RPC at colliders – from LHC and beyond

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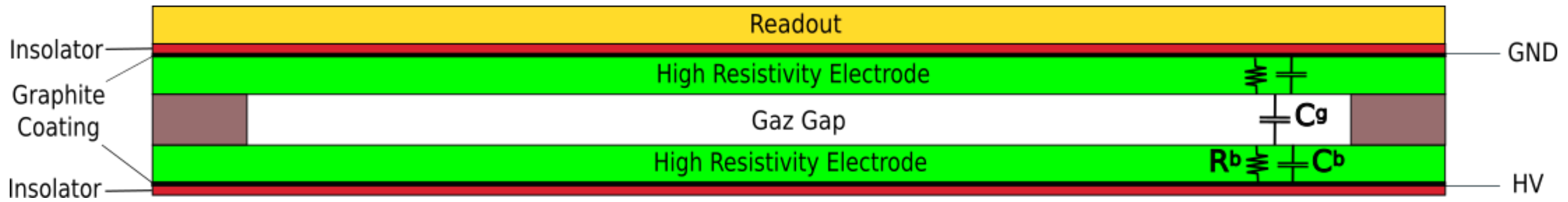
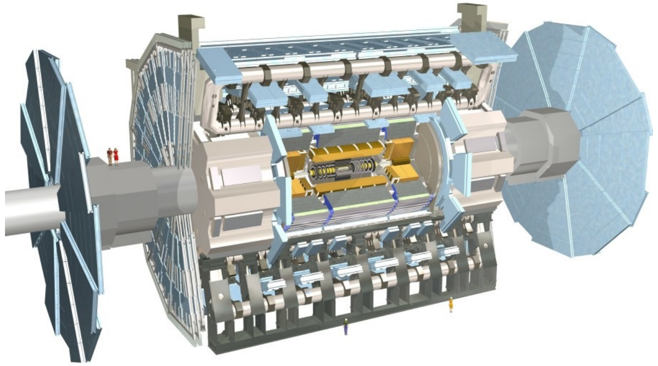
Resistive Plate Chamber - RPC

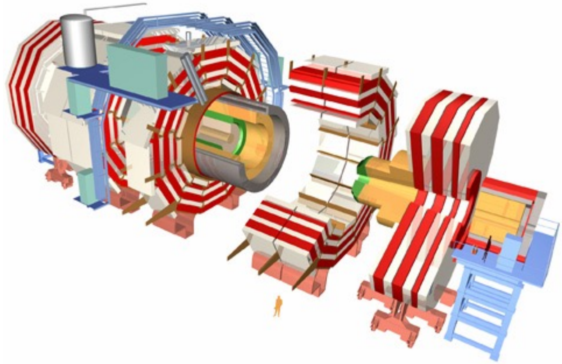


- Gas mixture is enclosed between two resistive electrode plates, whose outsides are painted with graphite to distribute high voltage across the electrodes.
- Easy to make in large size, low cost, good spatial and time resolutions, nice mechanical rigidity.
- Working mode: streamer and avalanche, the latter is more used nowadays in collider physics
- Gas system is necessary for circulation

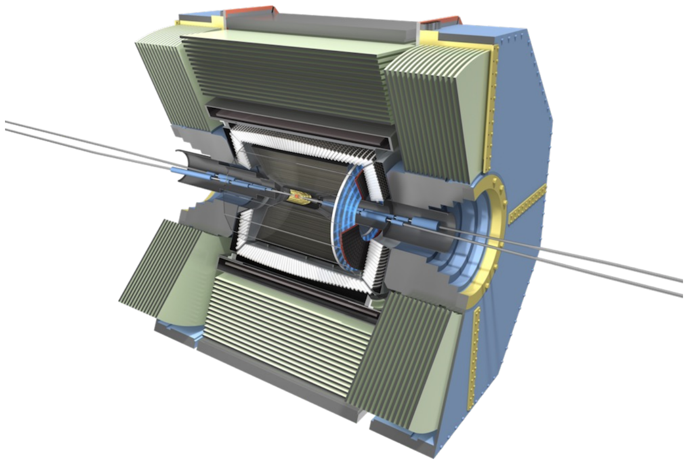
RPC at various colliders

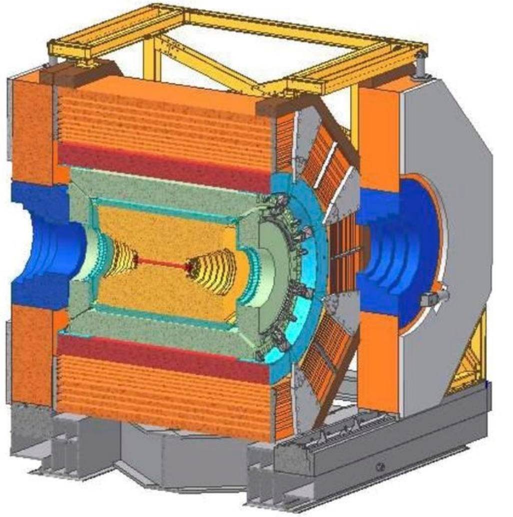
- Resistive Plate Chamber (RPC) is widely used in various experiments: ATLAS, CMS, ALICE, BeLLe, BES, …
  - Resistive materials: Bakelite; Glass
  - Single gap; Multi-gap



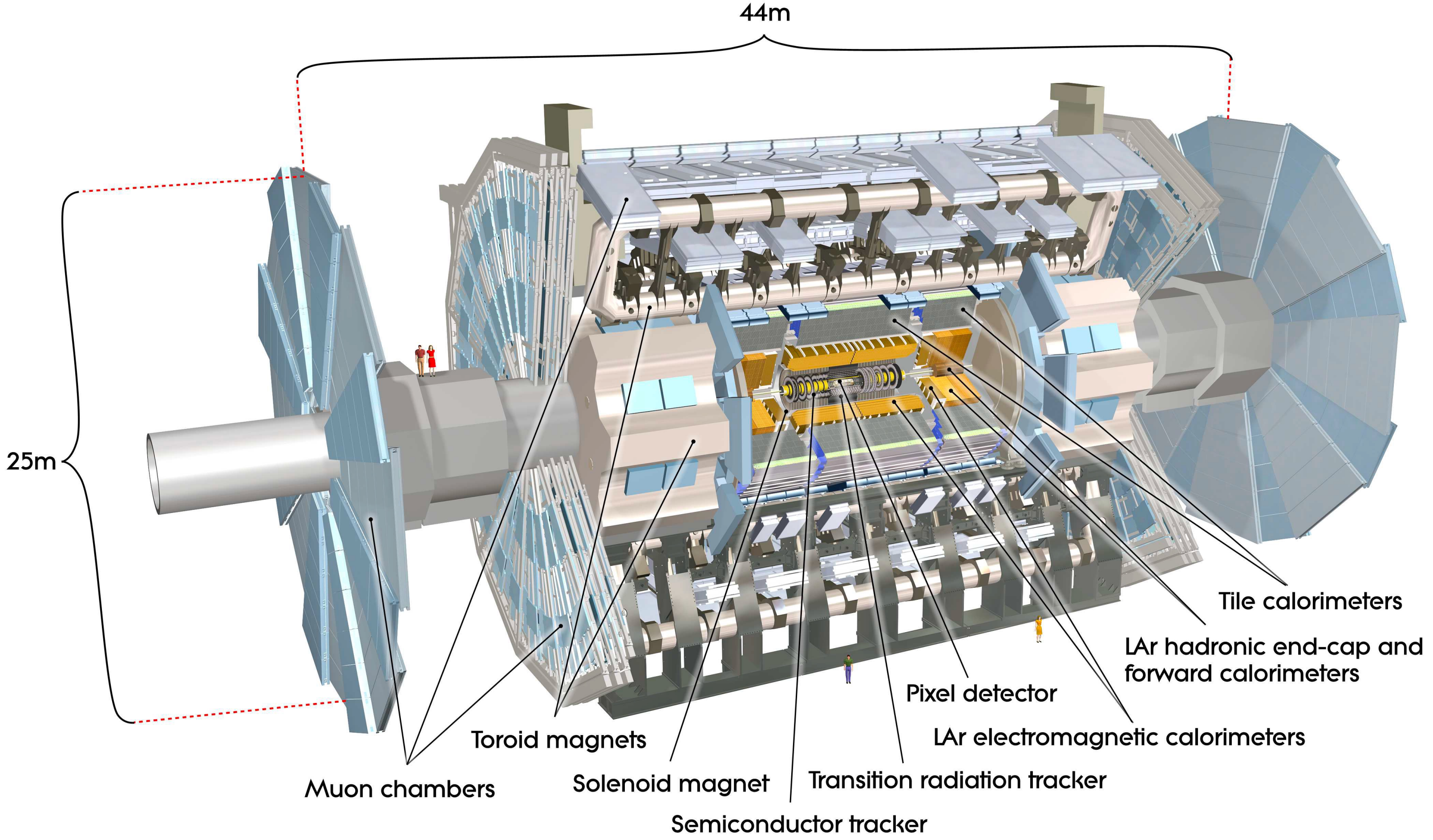


- Main parameters:
  - Gap width, Electrode thickness, Layers, …
  - Counting rate, efficiency, resolution of time and position

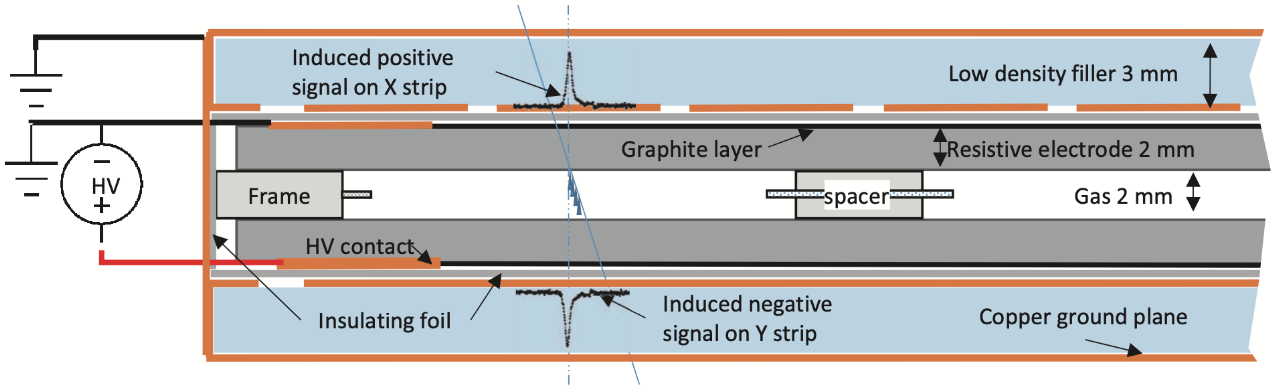




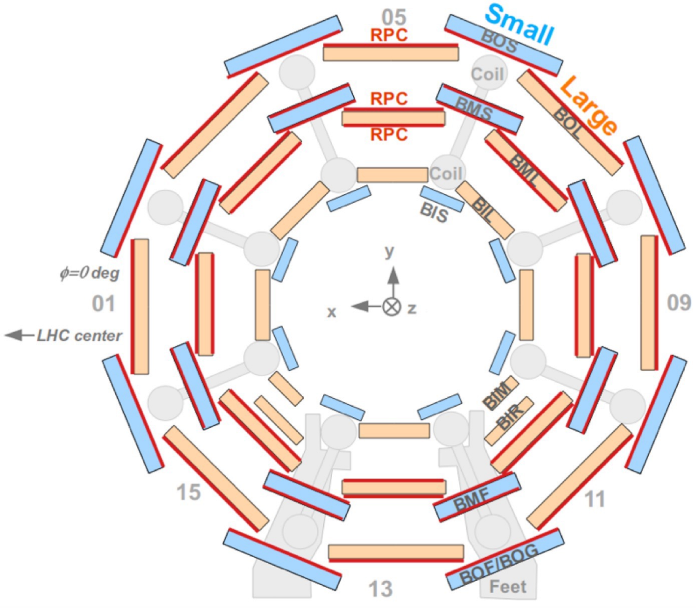
ATLAS Detector



ATLAS RPC



- Current RPC (bakelite):
  - 3 layers of doublet chambers, each with gap size 2mm
- Gas mixture:
  - Tetrafluorethane ($C_2H_2F_4$), Iso-Butane (Iso-C_4H_{10}), and Sulphurhexa fluoride (SF_6): 94.7%, 5%, 0.3%
- Readout: η- or ϕ-oriented strips on both sides of the chamber with FE electronics
- Use: for triggering, and also to reconstruct ϕ coordinate of tracks, and provide timing to reject cosmic muons and search for LLP



Current performance

Parameter	Value
Spatial resolution: η, ϕ	1 cm x 1 cm
Time resolution	1-2 ns
Muon efficiency	> 95%
Total surface	6785 m^2
Typical singlet surface	2 m^2
# of front-end channels	374,912
Designed duration	20 years
Long-term rate limit	100 Hz/cm^2
Peak luminosity	~2 x 10^{34} $cm^{-2}s^{-1}$

RPC in Run3: Gas Mixture Change

The RPCs are continuously flushed with a gas mixture of:

- $C_2H_4F_4$, the gas target for the primary ionization;
- i-C_4H_{10}, a quencher component that helps to avoid propagation of the discharge;
- SF_6, an electronegative component that helps to limit the growth of avalanches.

