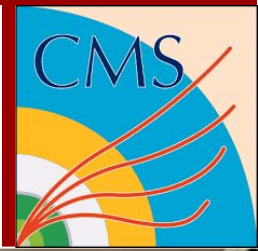
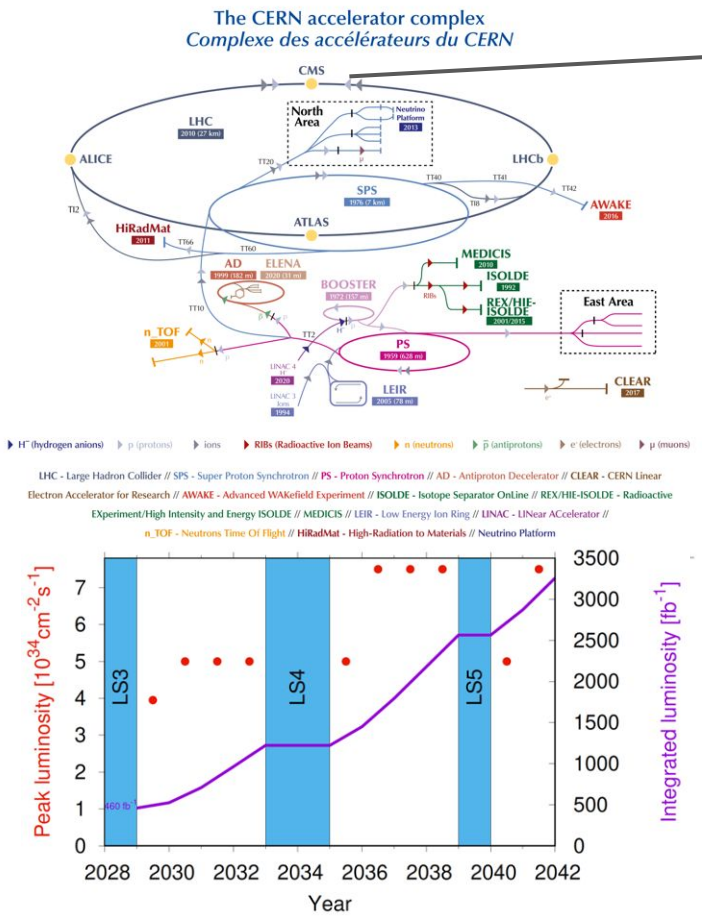
Innovative Resistive Plate Chambers for the CMS Phase 2 Upgrade:

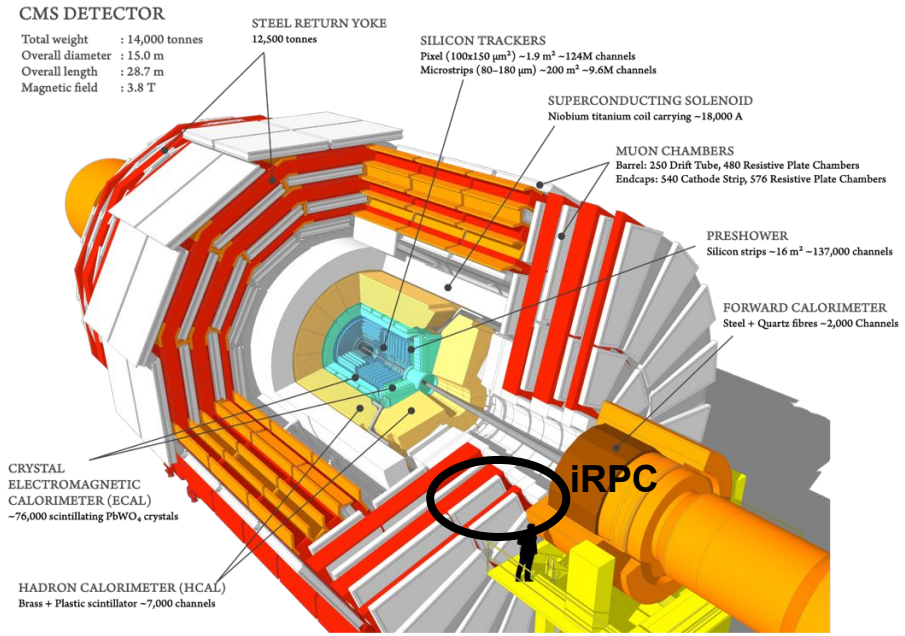
Project Summary, Construction, and Quality Assurance

Jules Vandenbroeck, Mehar Ali Shah
on behalf of CMS Collaboration



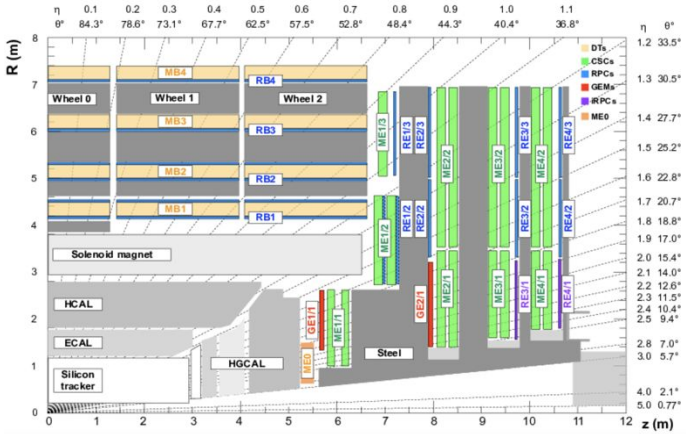
The Compact Muon Solenoid for HL-LHC

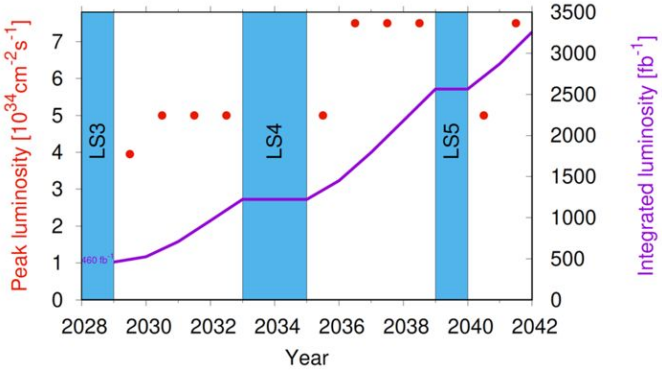




CMS is under Run III data taking and in the process of preparation to extend its sensitivity to new physics searches for the High-Luminosity LHC period starting in 2029, anticipated to feature a higher Instantaneous Luminosity to around 3000 fb^{-1}.

CMS muon LHC phase 2 upgrade

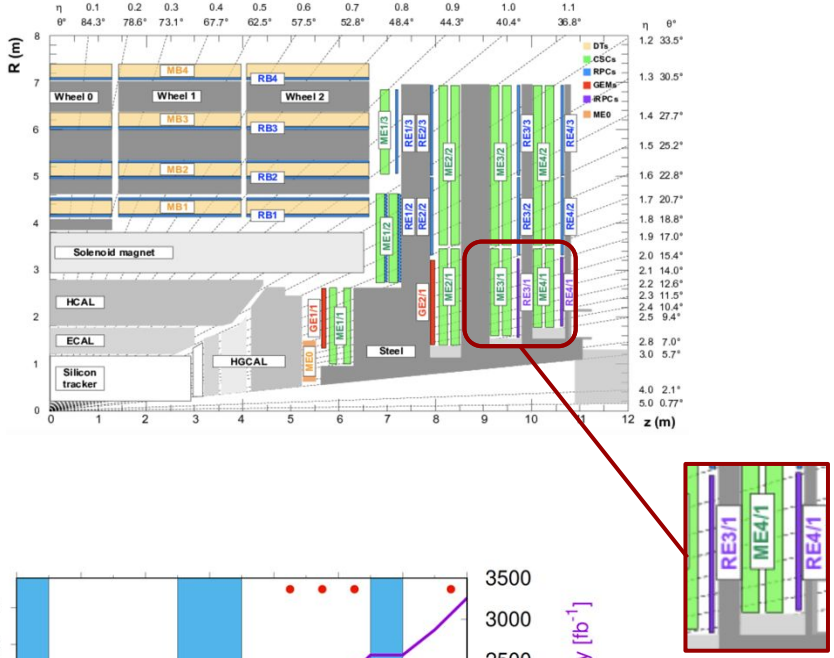


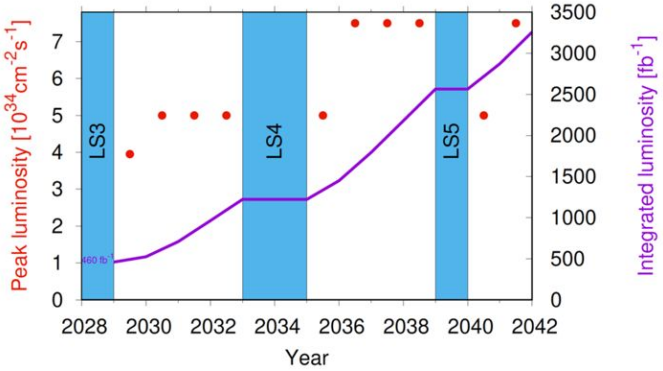


Muon system upgrade for HL-LHC ($|\eta| < 1.8$)

- **Existing DTs, CSCs and RPCs**
  ↪ upgrade the electronics!
- **Upgrade Link System of existing RPC system**
  ↪ improve timing resolution

