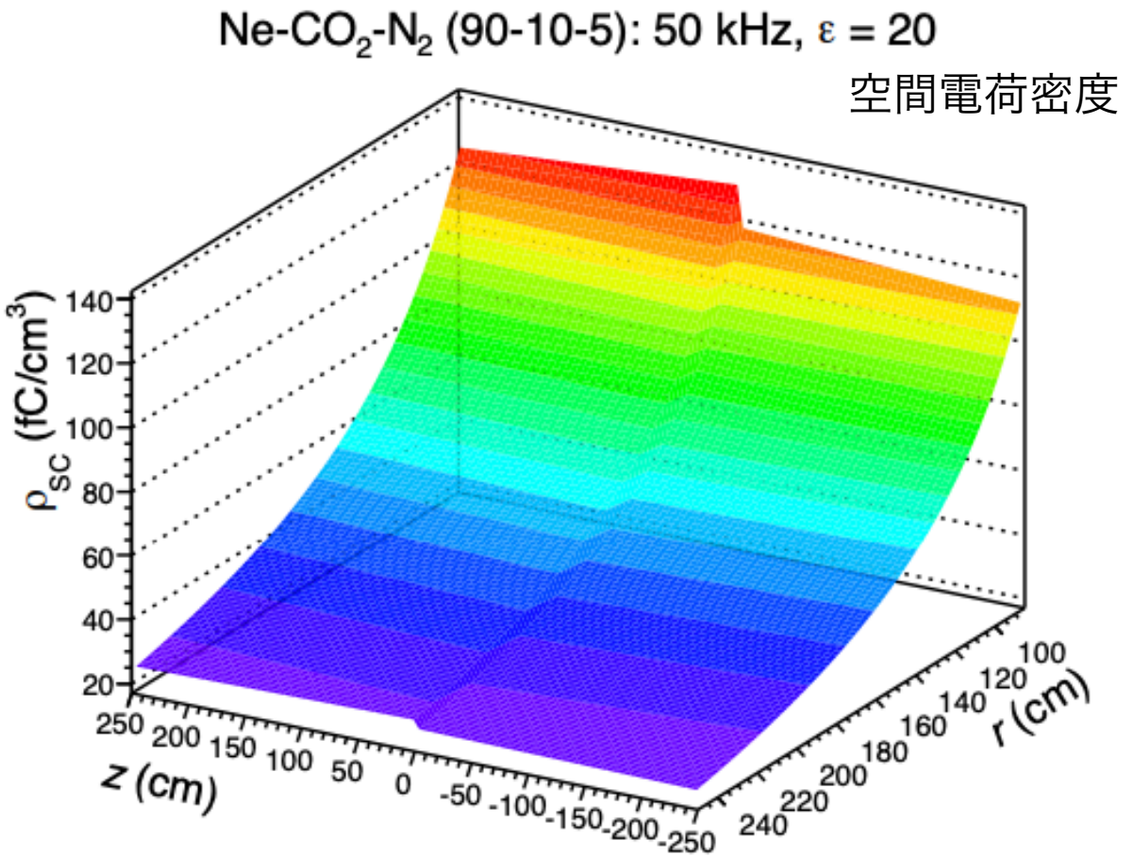
EPN (server/processors etc still under evaluation)