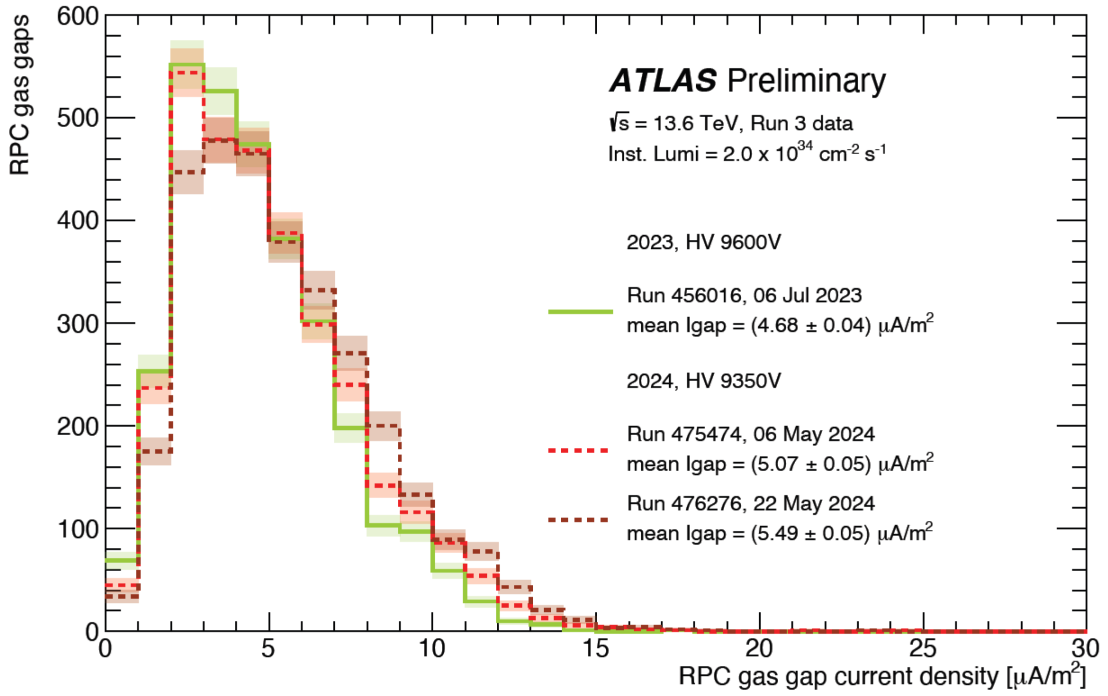
This gas mixture has a strong greenhouse effect, and it is currently being phased down in the European Union

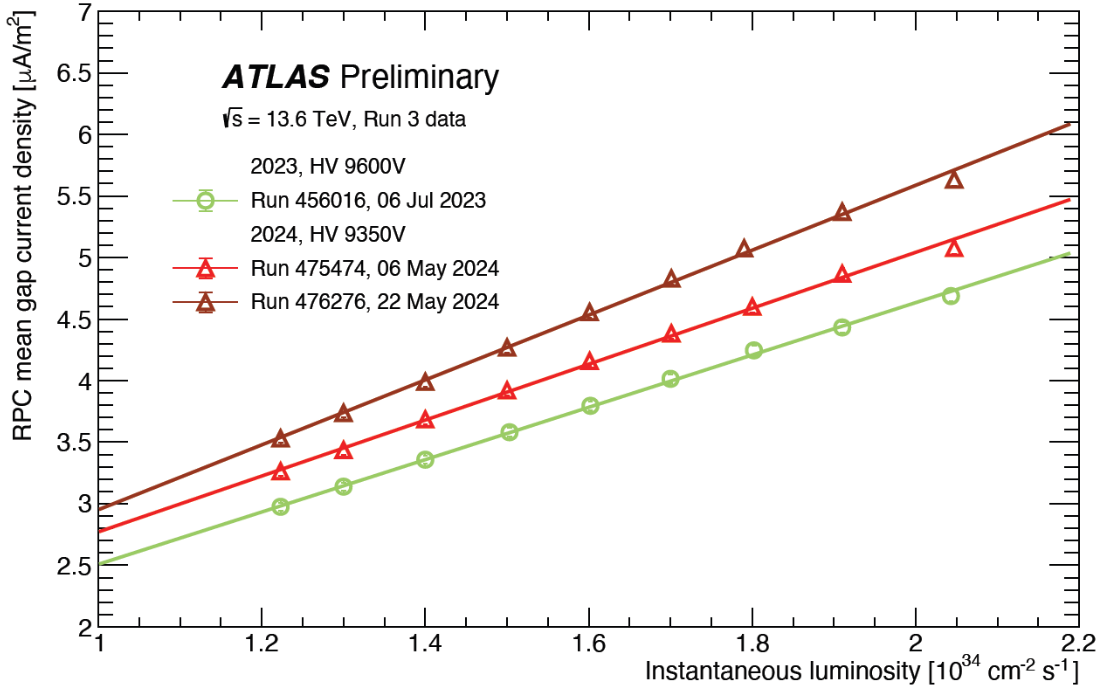
The gas mixture was changed in August 2023 during Run3:
from $C_2H_4F_4$ 94.7%, i-C_4H_{10} 5%, SF_6 0.3%
to $C_2H_4F_4$ 64%, CO_2 30%, i-C_4H_{10} 5%, SF_6 1%.

Foresee a ~14% reduction of the Global Warming Potential (GWP)

Gas gap current

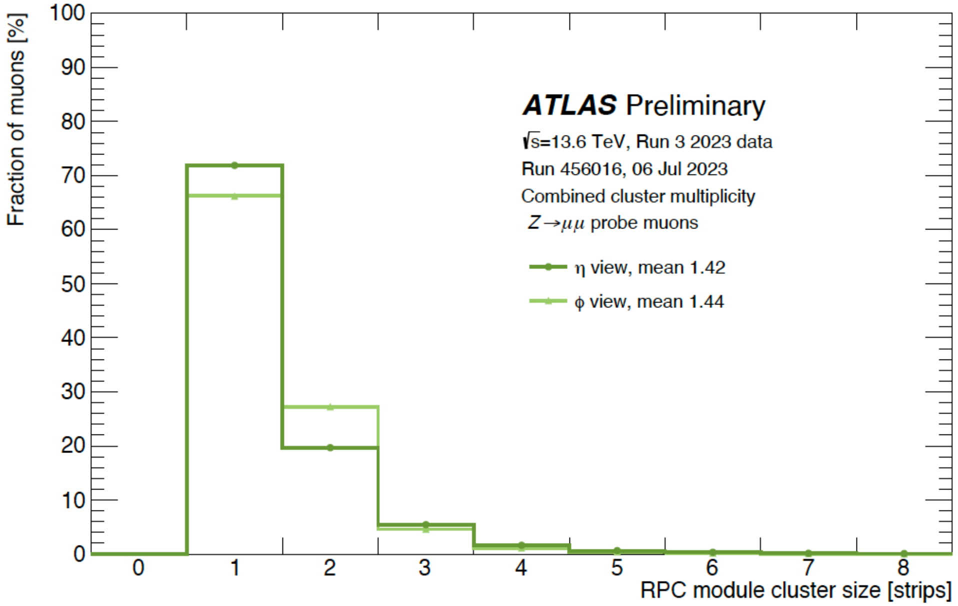
- An increase of the current density of the gas gaps of around ~17% in agreement with prototype results
- Linear increase of the RPC mean gap current density as a function of the instantaneous luminosity.