CMS muon LHC phase 2 upgrade





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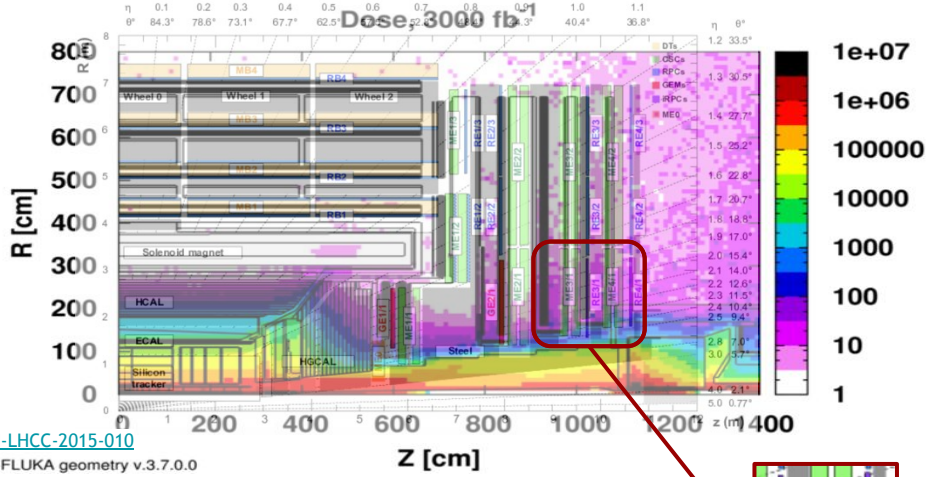
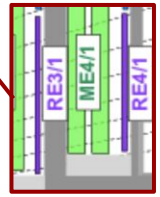
Installation of new detectors in the forward region

- **Gas Electron Multipliers:** ME0 and GE21
- **Improved Resistive Plate-Chambers (iRPC):** RE3/1 and RE4/1 **(72 iRPC chambers)**

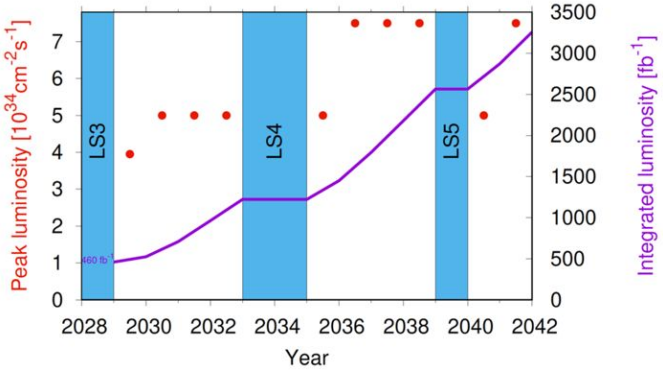
CMS muon LHC phase 2 upgrade



CERN-LHCC-2015-010
CMS FLUKA geometry v.3.7.0.0



max bkg. rate
~700 Hz/cm^2



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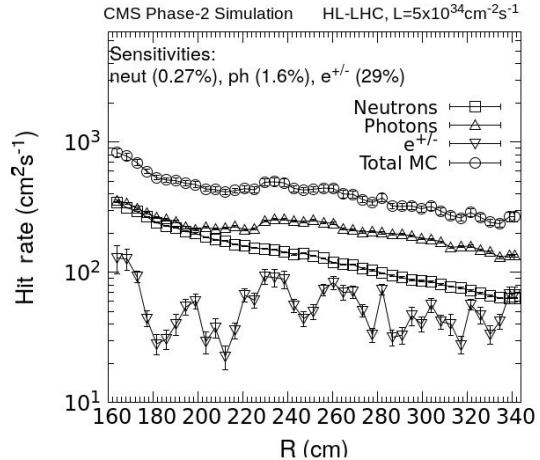

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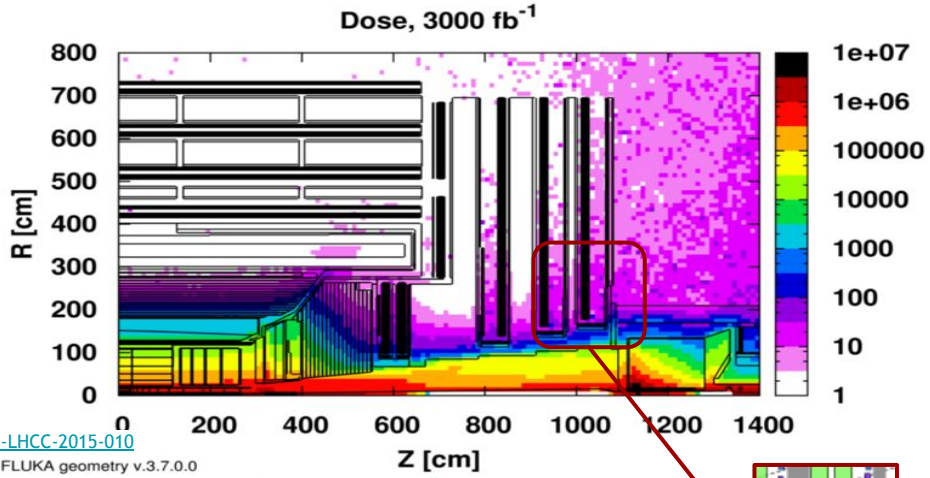

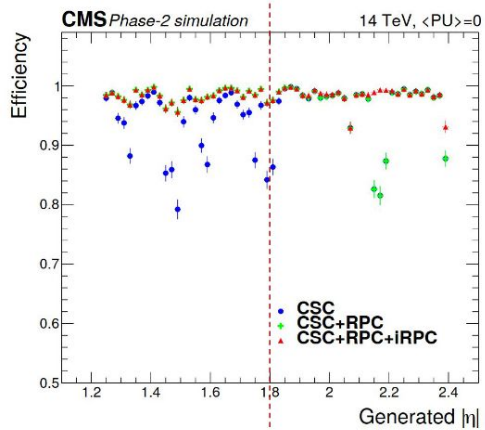

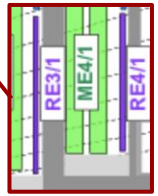

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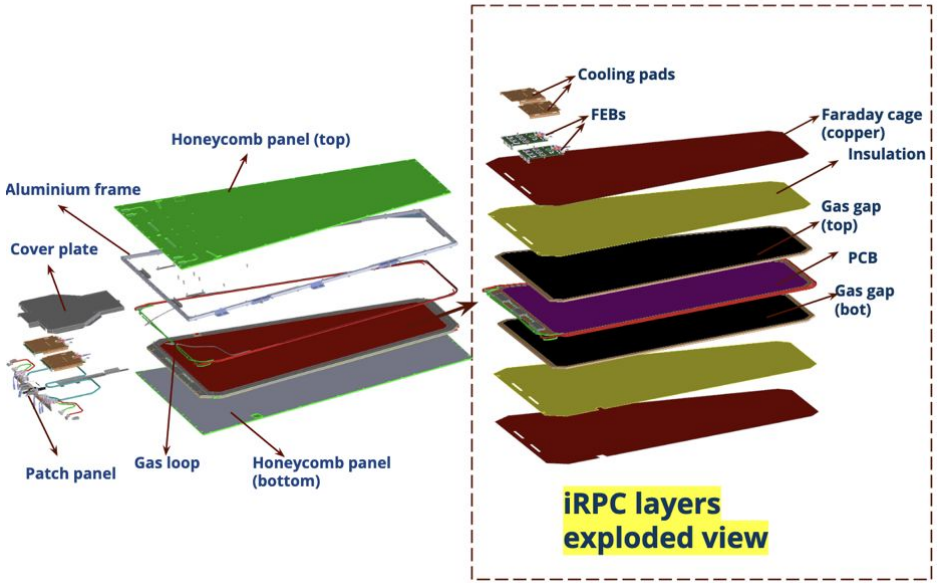
Motivation for iRPC installation of phase 2 upgrade

- high particle rate and high pileup environment due to increased luminosity in HL-LHC
- Extension of the RPC coverage in the high η region → improved L1 trigger efficiency and rate

iRPC: improved resistive plate chamber



	RPC	iRPC
HPL thickness (mm)	2	1.4
Number of gas gaps	2	2
Gas gap thickness (mm)	2	1.4
Resistivity (Ωcm)	1 - 6 x 10^{10}	0.9 - 3 x 10^{10}
Charge threshold (fC)	150	30 - 40
Space resolution in η (cm)	20 - 28	1.5
Space resolution in φ (cm)	0.8 - 1.9	0.3 - 0.6
Intrinsic timing resolution (ns)	1.5	0.5

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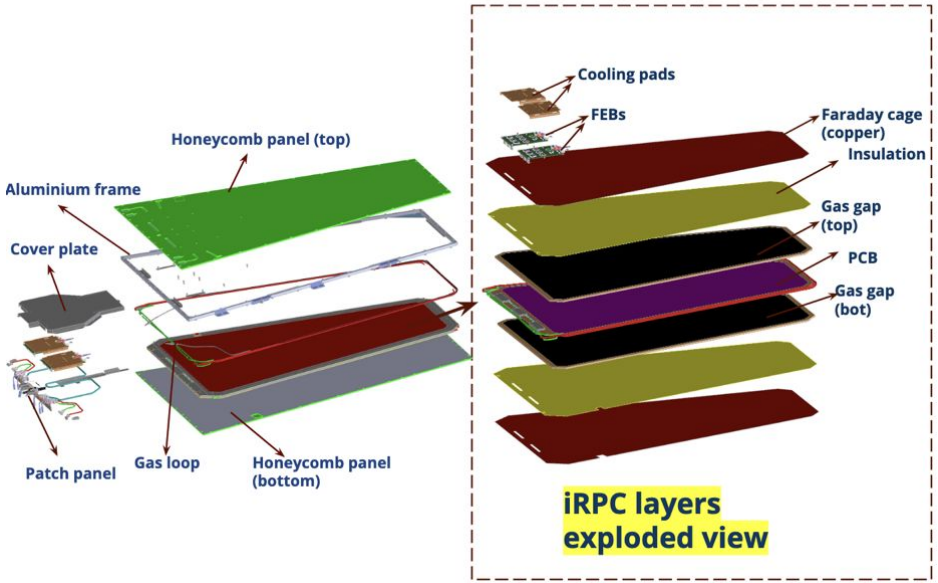

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iRPC FEB is equipped with low noise front-end electronics that can detect signals with a charge as low as 30 fC