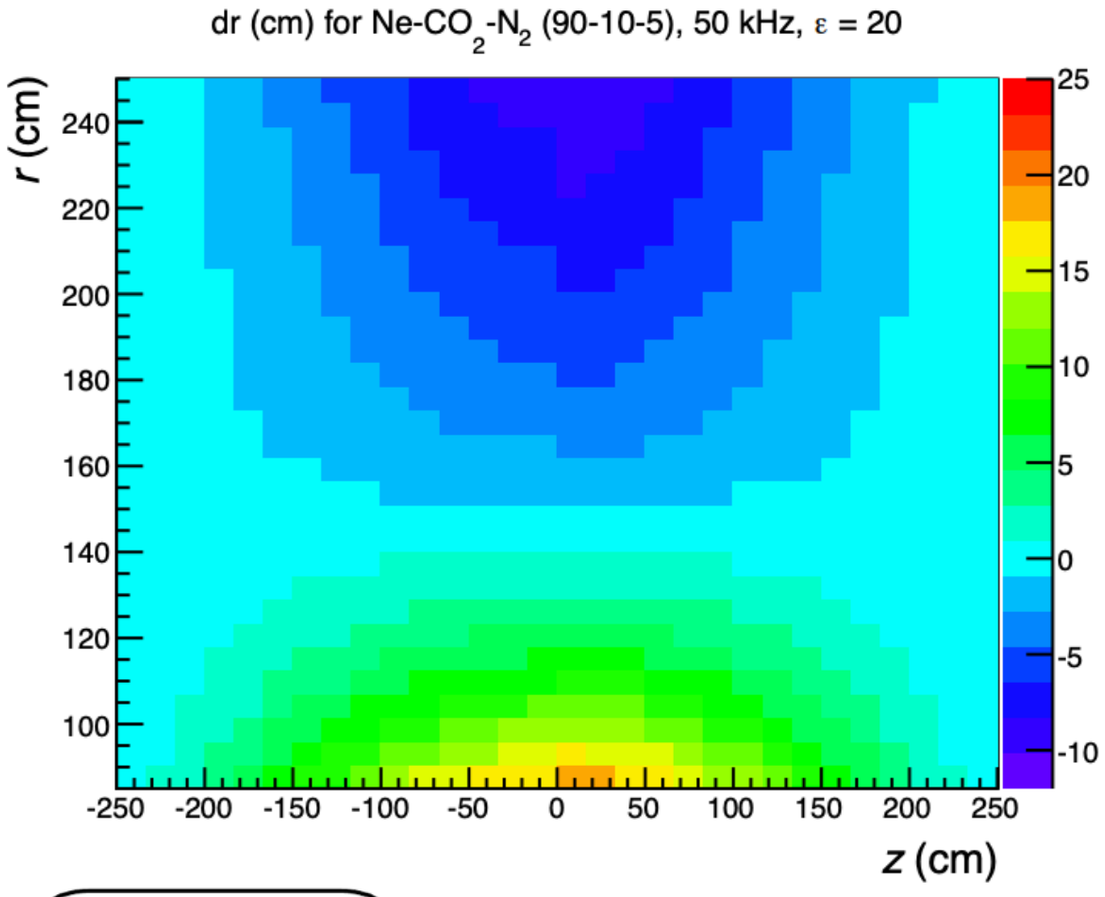
- ~750 EPN nodes and ~1000 GPUs will be needed.
- Full tracking by GPU
  - Online tracking by GPU was employed in HLT during Run2 operation. → x20-40 CPU
- Many developments are on-going
  - Hardware evaluation
  - Data transport between FLPs and EPNs Bandwidth (InfiniBand) test to storage
  - Load balancing
  - …

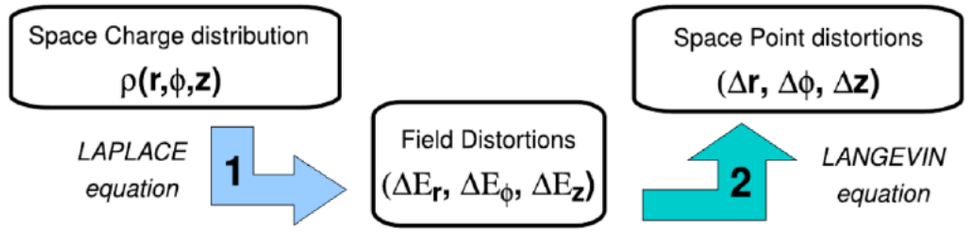
space-charge distortion correction

重イオンビーム衝突頻度：50 kHz
陽イオンドリフト時間：160 ms
→8000事象分の空間電荷がTPC検出器内部に蓄積



動径方向のずれ *O*(20 cm)