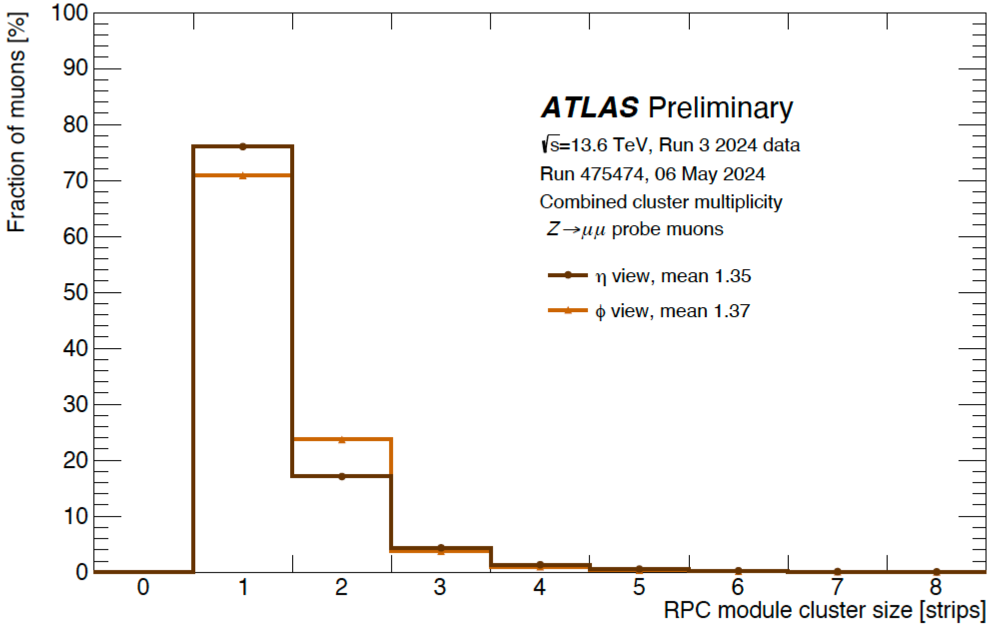




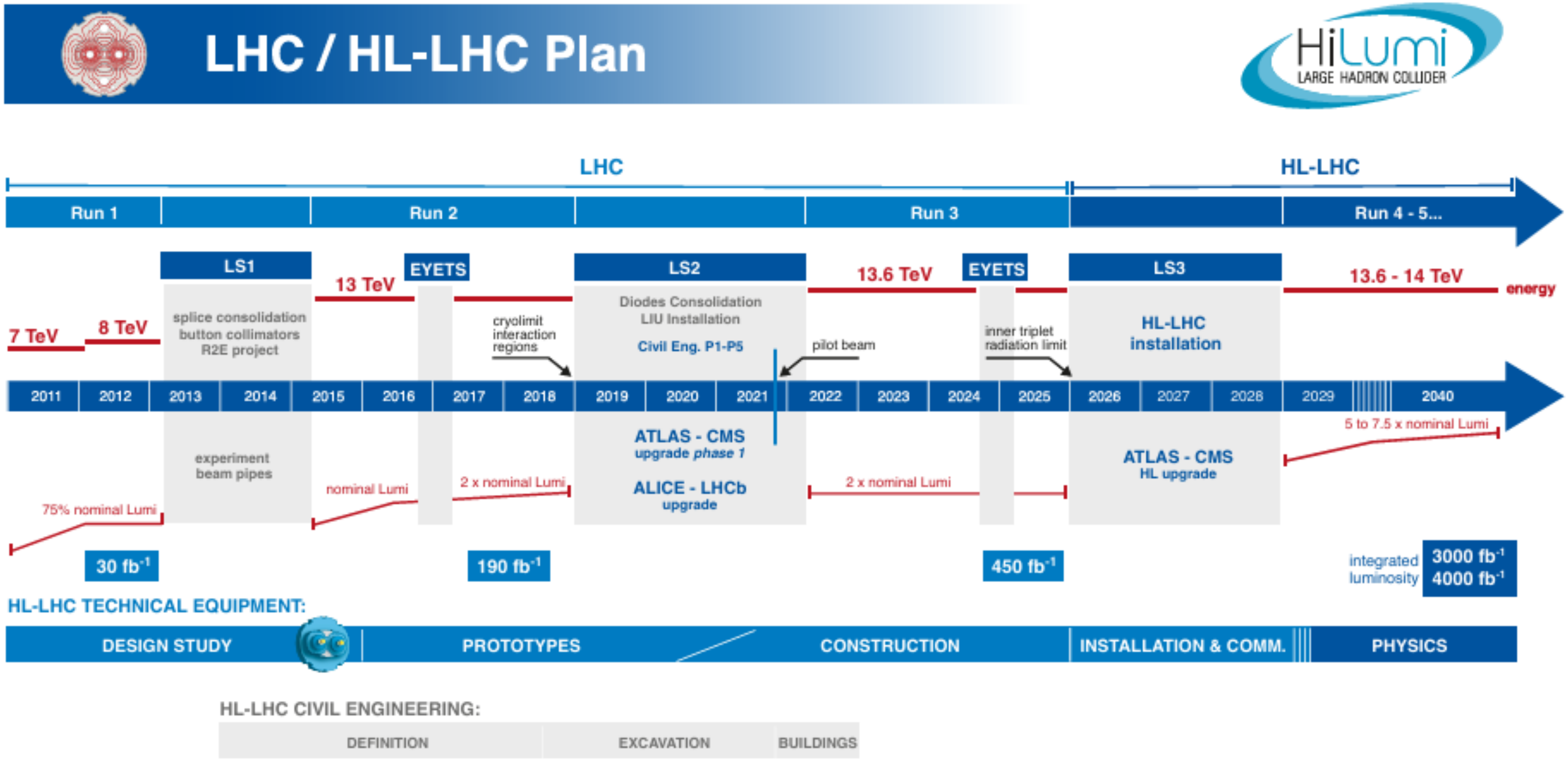
Cluster size at module level

The addition of CO_2 would increase the cluster size but the increased SF_6 component in the gas mixture limits the dimension of the avalanche. The combined effect yields a similar cluster size between 2023 and 2024, smaller in 2024 than in 2023. No signs of detector ageing effects yet.





High-Luminosity LHC



Thin-gap RPC of ATLAS Phase II

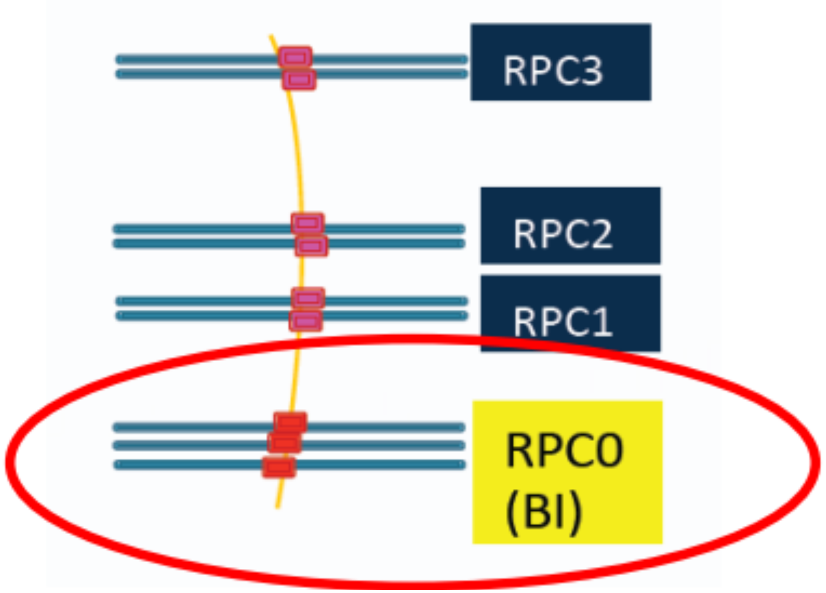
In the HL-LHC environment, the existing RPC faces the following problems:

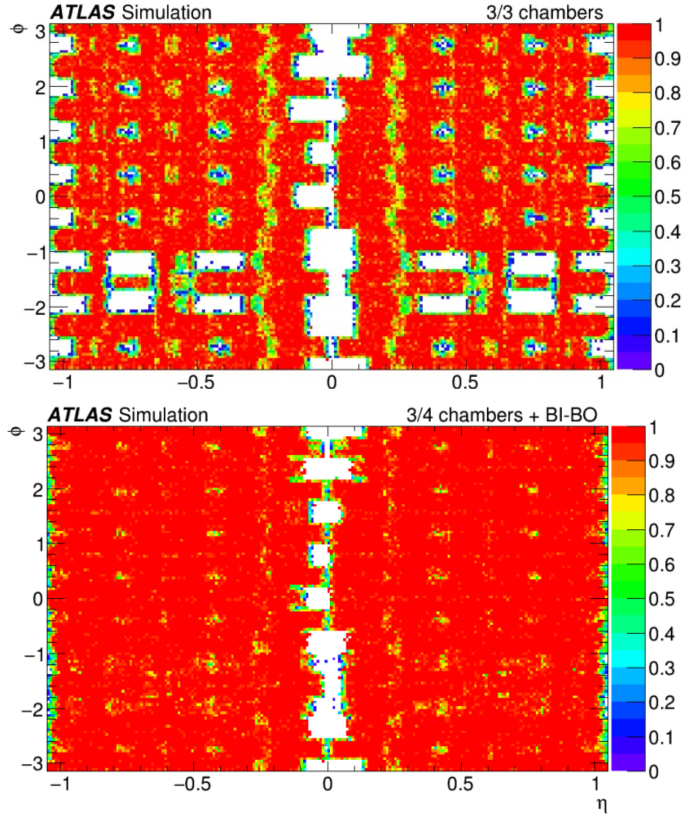
- Count rate capability of 2mm air gap <100 Hz/cm^2
- RPC has reached the design life of 10 years
- Can only operate at low voltage, which reduces efficiency
- System coverage is low

Solution:

- Add 3 layers of high-counting rate RPC in the inner layer of the barrel to improve redundancy and ensure triggering efficiency
- Use narrow air gap structure to increase counting rate, time resolution and life
- Substantially improve the coverage of the muon system

USTC, SJTU & SDU have been collaborating in this task on behalf of China





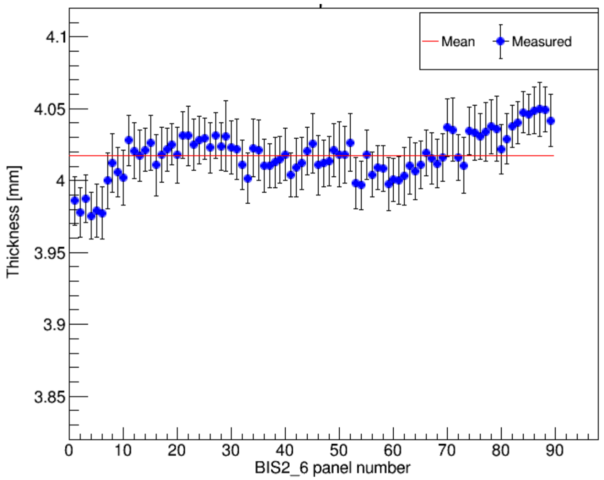
Detector R&D

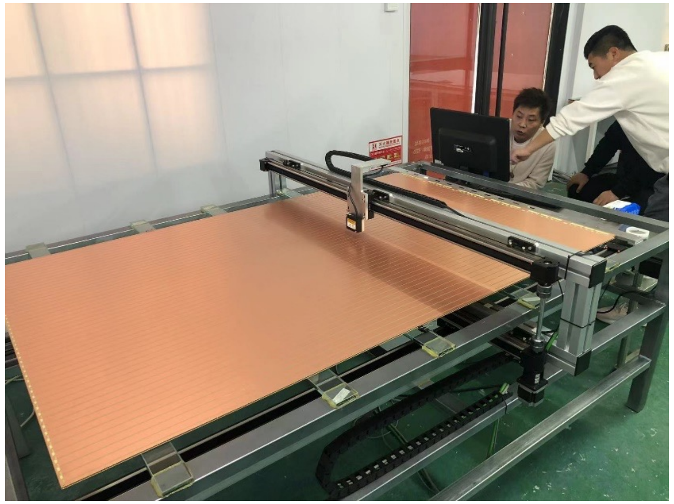
The main technical solutions for upgrading the RPC in Phase-II include:

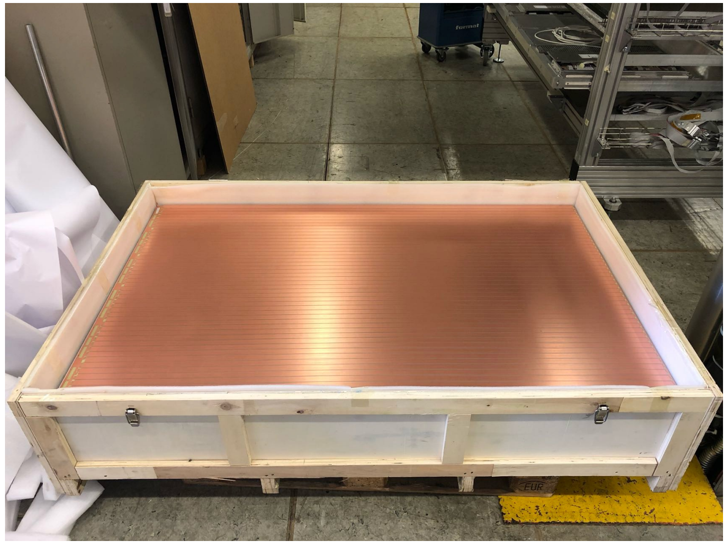
- Use a narrow air gap of 1 mm: reduce avalanche charge, increase the counting rate, increase the life of the detector, and improve time resolution
- Use a 1.4 mm bakelite thickness: improve the counting rate capability
- Use high-sensitivity, high signal-to-noise ratio front-end electronics: compensate for gas gain
- Use a dual-end readout method: reduce the number of channels, use time difference positioning, and improve position resolution

Readout panel

- Flatness Control of Honeycomb Readout Panel
- Main challenges:
  - Large readout panel: length ~1.7m, width ~1.1m
  - Thickness accuracy/flatness: < 100 μm
- Technical solution
  - Production process optimization
  - Effective thickness/flatness detection method