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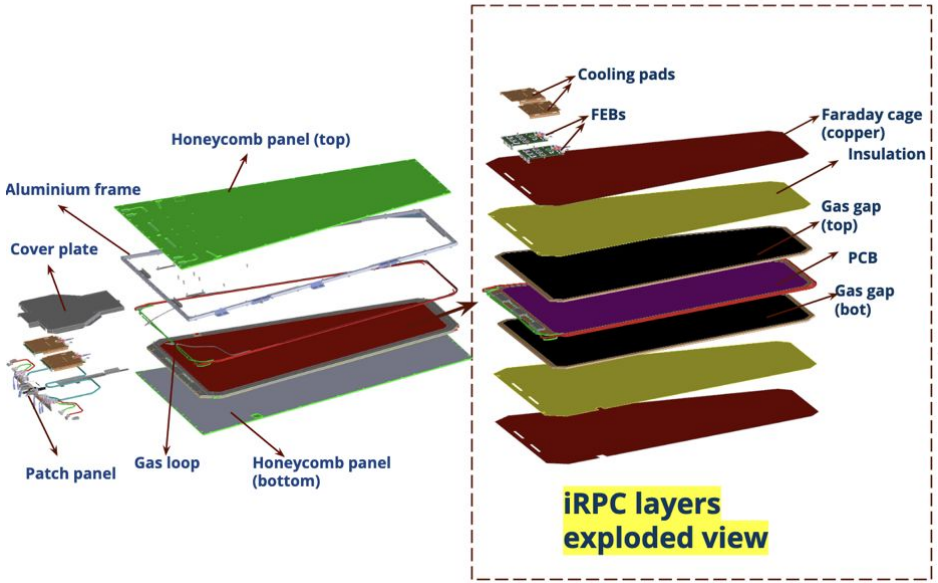

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2d readout for iRPC.

iRPC front-end electronics (FEB)

The FEB is composed of:

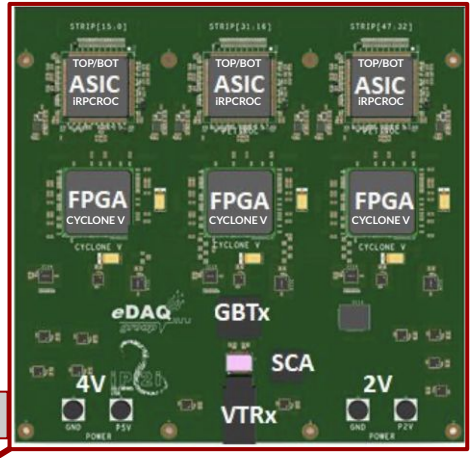
- ❑ 3 ERNI connectors of 32 channels each
- ❑ 6 ASICs PETIROC 2C
- ❑ 3 FPGAs Cyclone V
- ❑ GBTx/GBT-SCA/VTRx

Feb V2_2
2021
No X-talk/retrig.
iRPC Demo
Rad. tolerant

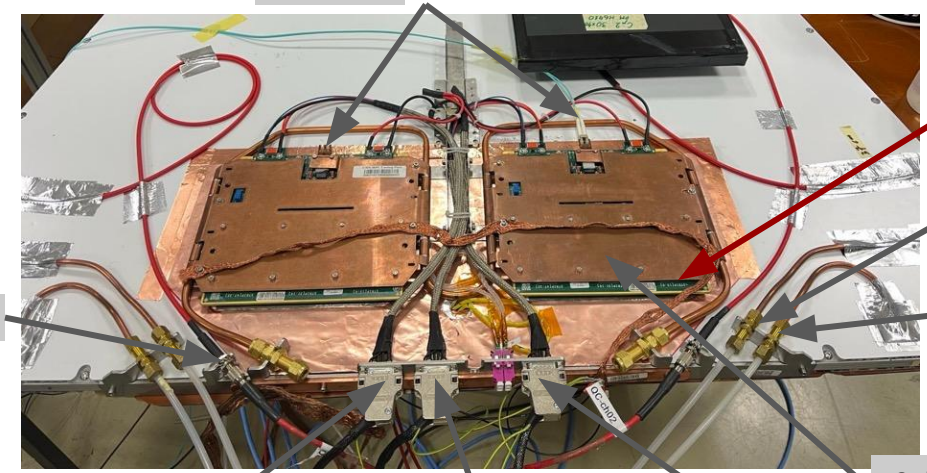
6 PetiROC2C +
3 FPGA Cycl. V
+ Optical GBT

Feb V2_3
2023-2024
Mass production

6 PetiROC2C
+ 3 FPGA Cyclone V
+ Optical GBT
+ Online firmware loading interface



Feb v2.3 PETIROC 2C



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2021 No X-talk/retrig. iRPC Demo Rad. tolerant	**2023-2024** Mass production
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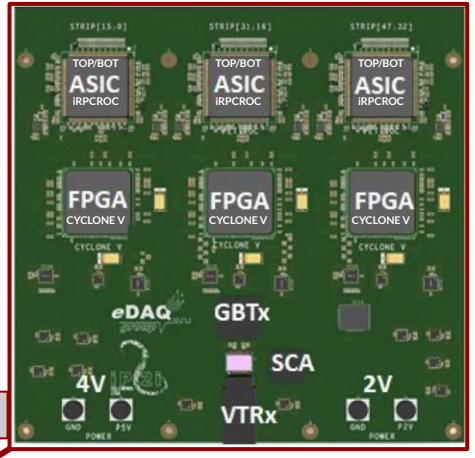

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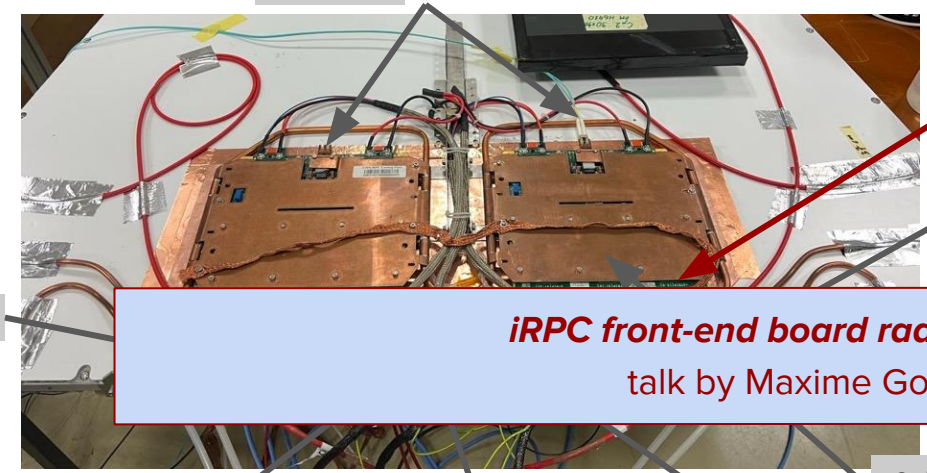


iRPC front-end board radout electronics

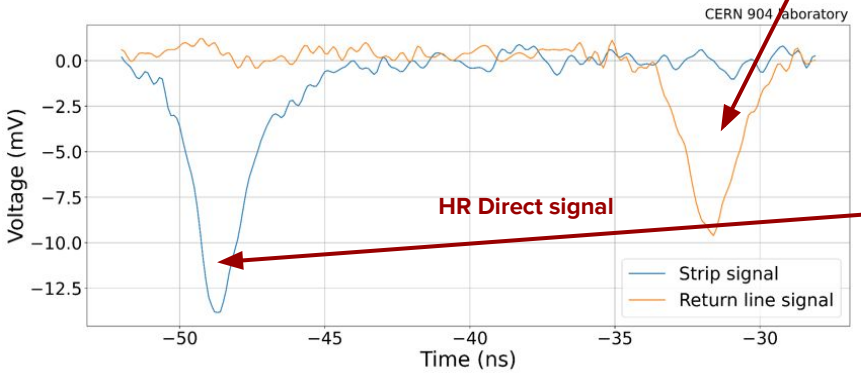
talk by Maxime Gouzevitch

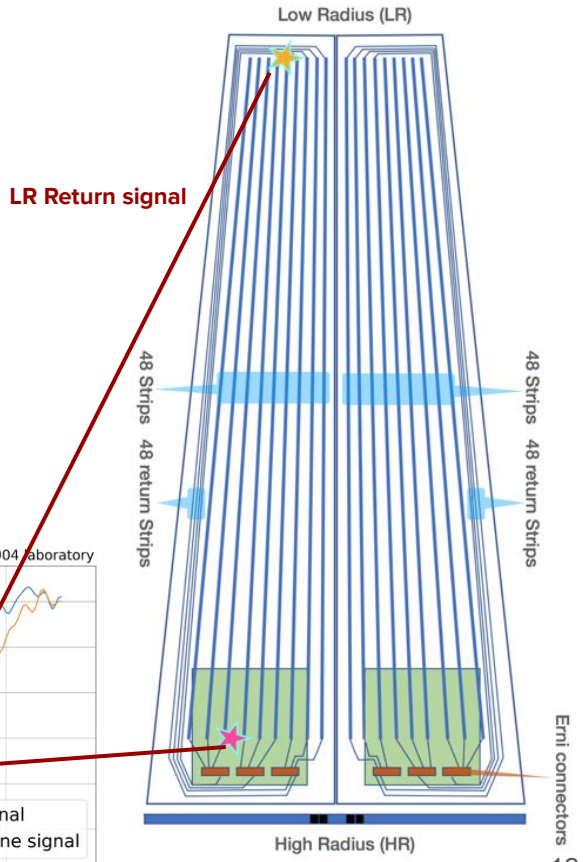
iRPC read out principle

a muon crossing the iRPC chamber induces a signal in strips outside the gaps and the signal is transported to the FEB.

If amplitude of the signal > channel threshold → PETIROC sends an output signal to the associated TDC channel and the signal is time tagged.

The 2D position information is obtained by reading out the TDC channels of the low and high radius of a strip and then measuring ΔT.