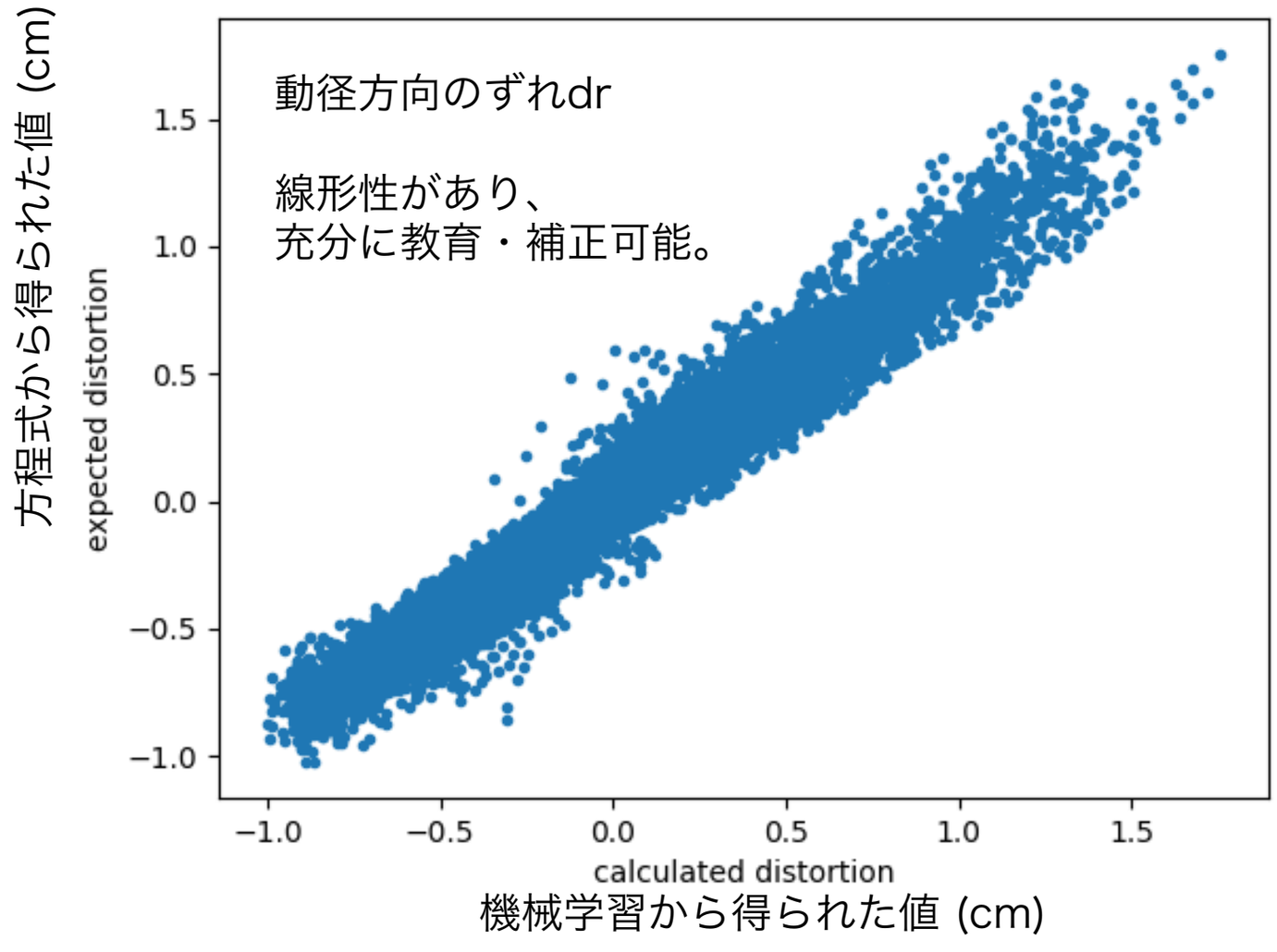


space-charge distortion correction

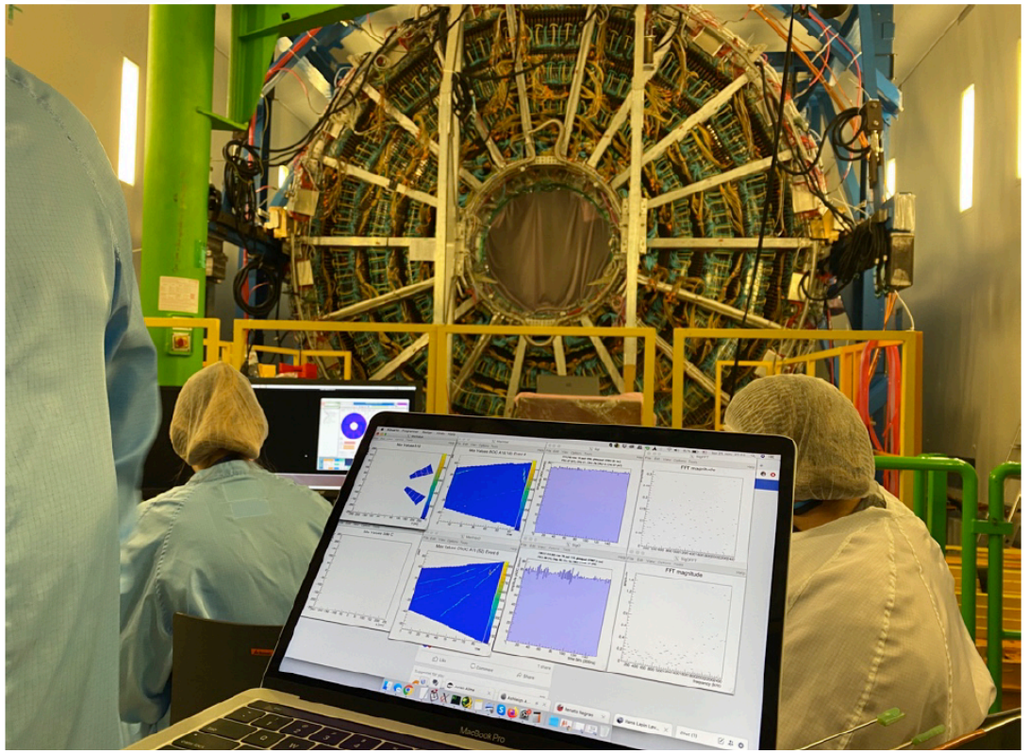
オンライン飛跡再構成のために端部パッド上でのずれ*O*(20 cm)を*O*(100 μm)までリアルタイムで高速補正
- 数分毎の読み出しチェンバーからの電流値→大局的ずれを補正*O*(mm)
- 5ms毎の読み出しチェンバーからの電流値→局所的空間電荷ゆらぎを機械学習で補正*O*(100 μm)