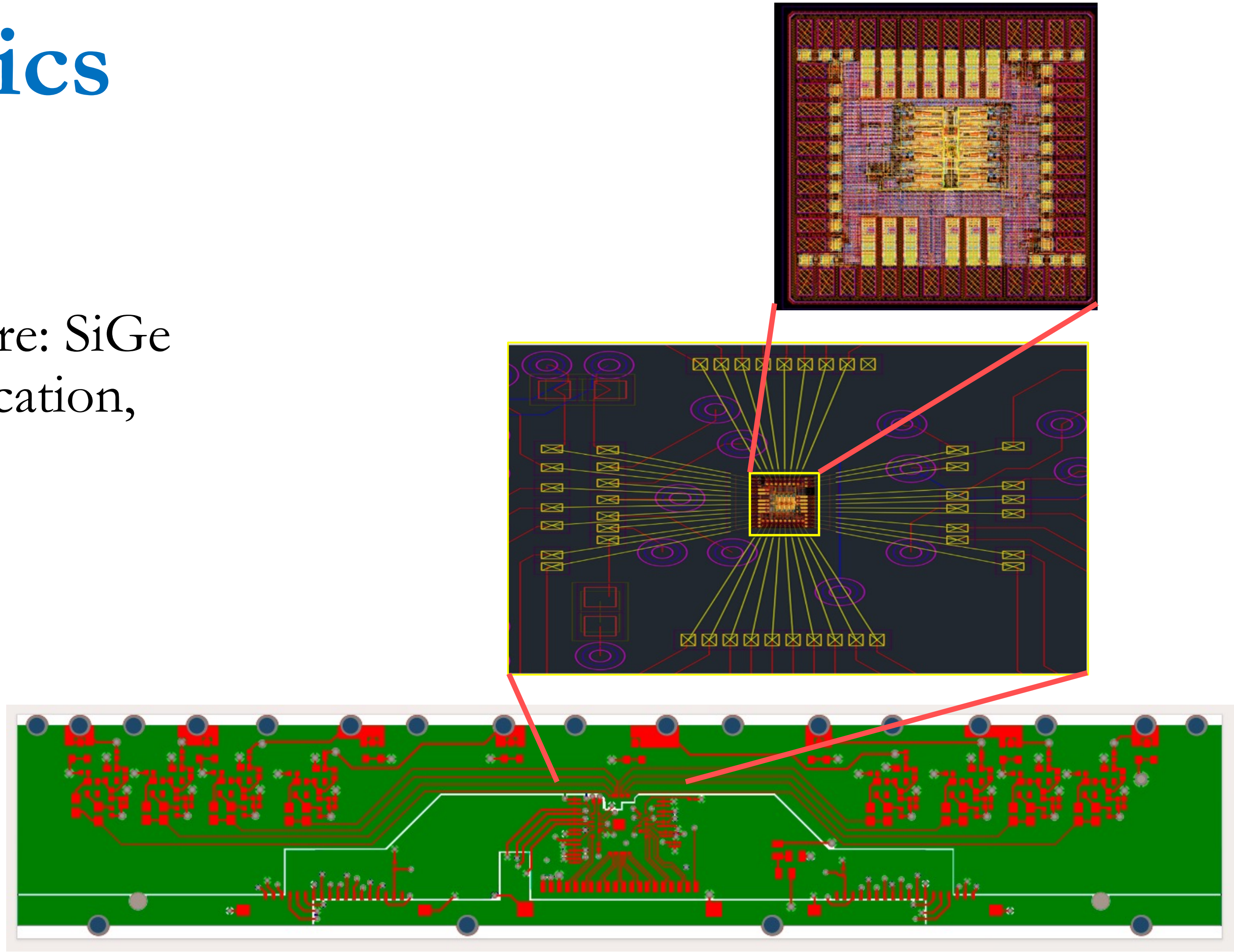






Front-end Electronics

- Main challenges:
  - Digital-analog combined circuit structure: SiGe pre-amplification + ASIC main amplification, discrimination, TDC
  - ASIC chip bonding and detection
  - Electronics batch functional testing

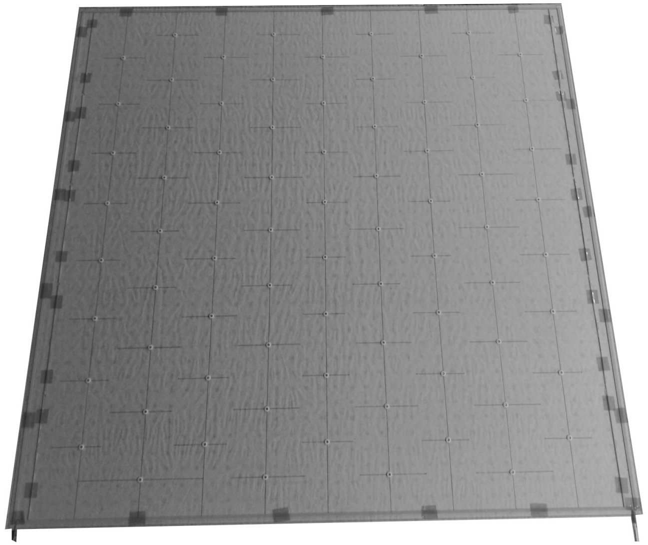


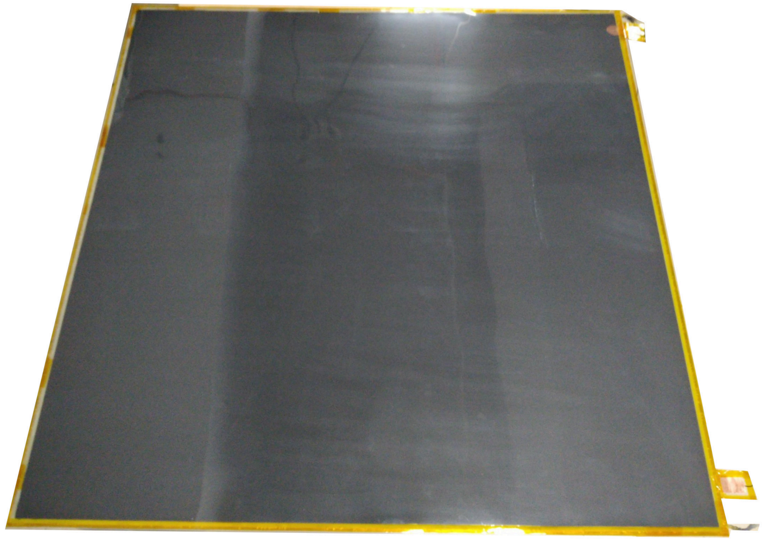
- Technical solution
  - Production and quality control
  - Establish functional testing process

Possible future consideration/improvement for CEPC

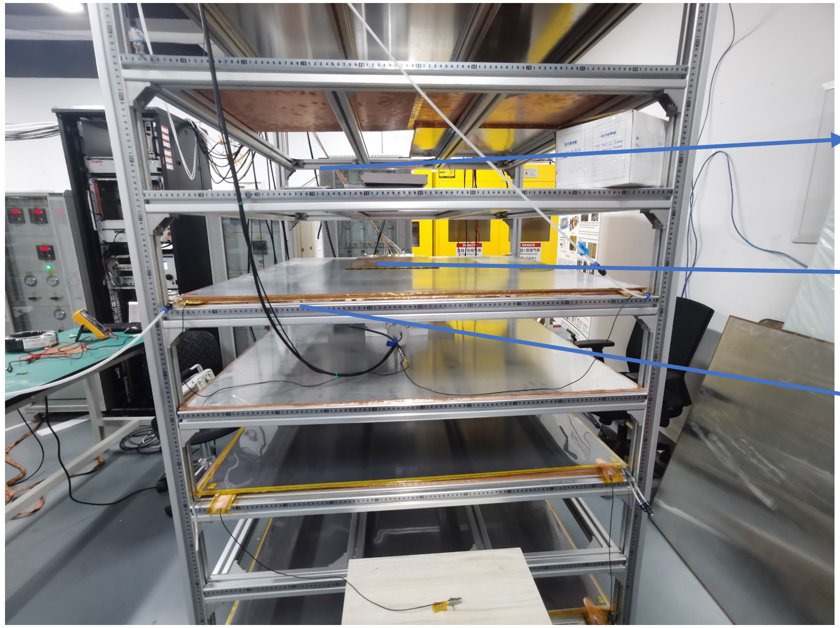
- Narrower chamber gap: better rate (ATLAS)
- MRPC: better time resolution, e.g. 70ps (ALICE)
- Bakelite vs glass: rate, surface smoothness, …
  - Some new type of glass could be explored, which has comparable resistivity as bakelite
  - Or, if the expected rate is not high, floating glass could also be used
- Gas: consider alternatives due to global warming potential