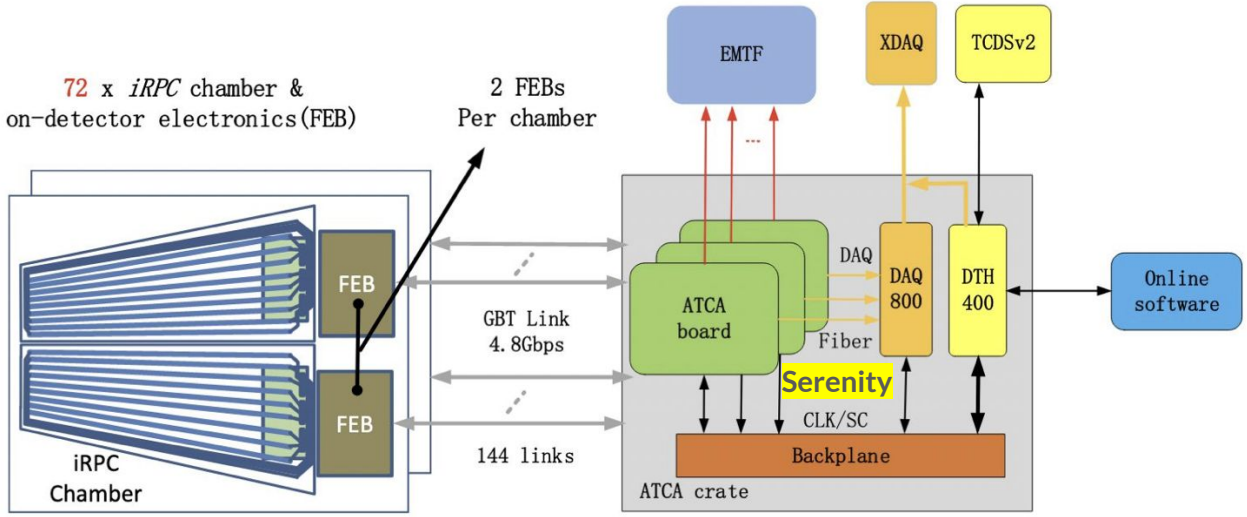


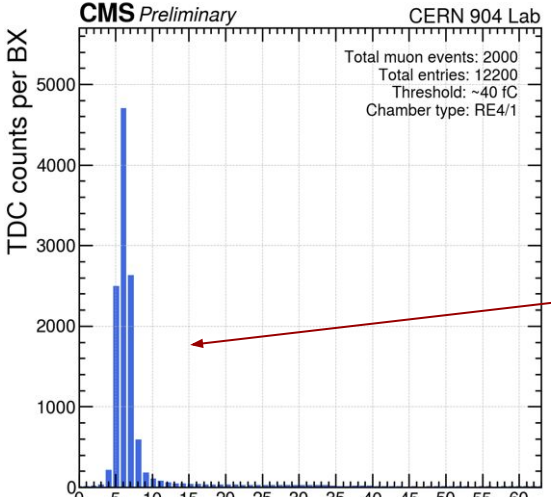


iRPC back-end electronics

Back-end functions

- ❏ fast/slow control and monitor
- ❏ cluster finding and trigger primitive generation
- ❏ timing reference adjustment
- ❏ data acquisition





Currently we are using uTCA based BE setup

FEB TDC data recorded in few BX, well inside the 20 BX trigger latency

Data transmission delay properly adjusted by Back-end

uTCA crate with BEB

iRPC back-end electronics

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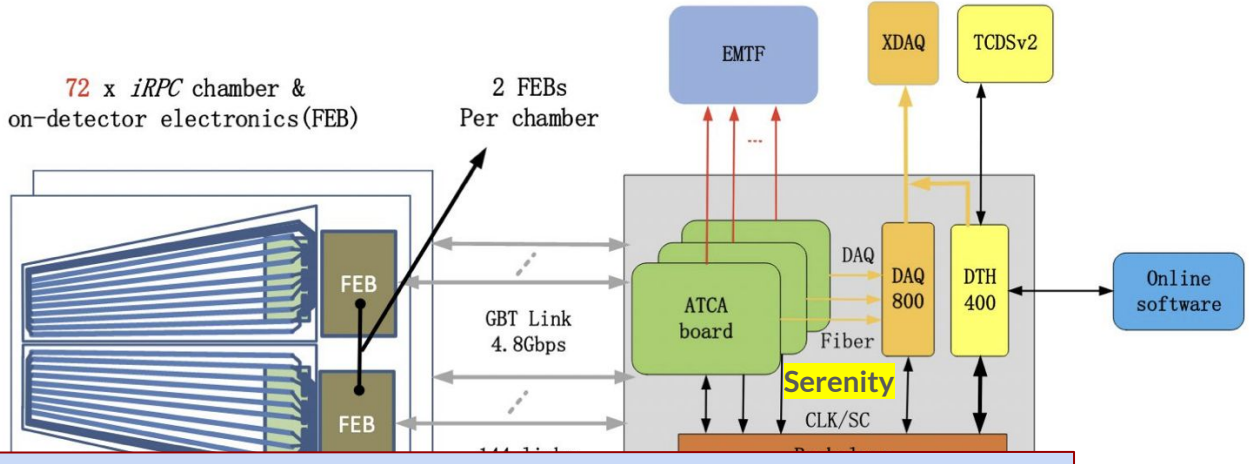
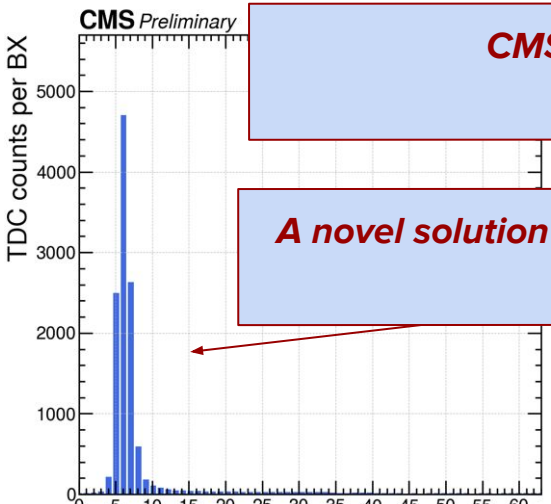


CMS iRPC cluster finding algorithm in Backend electronics

Poster by Qingfeng Hou



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A novel solution for managing latency in the CMS iRPC backend: Check-Sort-Push

Poster by Weizhuo diao

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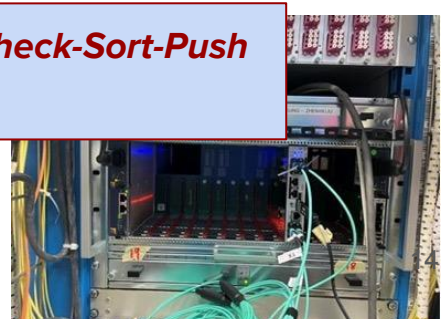

iRPC production and quality control

Production steps

Procure and test components. ➔ Send components to assembly sites ➔ Assemble chambers at assembly sites (CERN 904, Ghent) ➔ Ship chambers to CERN ➔ Final QC of chambers at CERN 904

QC1 - Chamber Components

HPL (Firm under INFN PV supervision), Strip PCB (Lyon), FEB (Lyon), Cooling system (Georgia)

QC2 - Gap validation

Gap in **Kodel** (gas leak, spacer bonding, dark current test (DC1), dark current stability (DC2))
At **assembly sites**: (gas leak, spacer bonding, dark current test)

QC3 - Chamber Assembly @ assembly sites

- QC3.1 Chamber Assembly Tests: Visual test, Gas Leak test
- QC3.2 Chamber Cosmic Tests with 1 portable FEB (noise, eff, cluster size, HV), Connectivity Test, Dark Current Test (DC1)

QC4 - Final Chamber Validation @ CERN 904

- QC4.1 - Final Chamber Tests: Cooling leak test, Gas leak test
- QC4.2 - Long Term HV Stability (DC2)
- QC4.3 - FEB-on-Chamber Test, Chamber Cosmic Tests (**with final FEBs**), Connectivity Test, Dark Current Test (DC1)

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At **assembly sites**: (gas leak, spacer bonding, dark current test)

QC defined (as for the legacy detector) : all results and procedures are stored in dedicatedly designed CERN IT based ORACLE construction DB.

QC3 -

- QC3.1 Chamber Assembly Tests: Visual test, Gas Leak test
- QC3.2 Chamber Cosmic Tests with 1 portable FEB (noise, eff, cluster size, HV), Connectivity Test, Dark Current Test (DC1)

904

- QC4.1 - Final Chamber Tests: Cooling leak test, Gas leak test
- QC4.2 - Long Term HV Stability (DC2)
- QC4.3 - FEB-on-Chamber Test, Chamber Cosmic Tests (**with final FEBs**), Connectivity Test, Dark Current Test (DC1)

iRPC construction overview

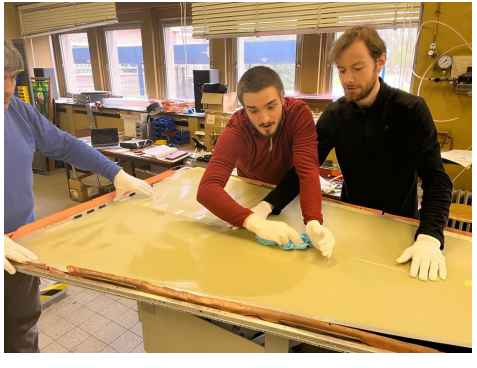
	Assembled	QC4.2 Long term HV stability	QC3.2 (cosmic test)	QC4.3 (final cosmic test)	Installed
RE3/1	31	24	19	2	2
RE4/1	37	25	23		
Total	68	49	42		2

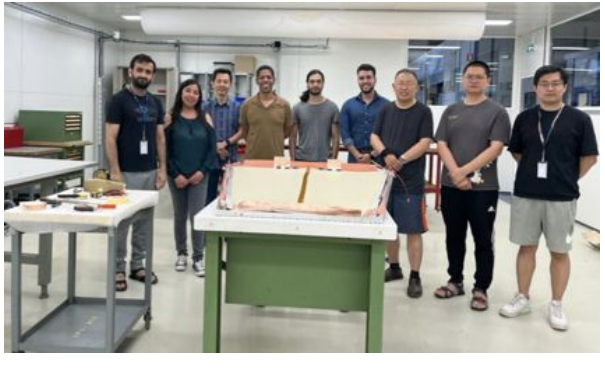
Construction sites:

GHENT UNIVERSITY

CERN

Mexican colleagues doing assembly @ CERN





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Strip PCB QC @ Lyon

connectivity, impedence, attenuation, propagation

HPL @ Firm under INFN Pavia supervision

Chamber mechanics @ ALDOWA in the Netherlands

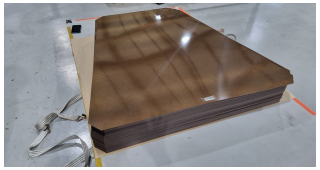
Cooling system

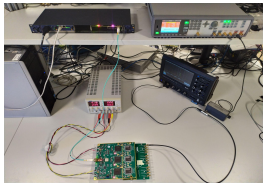
- ❏ Cooling frames tested at 20 Bar pressure (with N_2)
- ❏ FEB cooling plates @ Georgia

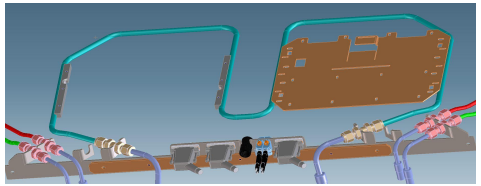
iRPC FEB cooling system

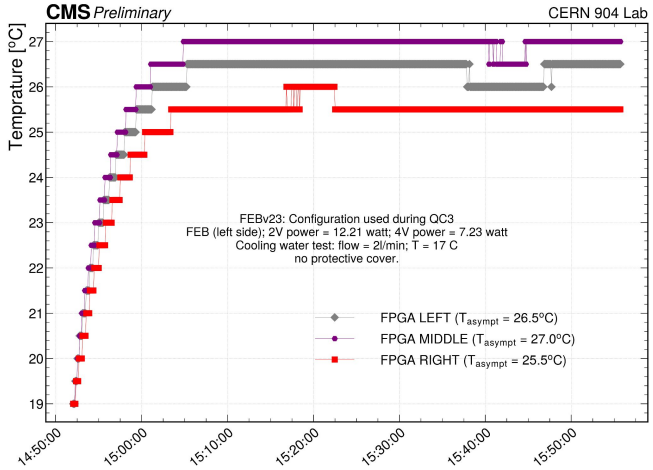
poster by Otari Kemularia

FEB QC Lyon









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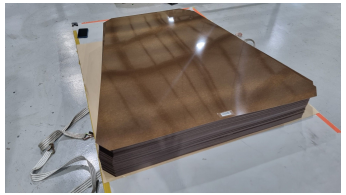
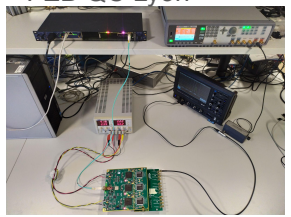
FEB v2.3 production @ FEDD France and QC in Lyon

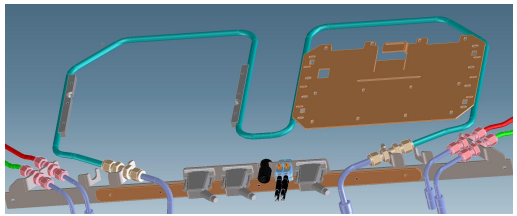
Quality control of iRPC electronic components (FEB + strip PCBs) and tests in hard radiation environment

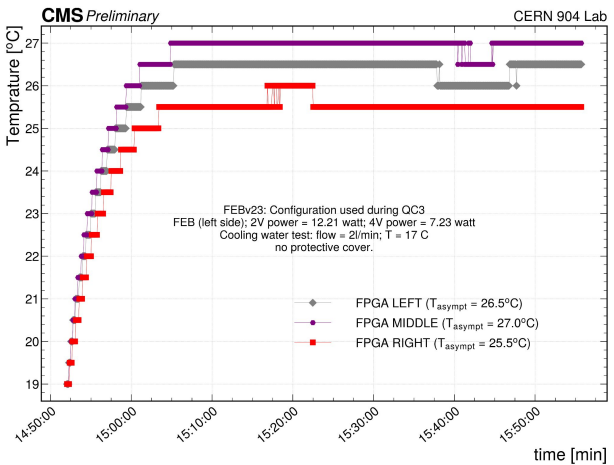
poster by Maxime Gouzevitch

FEB QC Lyon









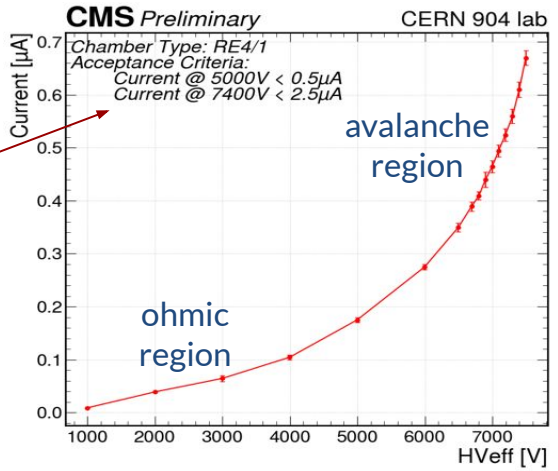
QC2: Gap validation *@ production & assembly sites*

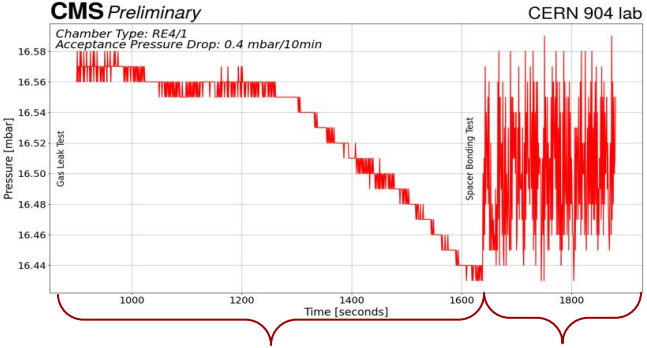
Gap pressure and spacer bonding test

- ❑ 15 mbar for 20 min monitor pressure loss
- ❑ spacer bonding test by applying pressure

dark current test

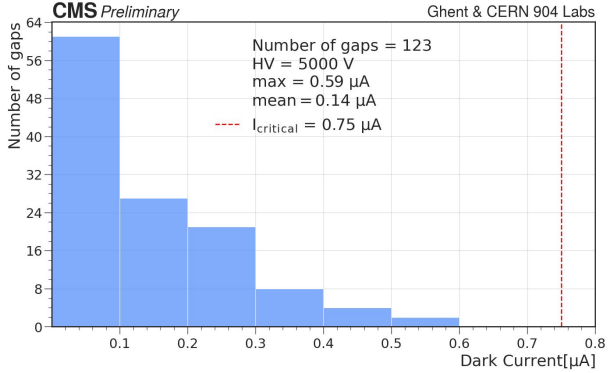
- ❑ monitor gap current over high voltage range
  → current acceptance criteria to validate gaps

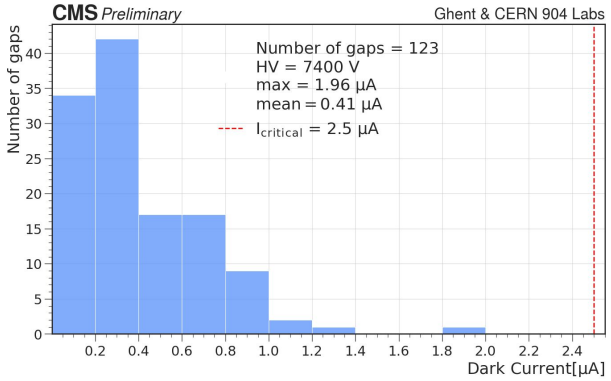




Leak test (drop < 0.4 mbar/10 min)

Spacer bonding test





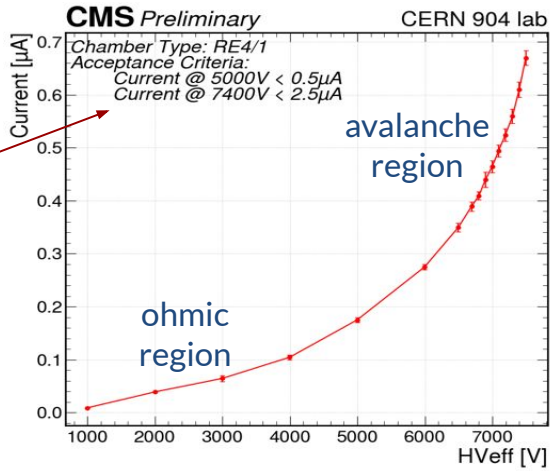
QC2: Gap validation *@ production & assembly sites*

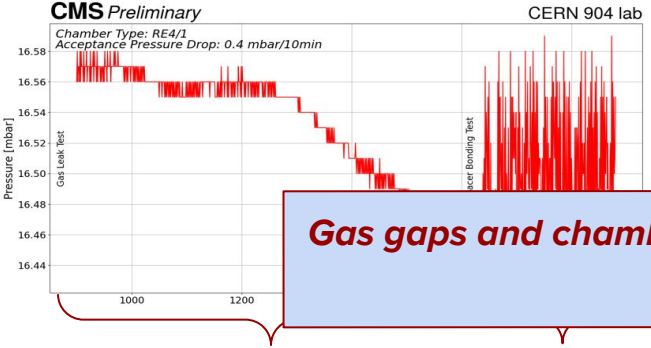
Gap pressure and spacer bonding test

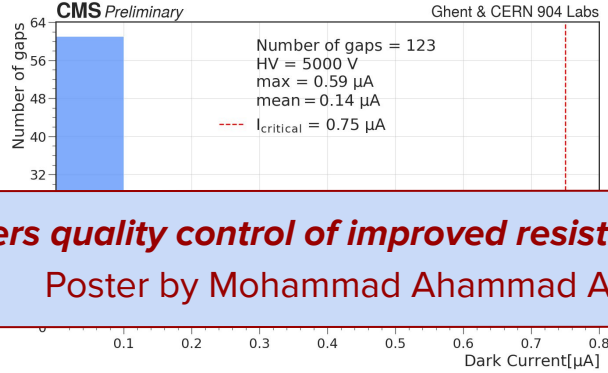
- ❑ 15 mbar for 20 min monitor pressure loss
- ❑ spacer bonding test by applying pressure