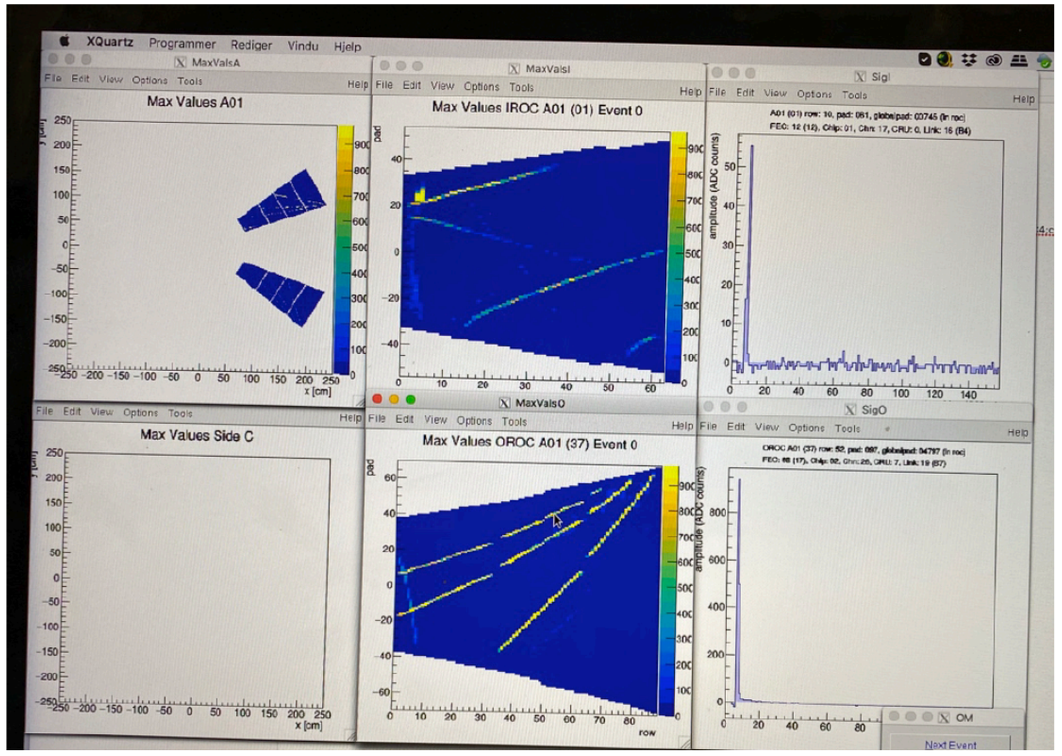
教師あり機械学習
Convolutional Neural Network with Keras
動径方向：17分割
ビーム軸方向：17分割
方位角方向：90分割

教育データ
空間電荷密度のゆらぎ：$\rho_{SC} - \langle\rho_{SC}\rangle$
端部パッド上でのずれのゆらぎ：$dr - \langle dr\rangle$