SJTU RPC activities





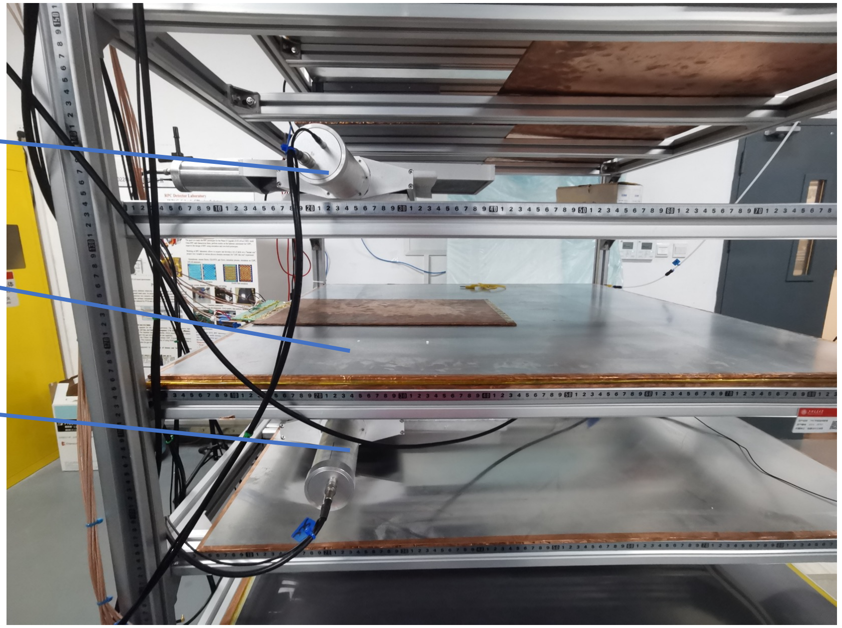
1m*1m*1.2mm glass RPC



Scintillators

RPC

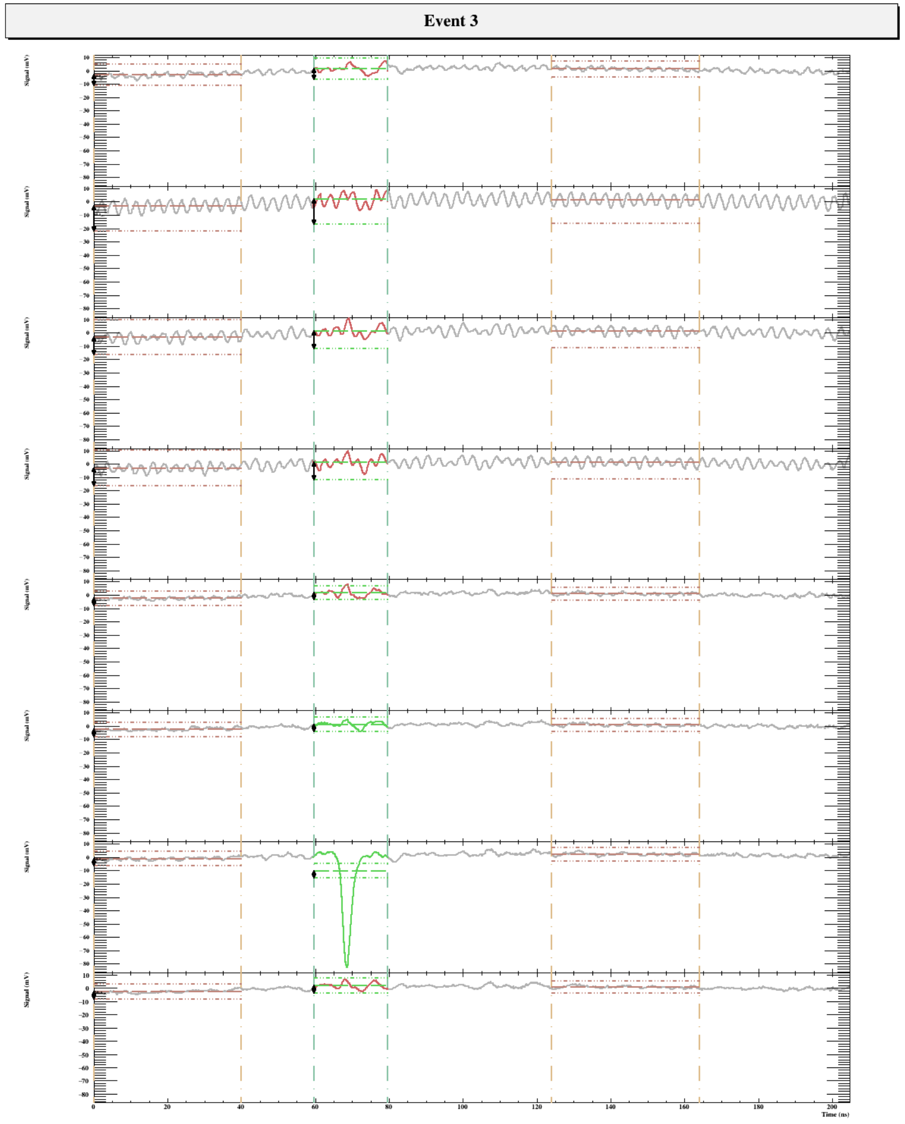
Scintillators

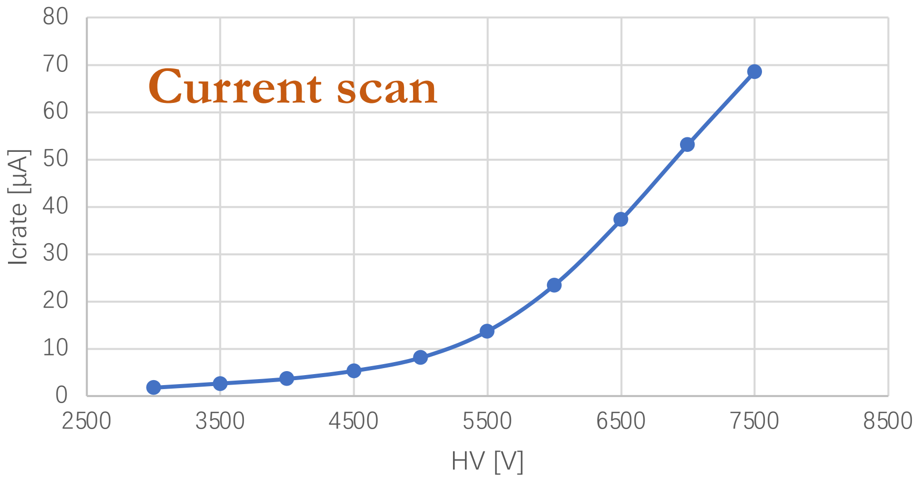


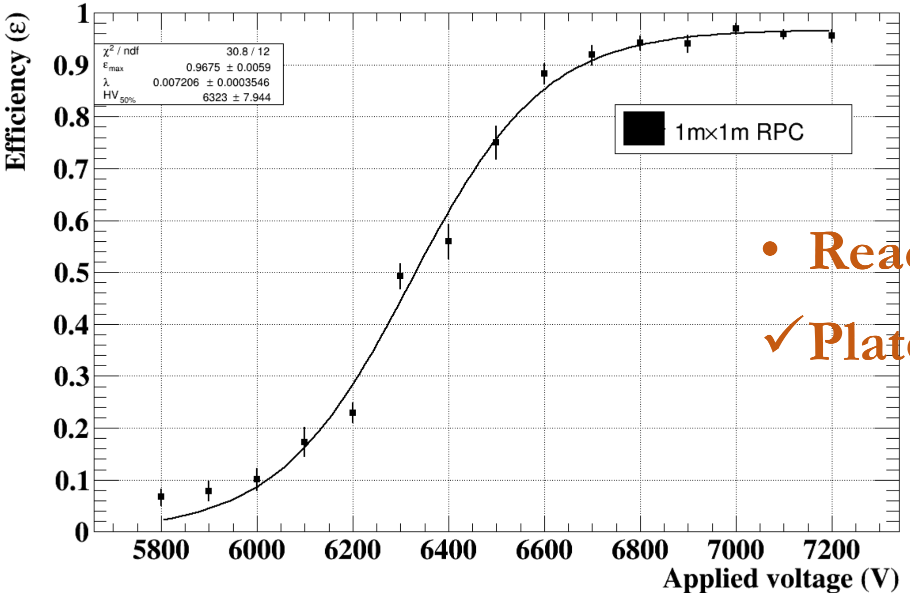
Test setup

RPC Test

- 2 noise regions to define the baseline
- Extract signal when max>5σ







- Reach plateau at ~6900V

✓ Plateau efficiency > 95%

Time Resolution

Find the time when the signal amplitude reach $\alpha \times (\text{peak} - \textit{baseline})$ $(\alpha \in [0, 1])$

As $t_{sc1}, t_{sc2}, t_{RPC}$ separatly

$$\Delta t_{12} = t_{sc1} - t_{sc2}$$

$$\Delta t_{RPC} = t_{RPC} - \frac{t_{sc1} + t_{sc2}}{2}$$

(Assume $\sigma_{t_{sc1}} = \sigma_{t_{sc2}} = \sigma_{t_{sc}}$)

$$\Longrightarrow \sigma_{\Delta t_{12}} = \sqrt{2} \times \sigma_{t_{sc}}$$

$$\Longrightarrow \sigma_{\Delta t_{RPC}} = \sqrt{\frac{\sigma_{\Delta t_{12}}^2}{2} + \sigma_{RPC}^2}$$

$$\Longrightarrow \sigma_{RPC} = \sqrt{\sigma_{\Delta t_{RPC}}^2 - \frac{\sigma_{\Delta t_{12}}^2}{2}}$$

FDU provided scintillators of high time resolution for triggering

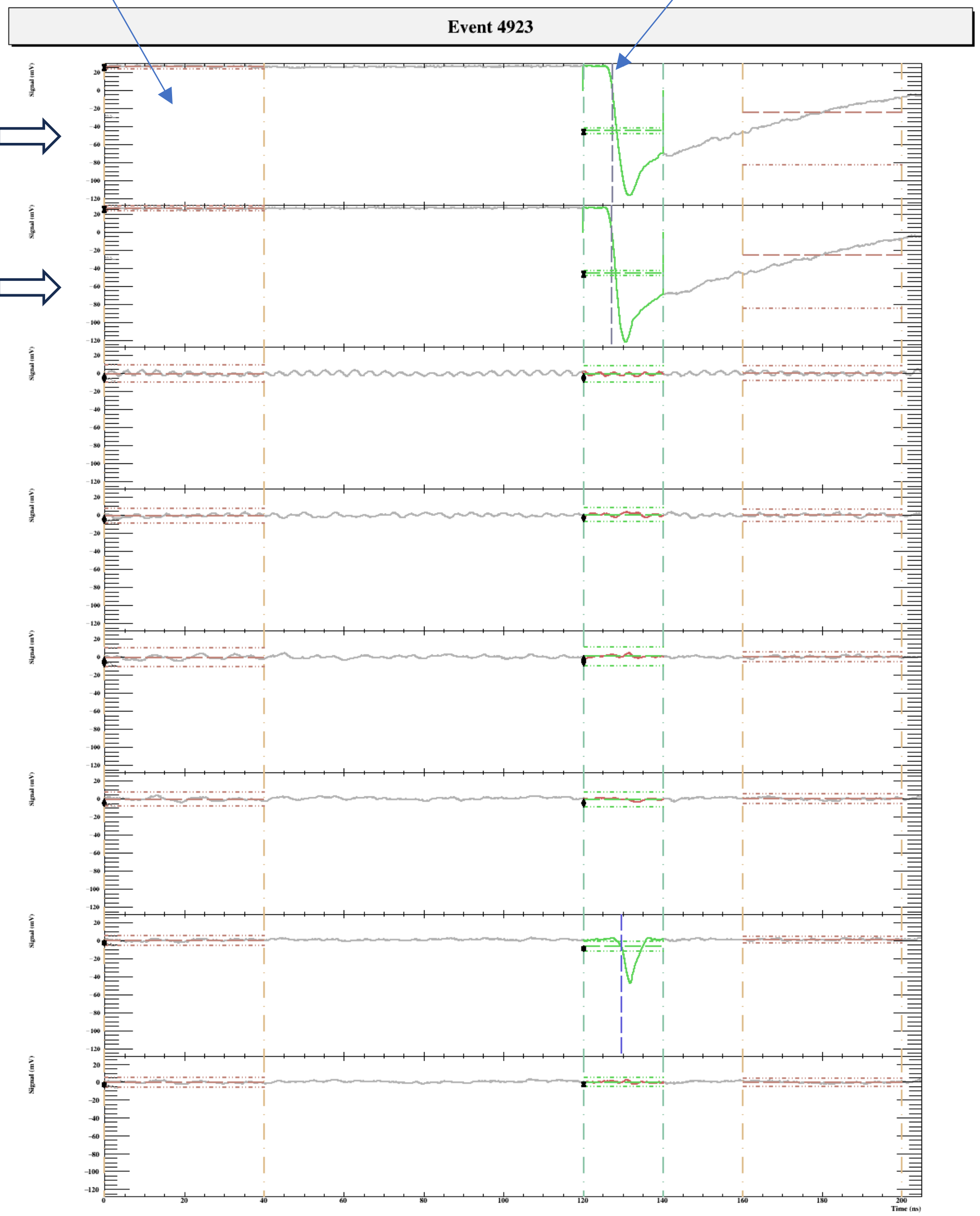
Time when signal reach the set threshold