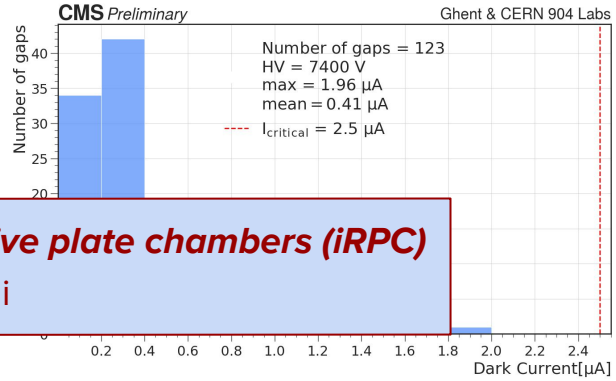
dark current test

- ❑ monitor gap current over high voltage range
  → current acceptance criteria to validate gaps









Gas gaps and chambers quality control of improved resistive plate chambers (iRPC)

Poster by Mohammad Ahammad Ali

Leak test (drop < 0.4 mbar/10 min)

Spacer bonding test

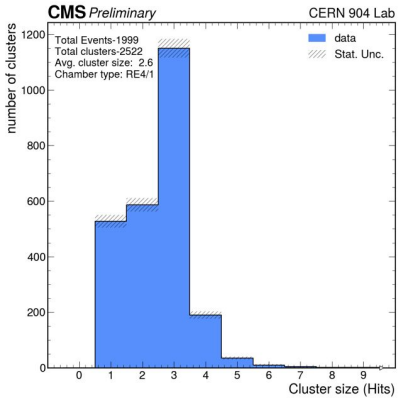
QC3: chamber quality control

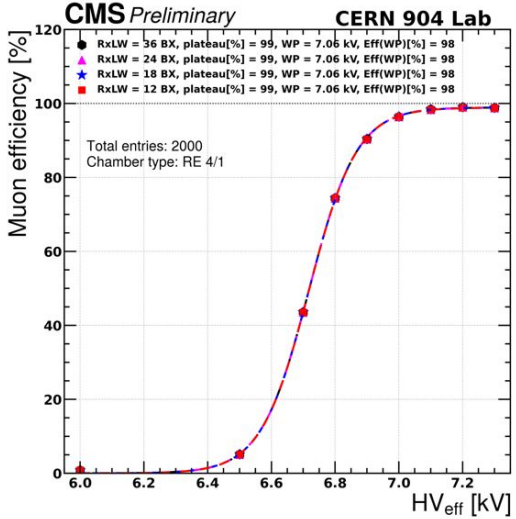
QC3.1 Chamber Assembly tests

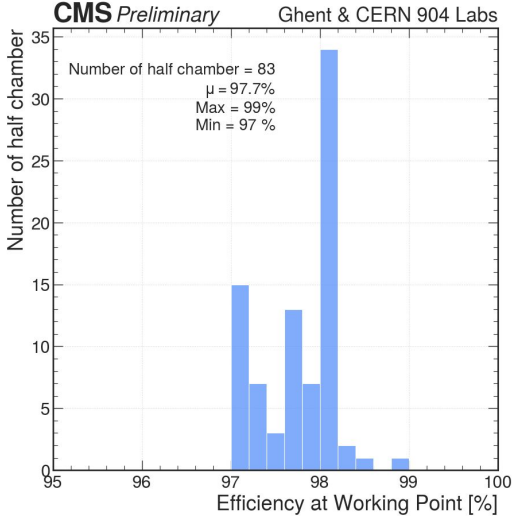
Visual test. Connectivity test, Gas leak test, dark current test

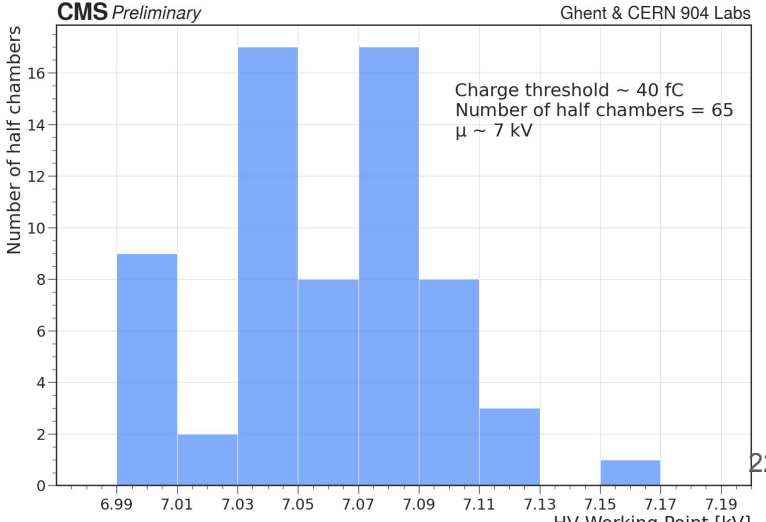
QC3.2 Cosmic efficiency test

- Tests with portable FEBv2.3
- 3-fold coincidence (30 x 40 cm^2 scintillator area)
  - Moving now to 20 x 100 cm^2 scintillator area
- 1 double gap scan, 2 single-gap scans, noise & current scans
- 11 HV points with 2K events/HV-point for eff and 15K for noise







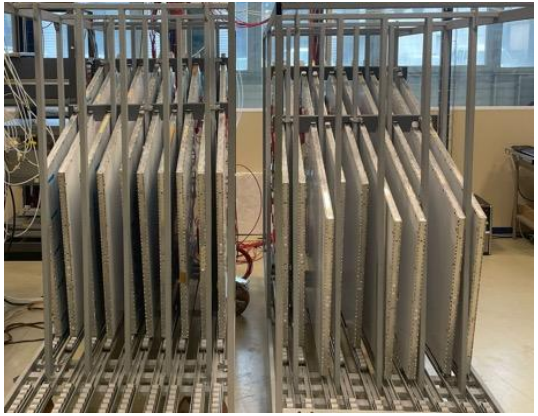


QC4: final chamber validation

quality control after final chamber assembly with final FEBs (v2.3)

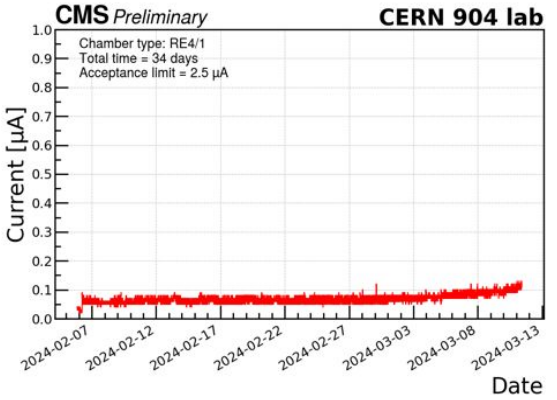
QC4.1 Cooling & Gas leak test

- ❏ cooling test follows QC1 procedure
- ❏ gas leak test follow QC2.1 with 5 mbar

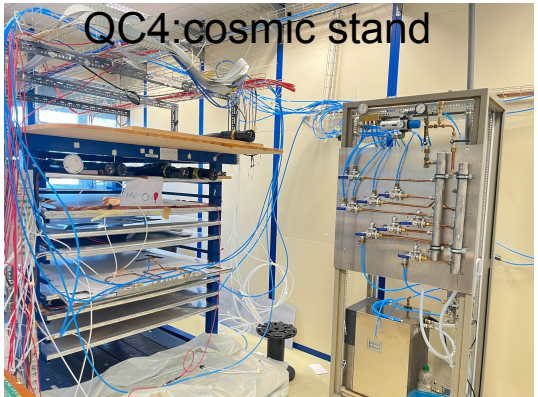


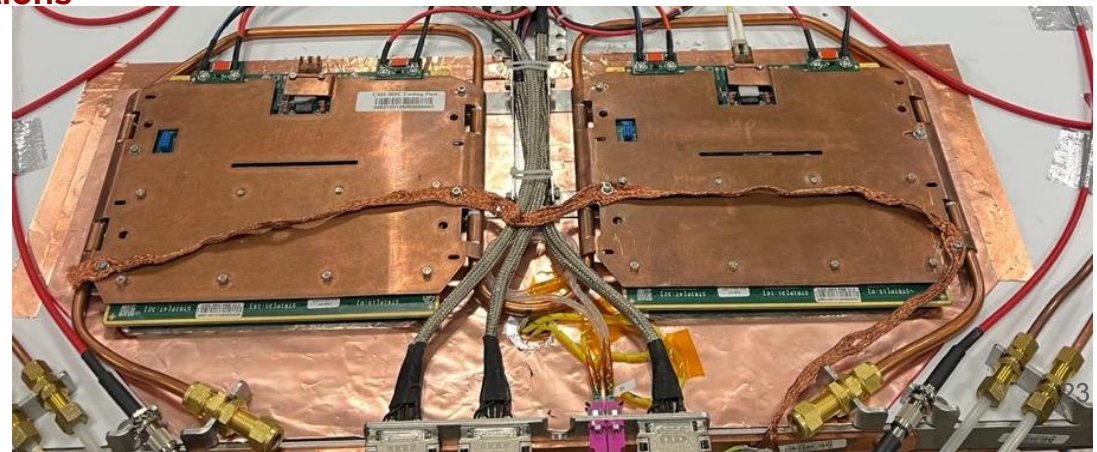
QC4.2 HV current stability

- ❏ current monitoring at WP for 1 month
- ❏ acceptance: current < 2.5 µA



QC4.3 Final cosmic test in CMS like conditions



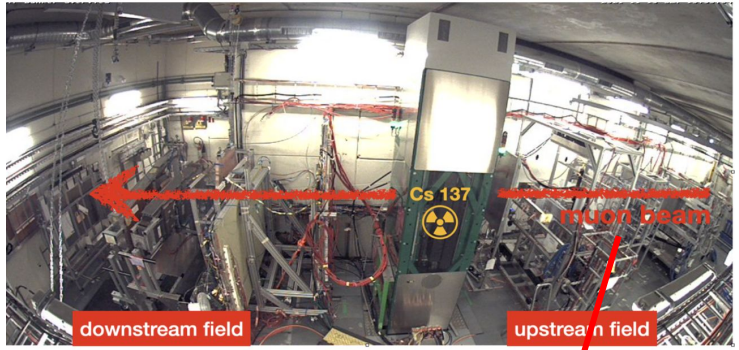


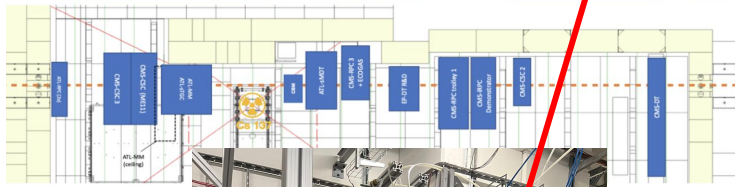
iRPC performance under gamma background

Gamma irradiation facility (GIF++)