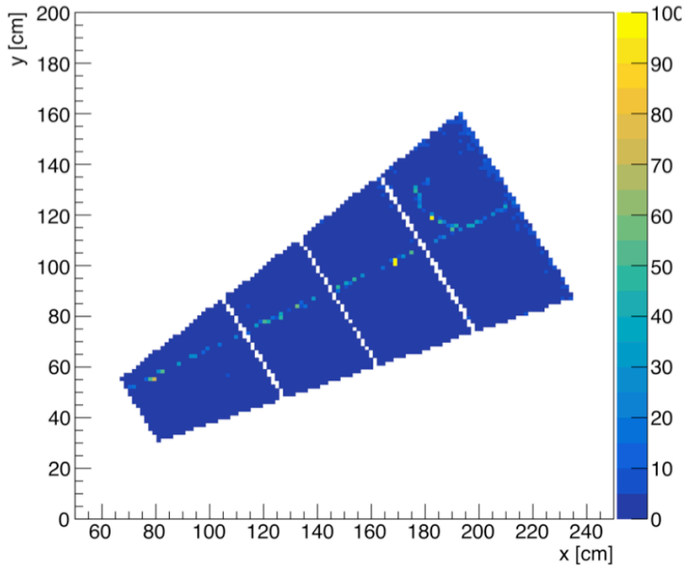
Pre-commissioning at P2

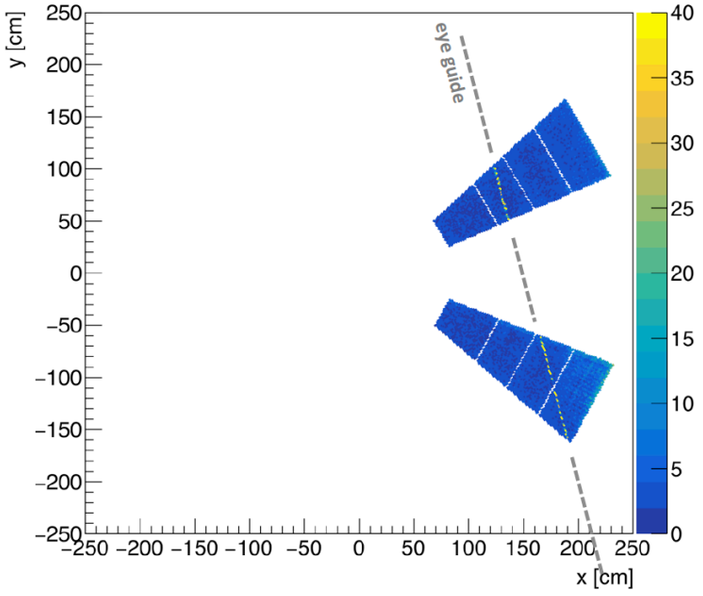




Status on 21 Nov: Operating gas mixture not yet nominal. Field Cage at 90 kV. GEM stacks in A01 and A16 at 98%. Laser tracks in TPC