Time window to calculate the *baseline*

Sc1

Sc2

RPC channels

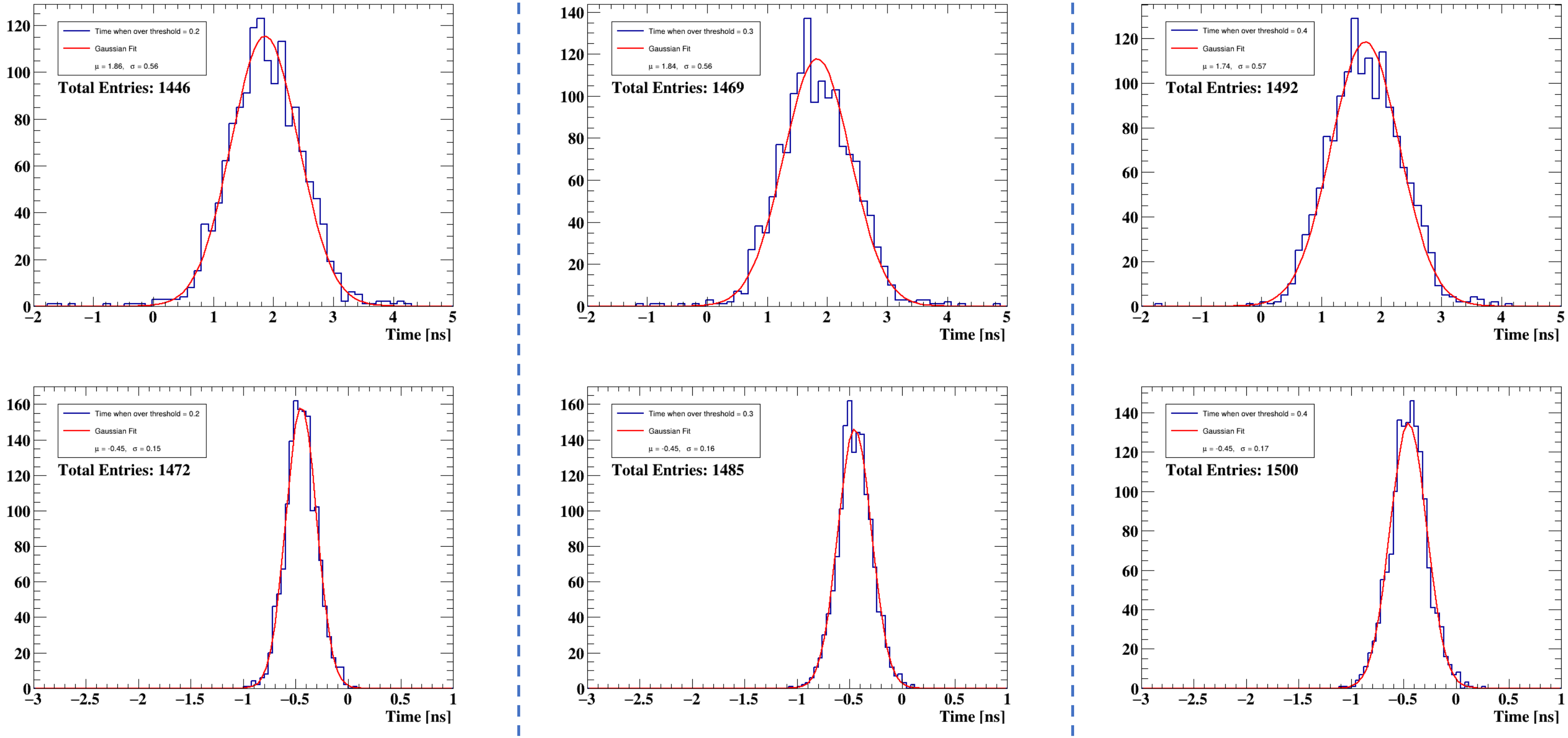


Time Resolution

Threshold = 0.2 | Threshold = 0.3 | Threshold = 0.4

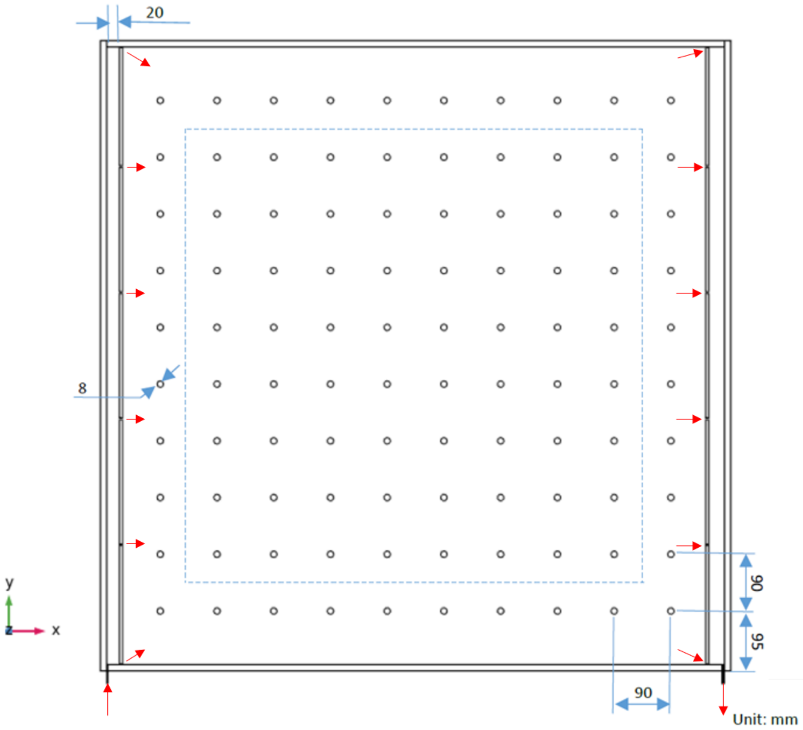
Δt_{RPC}:

Δt_{12}:

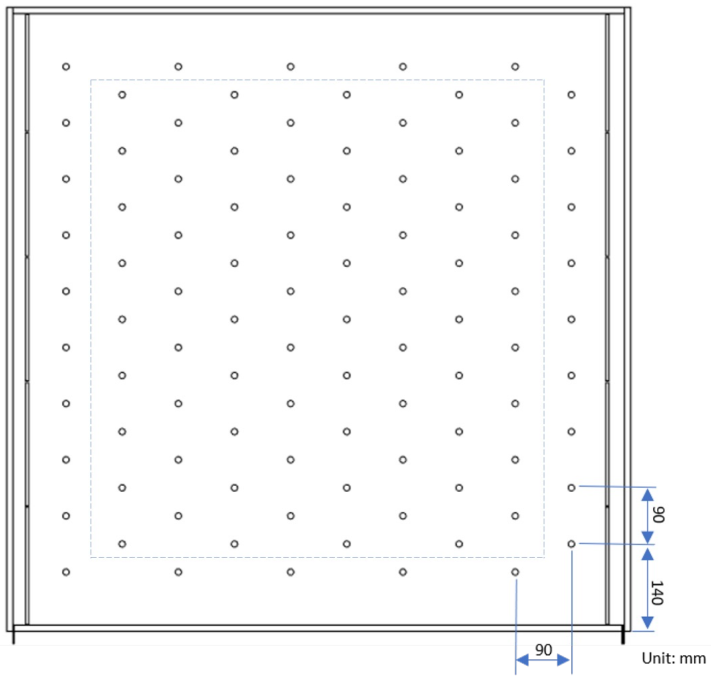


- $\sigma_{RPC} = \sqrt{\sigma^2_{\Delta t_{RPC}} - \frac{\sigma^2_{\Delta t_{12}}}{2}} \approx 550ps$, for 1.2mm gas gap

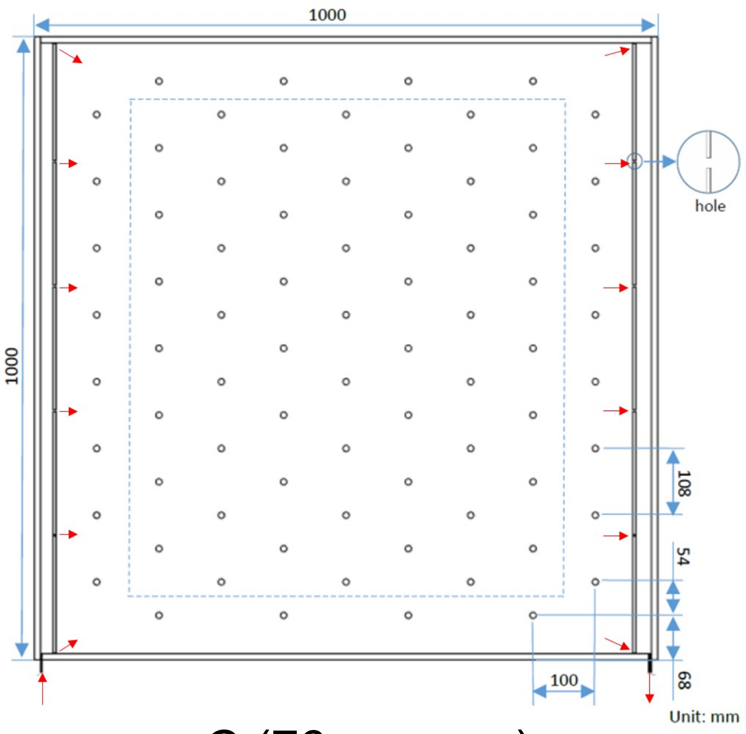
Geometry of RPC models



A (10×10 spacers)



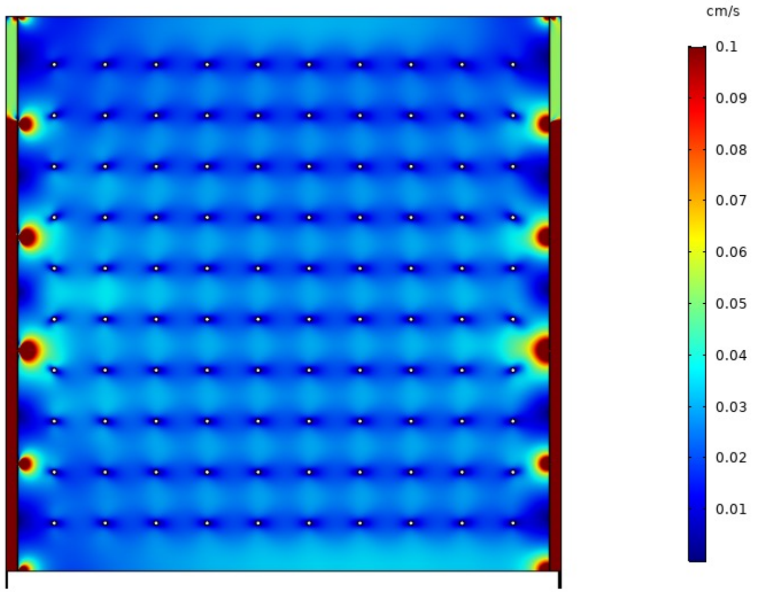
B (95 spacers)



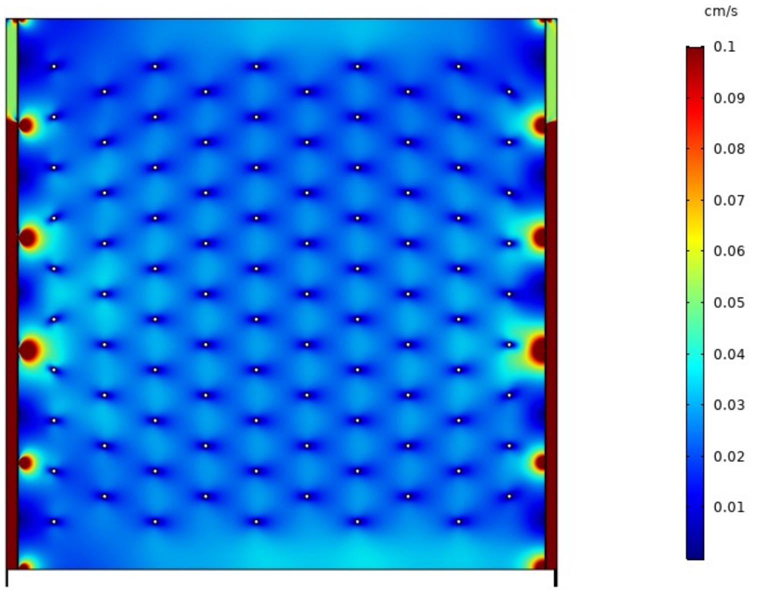
C (76 spacers)

- Red arrows show the routine of the gas flow
- The center part of the chamber marked by the dashed lines is used for result comparison

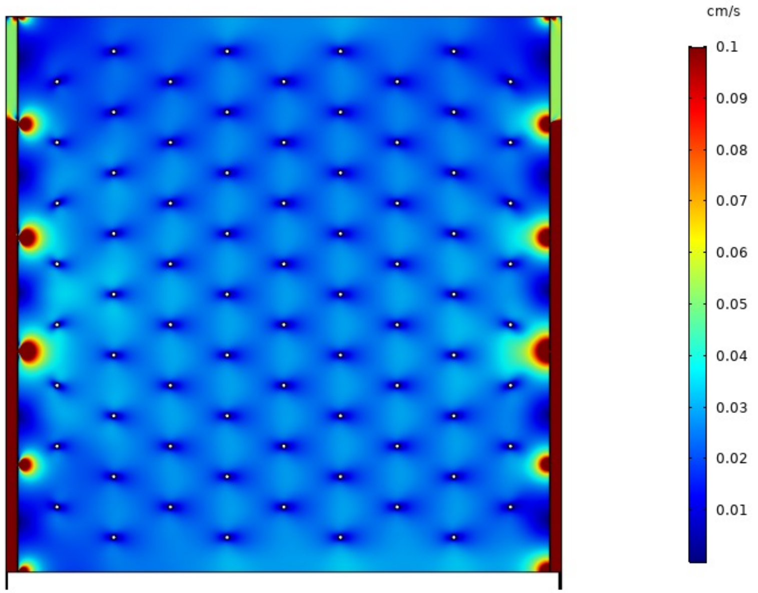
Velocity inside the chamber(Input: 1L/h)