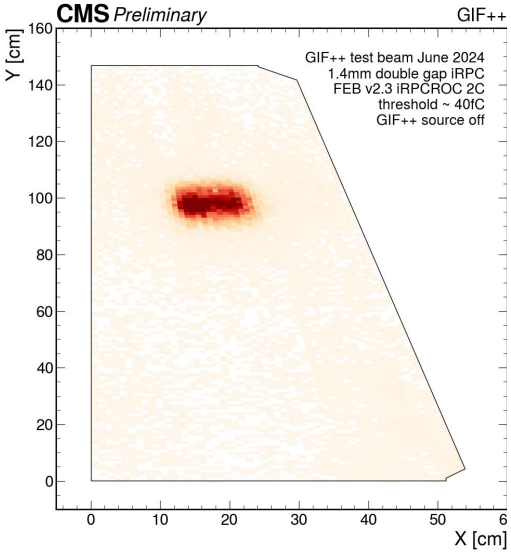
- 12 TBq ^{137}Cs gamma source 662 KeV
- Muon beam ~ 150 GeV/c

→ Test iRPC performance in HL-LHC background conditions

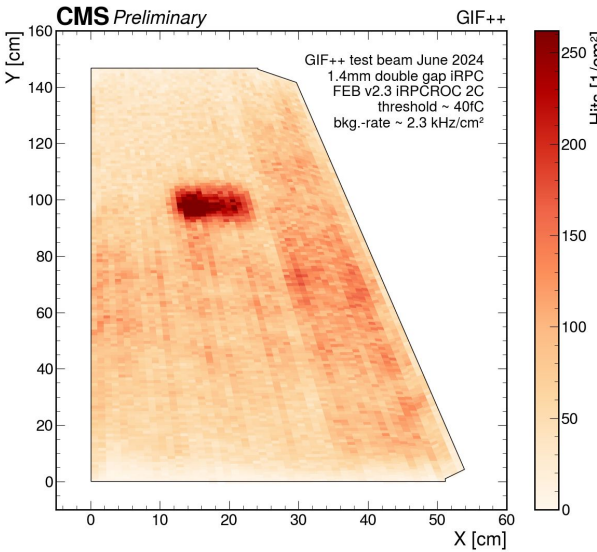




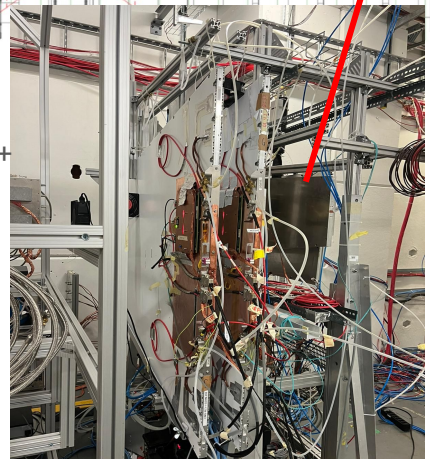
GIF++ source off



bkg. rate ~ 2.3 kHz/cm²



2 iRPC in Gif++



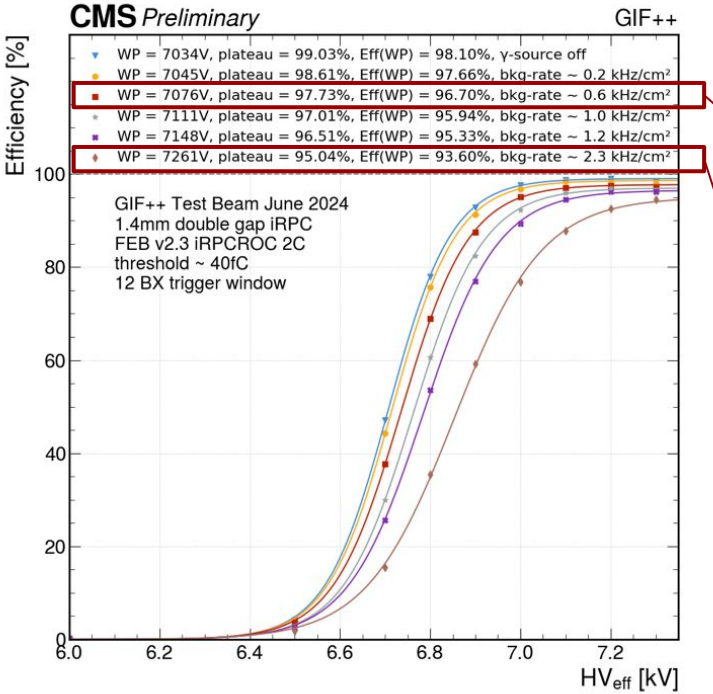
iRPC performance under gamma background

Gamma irradiation facility (GIF++)

- 12 TBq ^{137}Cs gamma source 662 KeV
- Muon beam ~ 150 GeV/c

Studies ongoing with fine-tuned threshold and further optimised FEB configuration