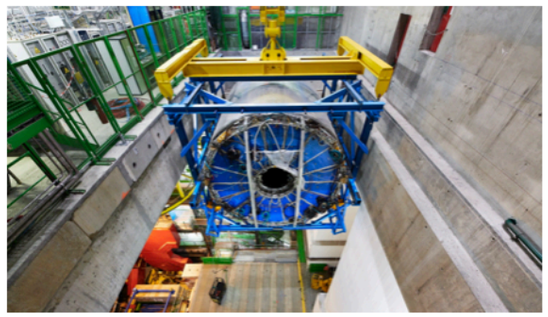
Cosmic tracks in GEM TPC

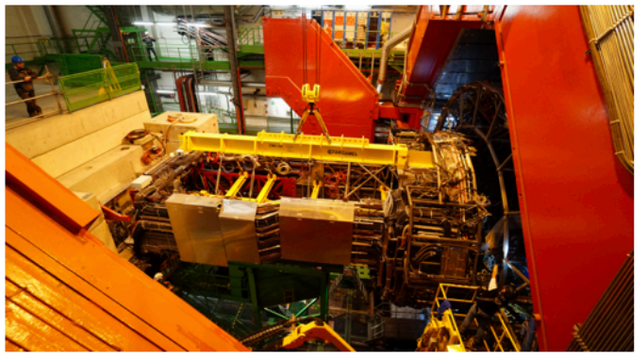


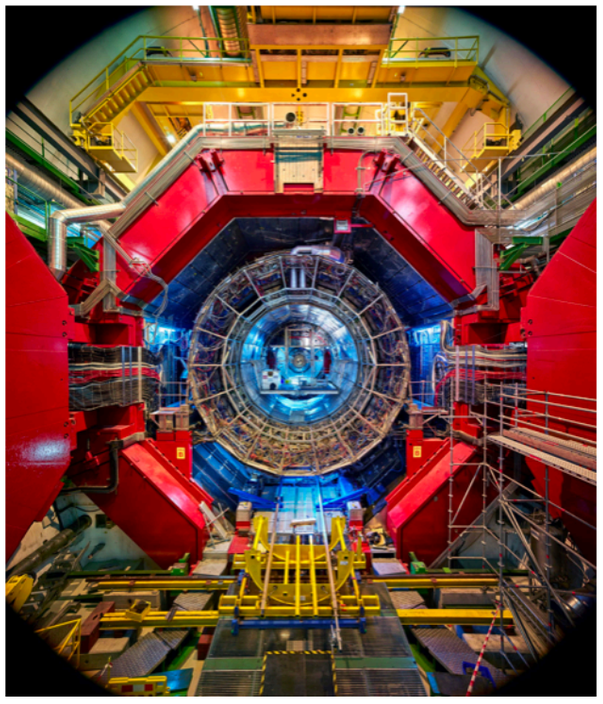


Timeline for the completion of upgrade

7/1/2019







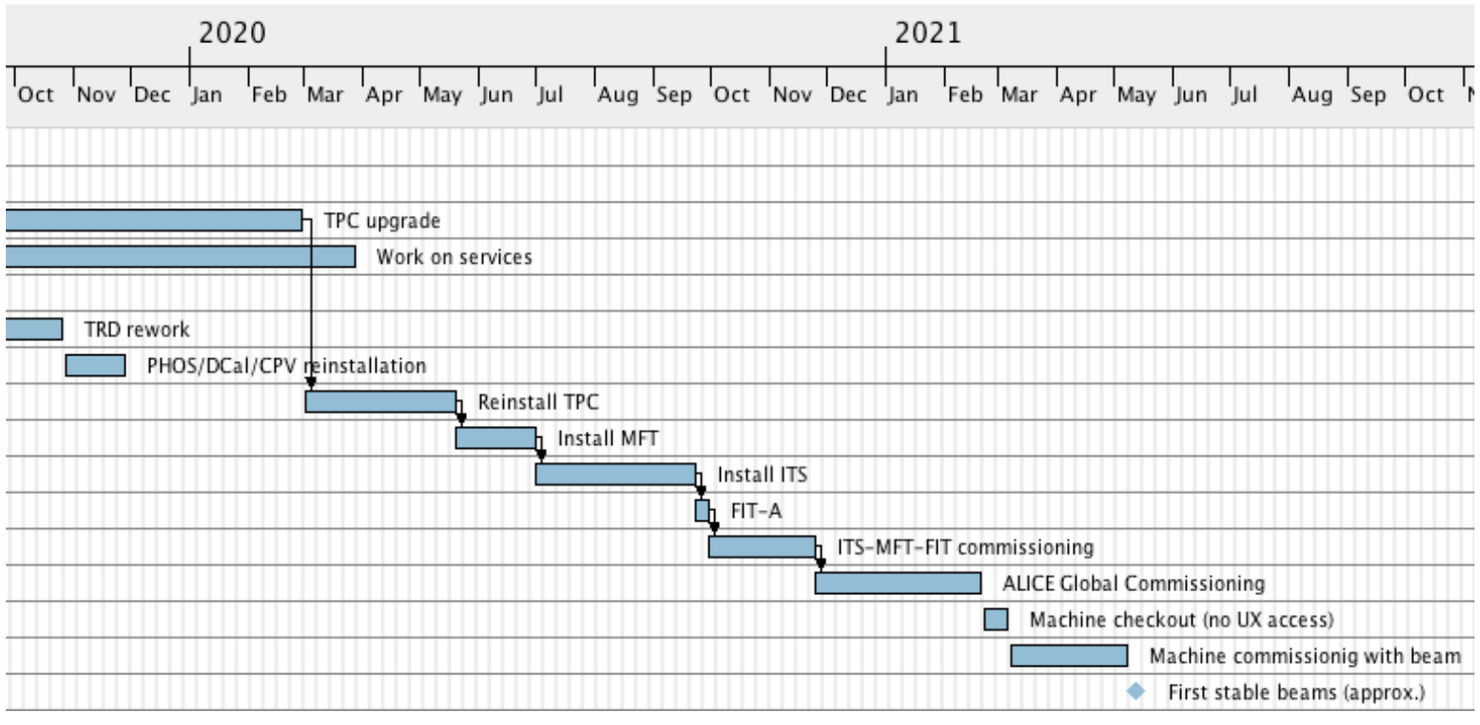
2020年3月~:TPCの再設置

2020年6月~: MFTの設置

2020年7月~: ITSの再設置

2020年11月~: コミッショニング

(2019-2020: Run coordinator:郡司)