A



B



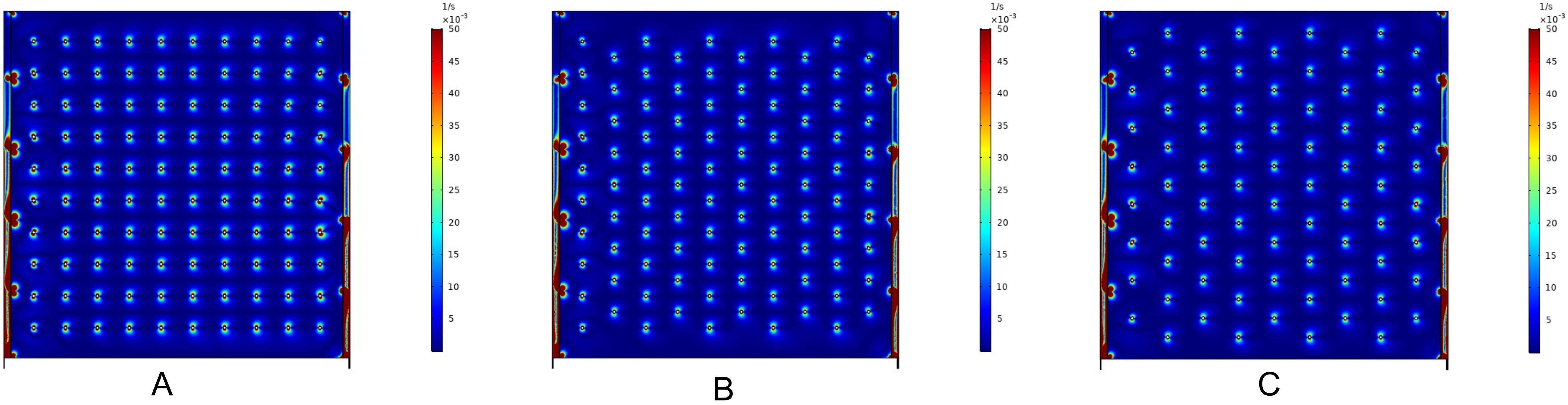
C

Model	A	B	C
Mean velocity(mm/s)	0.238	0.234	0.241
RMS of velocity(cm/s)	0.049	0.045	0.042
RMS/mean	20.3%	19.3%	17.5%

· Shifting the spacers helps to make the distribution of velocity more uniform

· The distribution of velocity gets more uniform after reducing the number of the spacers

Vorticity inside the chamber(∇×v)

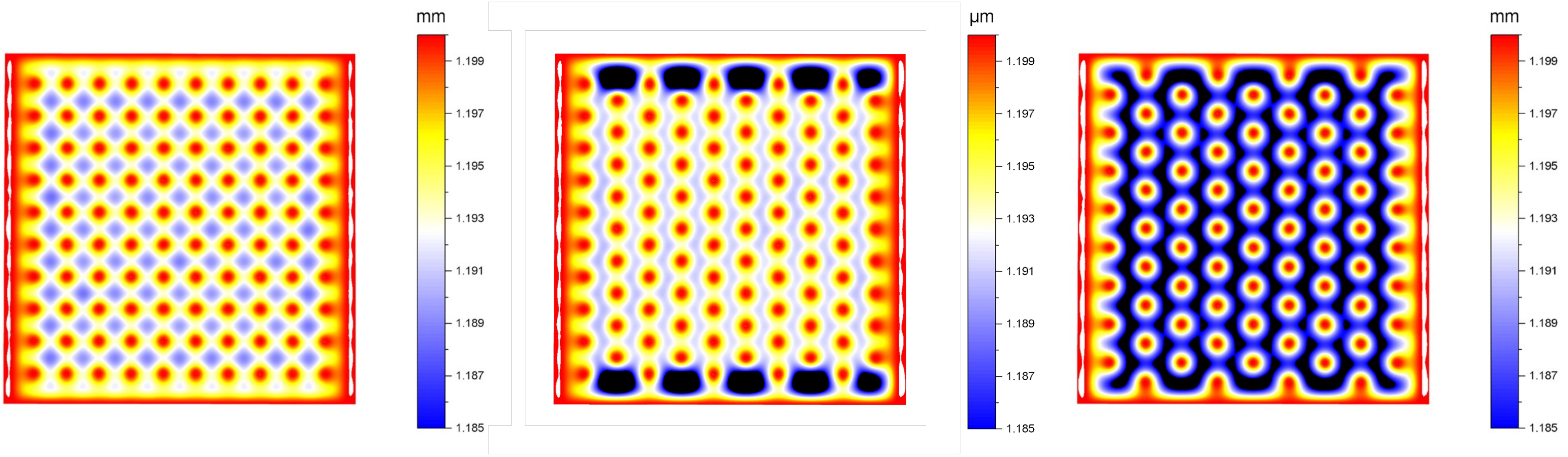


Model	A	B	C
Mean vorticity near spacers region(1/s)	0.0199	0.0198	0.0196
RMS of vorticity near spacers region(1/s)	0.0129	0.0129	0.0127
Mean vorticity excluding the vicinity of spacers(1/s)	0.0022	0.0021	0.0018
RMS of vorticity excluding the vicinity of spacers(1/s)	0.0028	0.0029	0.0026

Shifting the spacers and reducing the number of spacers can reduce the vorticity inside the gas gap (less vortex region)

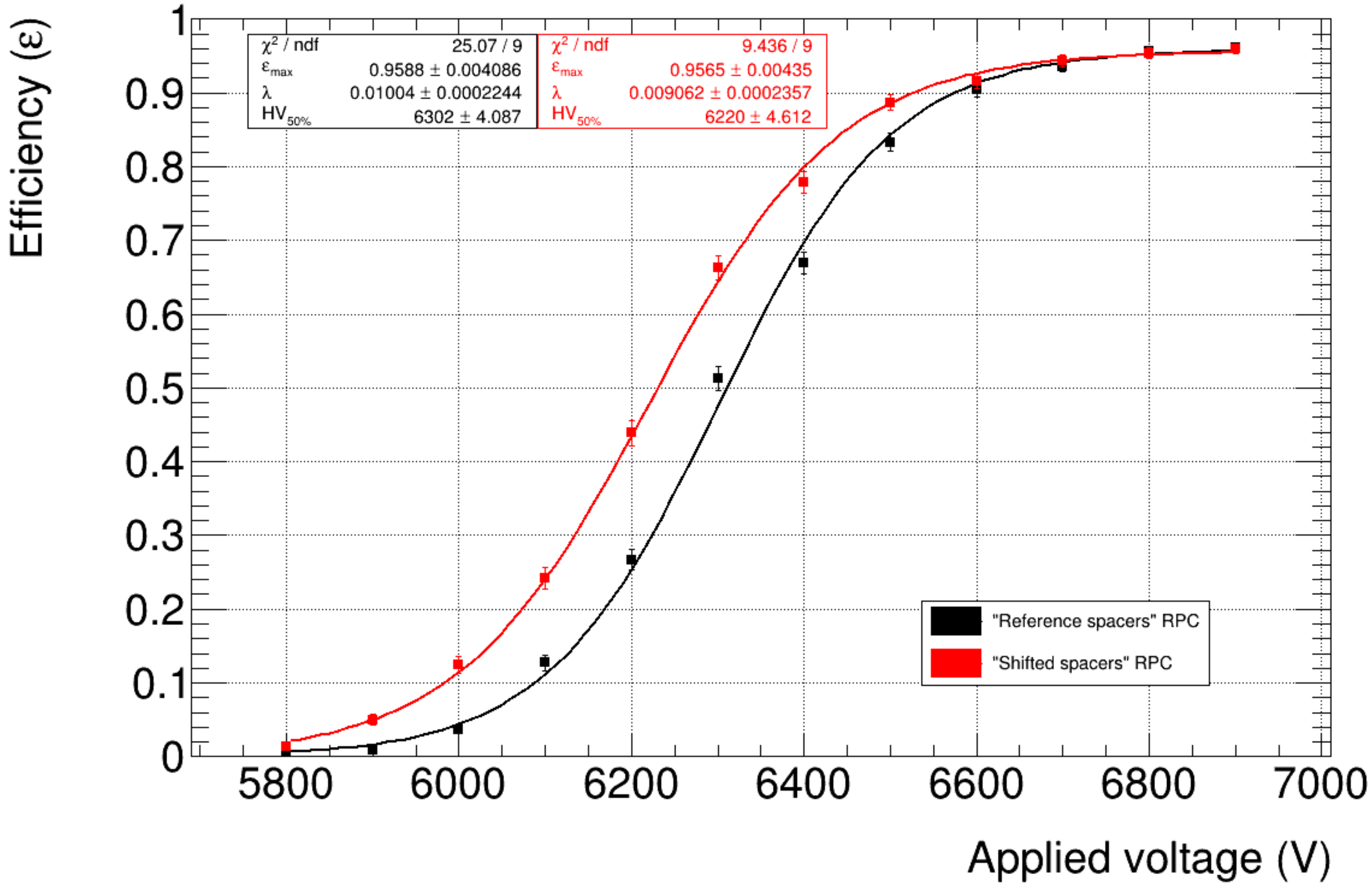
Deformation of the glass electrodes

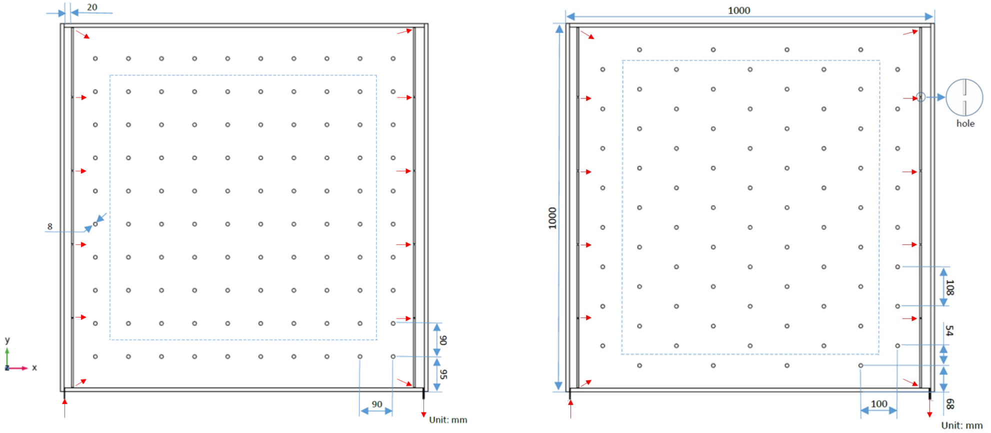
The simulation of chamber deformation on the electrodes is carried out by using pressure of gas flow and an electric field between two electrodes which is applied at 6.6 kV (working voltage of our RPC).



Distribution of the thickness of the gas gap after deformation(1.2mm before)

Construction and test of the RPCs





The efficiency plateaus are comparable for the two chambers, both greater than 95%

JINST 16 P12022

Summary

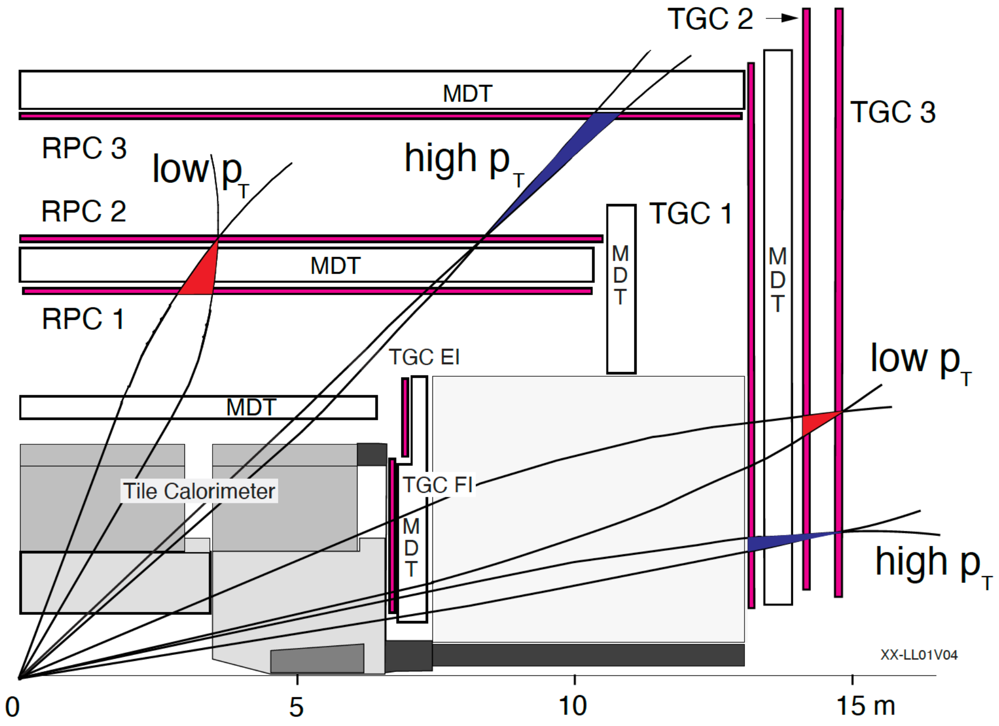
- RPC, a mature detector technology, is widely used at the LHC, and has performed well in challenging data taking, as illustrated by ATLAS
- Phase II upgrade further exploited RPC's potential, in particular in counting rate.
- Alternative gas mixture has been explored and so far proved successful.
- As for CEPC, the RPC design/role would be adjusted by the physics goal and data taking/beam requirements. Glass(floating or new type) could be considered, with a new gas mixture foreseen.

backup

RPC Trigger

The RPC system provides the L1 hardware muon trigger in the barrel. Two types of muon triggers:

- Low-pT triggers require a coincidence between two of the innermost chambers in BM.
- High-pT triggers require a coincidence between a BM pivot chamber and a BO chamber.