→ Test iRPC performance in HL-LHC background conditions



@ expected background rate for HL-LHC

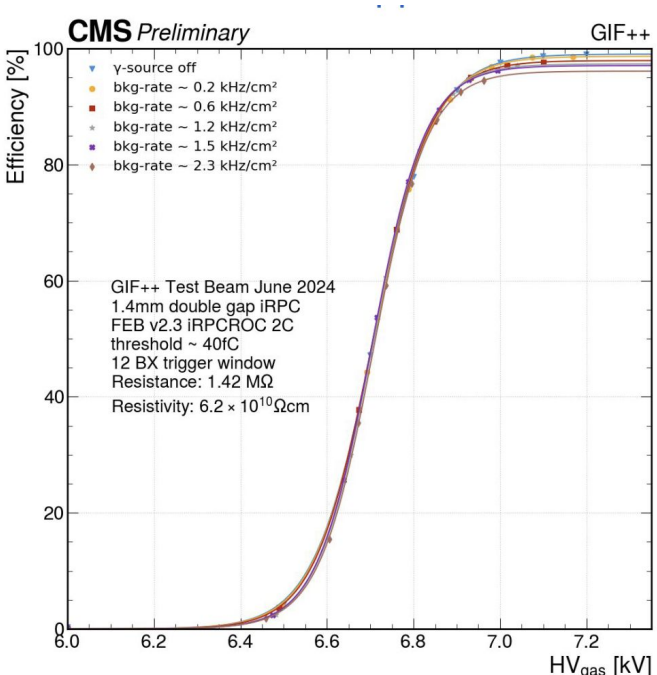
→ efficiency: 96.70%

→ working point: 7076V

@ safety factor 3 of HL-LHC background

→ efficiency: 93.60%

→ working point: 7261V

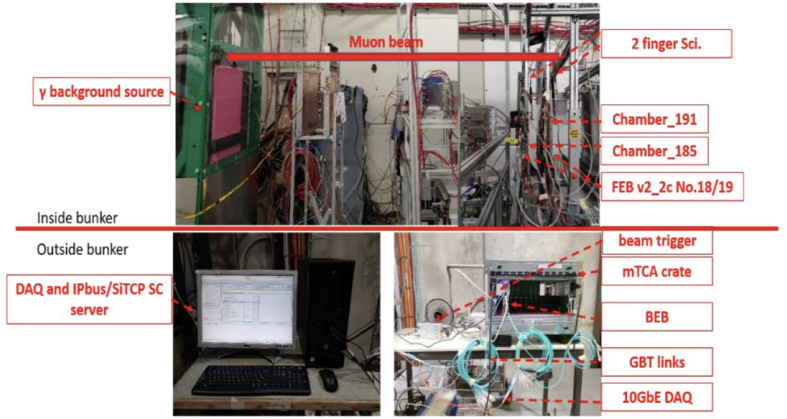


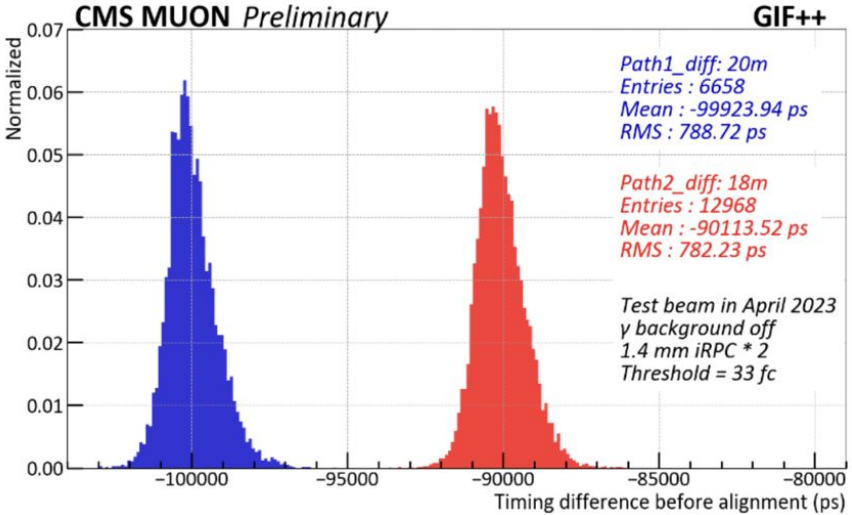
iRPC time resolution

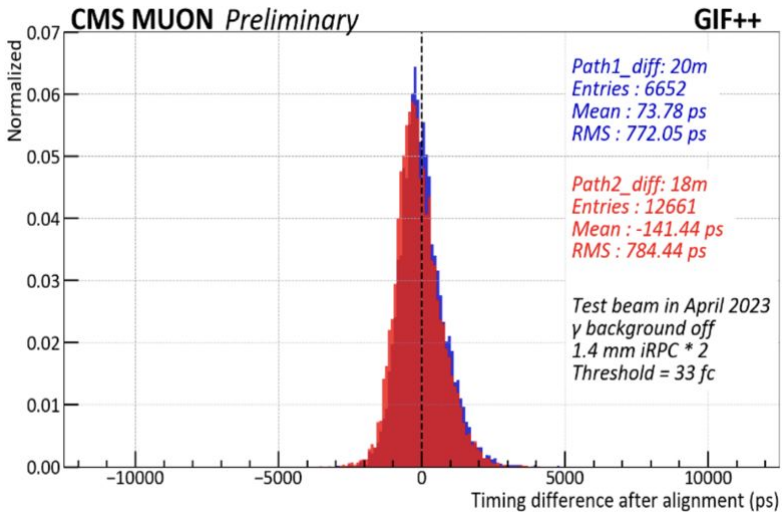
time resolution measurement at GIF++

- time resolution performed with 2 identical chambers and a muon beam
- absolute timing resolution after alignment by back-end:

$$\frac{780}{\sqrt{2}} \approx 550 \text{ ps}$$







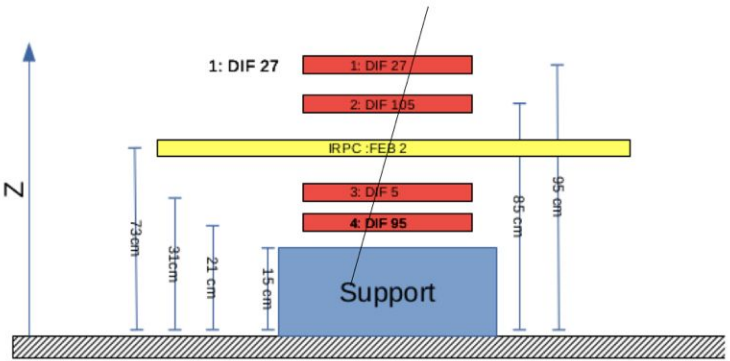
iRPC space resolution

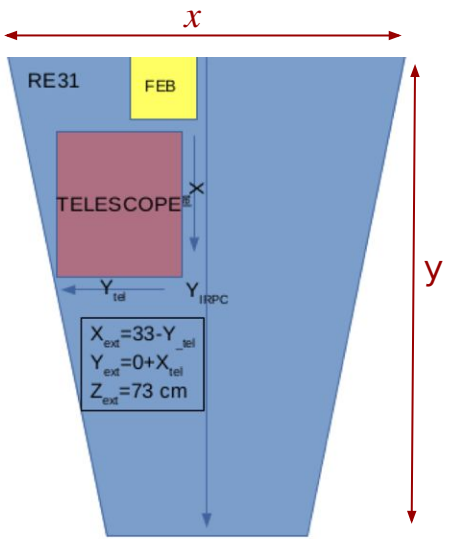
Cosmic muon telescope in Lyon University IP2I

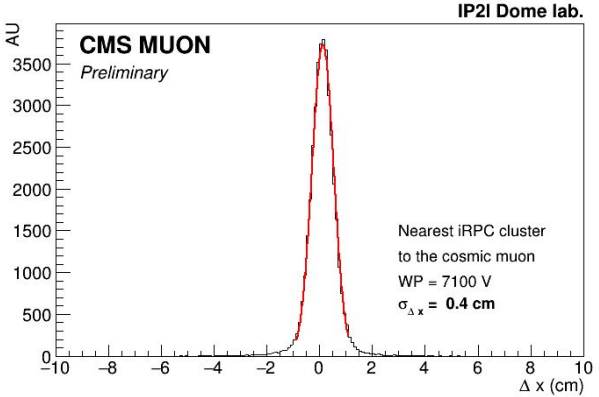
- 4 control RPC-chambers
- space resolution measurement of iRPC:

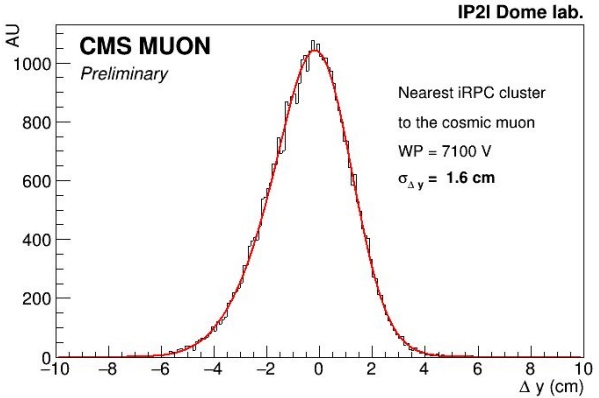
  σ_x = 0.4cm (depends on **strip pitch** in the telescope region)

  σ_y = 1.6cm (depends $\Delta T = T_{HR} - T_{LR}$ resolution)









iRPC Installation in CMS

4 demonstrator chambers (RE+4/1/15,16 and RE+3/1/15,16) were installed in CMS in the end of the Long Shutdown 2 (2021-22), 4 FEBs v2.1 and 4 FEBs v2.2:

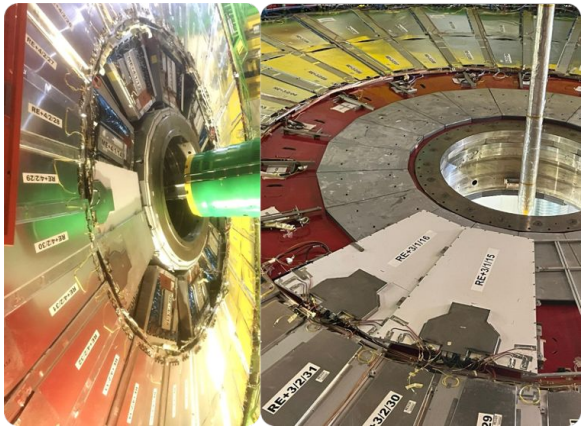
- **Noise < 1Hz/cm^2** with final end cap disk grounding
- FEB **temperature stable** in CMS endcap closed mode with water cooling
- HV currents showing **smooth operation** during LHC Run III
- **Normal operation** in 3.8 T magnetic field

2 mass production final chambers with final FEBs installed in CMS last YETS (2023):

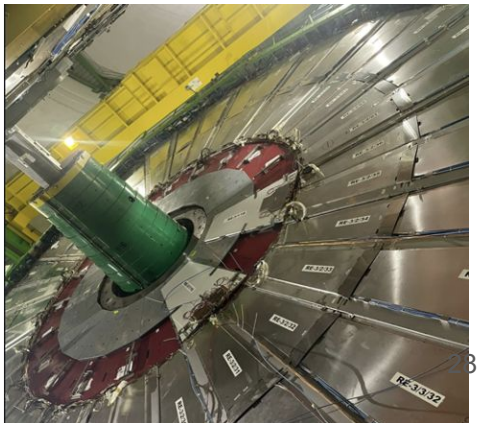
- RE-3/1/16 and RE-3/1/18

All **services are already installed** since LS2 waiting for all 72 chambers

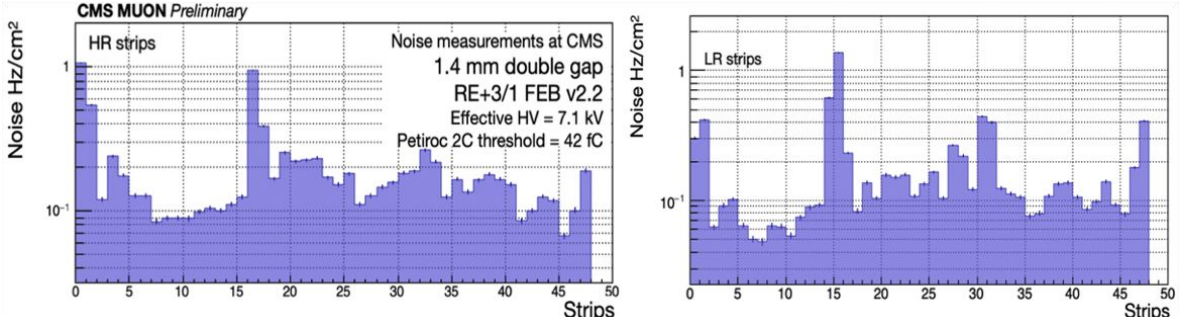
iRPC demonstrator



2 iRPC in CMS



All 70 remaining chambers are expected to be installed next YETS 2024-2025 access time



Summary

iRPC is an innovative design detector to operate during HL-LHC in CMS at High Eta region

- ➔ Production and QC ongoing: **68/72** chambers manufactured and QC (with portable and pilot production FEB). Completion expected by end of **September 2024**
- ➔ iRPC space resolution is Δ**x = 0.4 cm** and Δ**y = 1.6 cm**, improved wrt to present Δ**x = 1-2 cm** and Δ**y = 20-30 cm**
- ➔ iRPC timing resolution is Δt ~ 0.5 ns, improved wrt to present Δ**t ~ 1.5 ns**
- ➔ At **~600 Hz/cm2** and with a threshold of **~40 fC**, the iRPC chambers have a performance of:
  - ◆ **96.7 %** muon efficiency
  - ◆ Working point **~ 7076 V**

- ➔ Demonstrators in P5 have already shown less than **1Hz/cm2** of noise and stable operation in CMS conditions
- ➔ First 2 final chambers installed and commissioned last December 2023 in CMS
- ➔ Chamber construction (with FEB) expected to be completed by the November 2024, installation planned in **January 2025**

Thanks for your attention