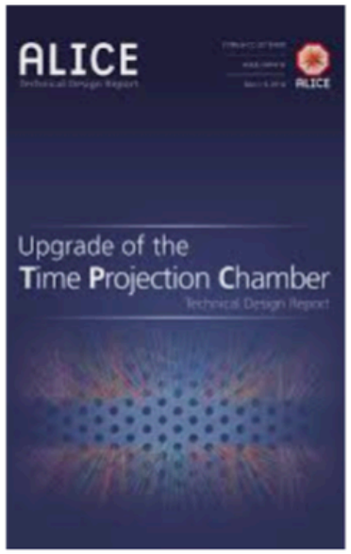
まとめ

- ALICE実験の高度化が順調に進行中
- 中央飛跡検出器(タイムプロジェクションチェンバー)の開発、要求仕様の策定とそれを満たすGEM検出器の開発に携わってきた
- GEMのmass production, QA, chamberの製作が終わり、TPCへの据付作業も無事に終了した
- 11月頃から、読み出しテストや宇宙線を用いた動作試験を進めている
- その一方で、データ収集系(CRUとEPNでのデータ処理)の整備を進めている
  - FPGAでのデータ処理(baseline and common mode correction, ZS, cluster finder)
  - GPUでのトラッキング
  - GPUや機械学習を用いた空間電荷効果補正
- 来年度の中頃から、全システムのコミッショニングを行う

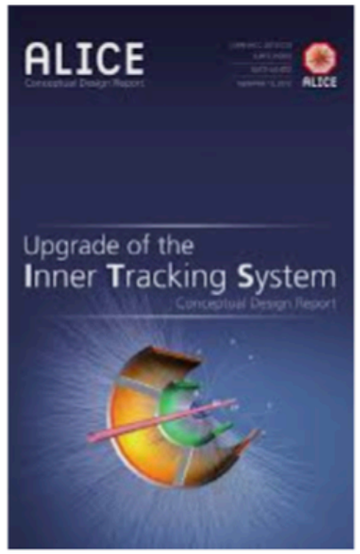
資料 (LoI, CDR, TDR)

CERN-LHCC-2012-012

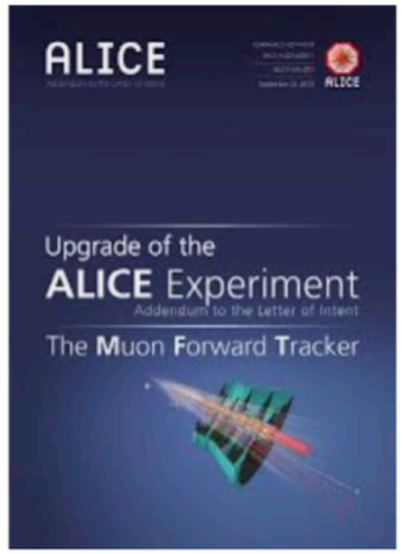
CERN-LHCC-2013-019



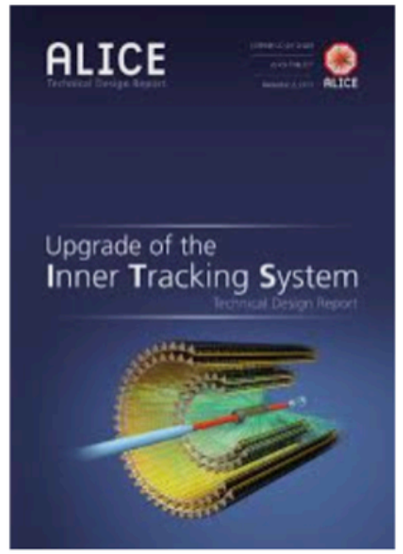
CERN-LHCC-2013-020



CERN-LHCC-2012-013



CERN-LHCC-2015-001



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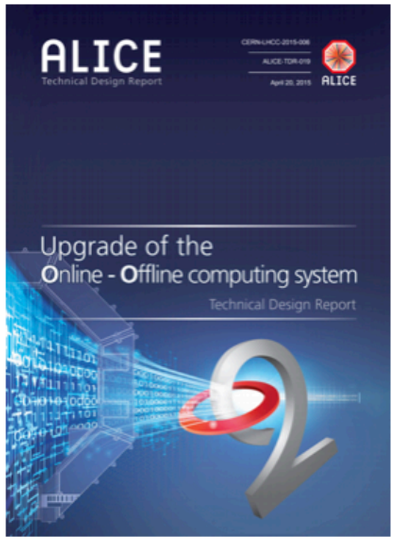

CERN-LHCC-2015-006