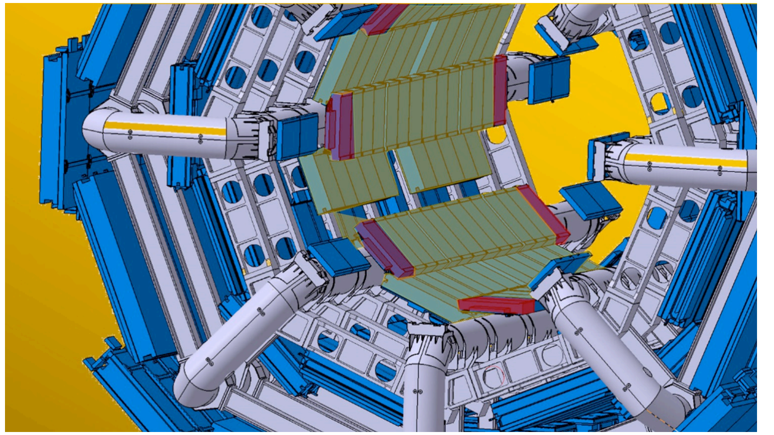
The barrel trigger system is sub-divided into 432 projective towers, each provided with on-detector trigger and readout electronics boards containing the processor boxes (PADs) for low- and high-pT triggers.

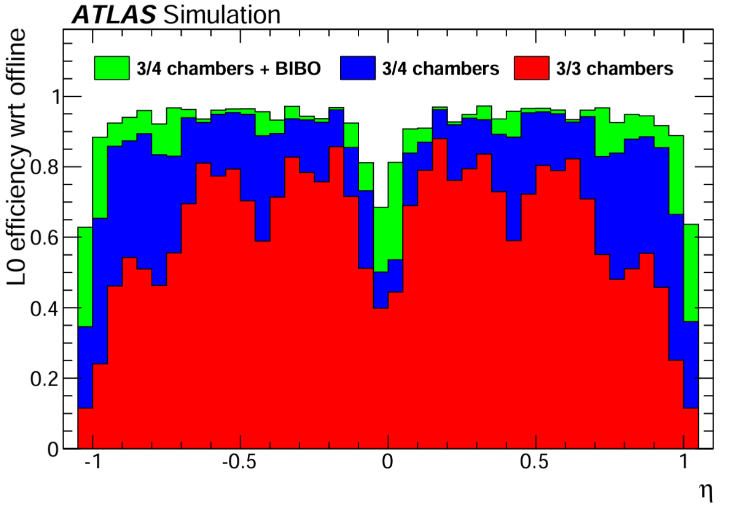
Phase II RPC upgrade

The HL-LHC luminosity increase ($7.5x10^{34}$ cm^{-2} s^{-1} at $\sqrt{s} = 14$ TeV pp, average number of interactions per bunch crossing $\langle\mu\rangle = 200$) foresees a major upgrade for the ATLAS Muon Trigger system.

- Improved trigger redundancy (from 6 to 9 layers)
- Increased trigger acceptance (from 78% to 92%, and to 96% by requiring BI-BO coincidence)
- Improved time resolution for time-of-flight measurements: new thin-gap RPCs (1 mm) and new read-out electronics (0.4 ns for BI RPCs, from 2 ns to 1.1 ns for legacy RPCs)

  - BI RPC detector surface: 472 m^2
  - 306 BI RPC triplets
  - 8262 new front-end boards

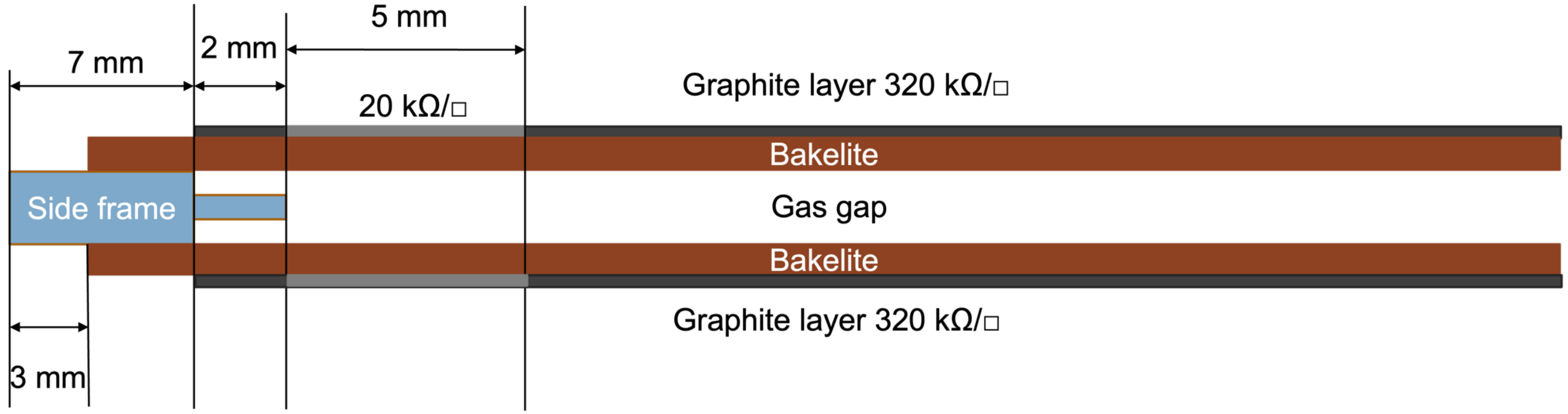




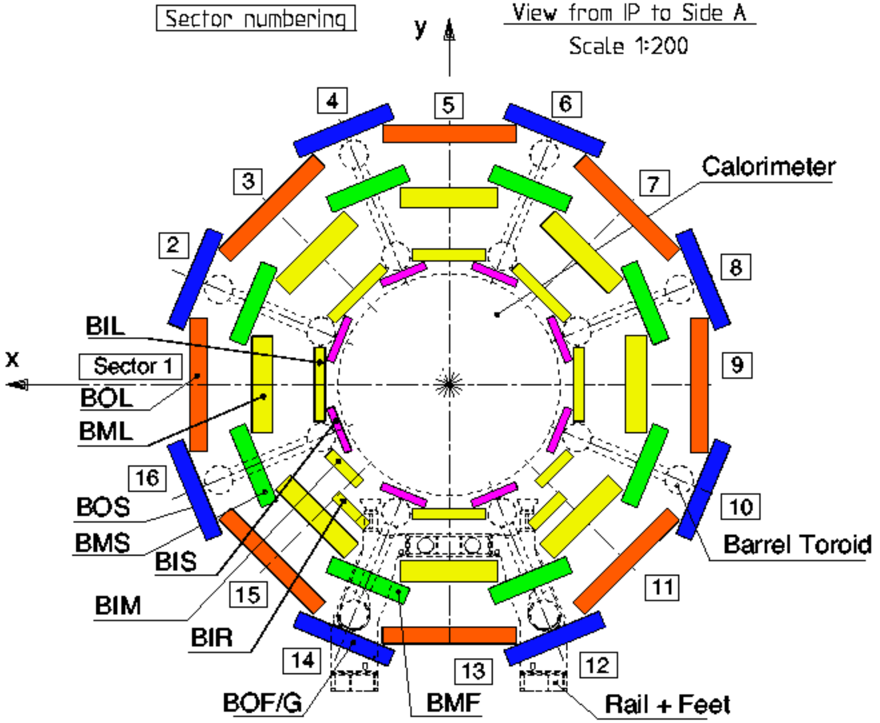
New gas volumes

A new gas volume has been developed. Many improvements with respect to ATLAS Legacy RPC detectors:

- Gas gap thickness: 2 mm -> 1 mm;
- Electrodes thickness: 1.8 mm -> 1.4 mm.
- Redesigned gas distribution and smaller sized gas pipes
- New HV cable connection on gas volume side;
- Graphite layer resistivity reduced from 500 kΩ/□ to 320 kΩ/□ and footprint redesigned to reduce current leaks



ATLAS RPC


Sector numbering
View from IP to Side A
Scale 1:200
y
x
Calorimeter
BIL
Sector 1
BOL
BML
BOS
BMS
BIS
BIM
BIR
BOF/G
BMF
Rail + Feet
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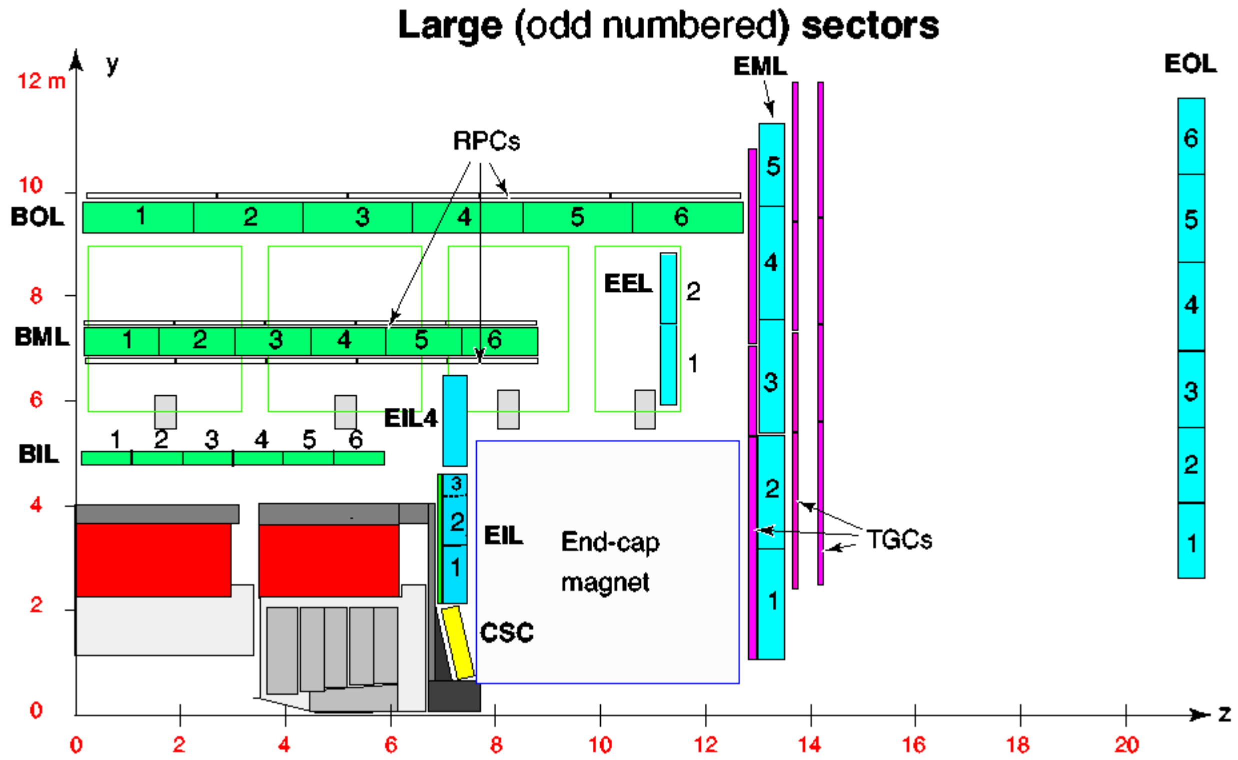
Large (odd numbered) sectors
12 m
y
RPCs
EML
EOL
BOL
BML
BIL
EEL
EIL4
EIL
End-cap
magnet
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TGCs
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2
4
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