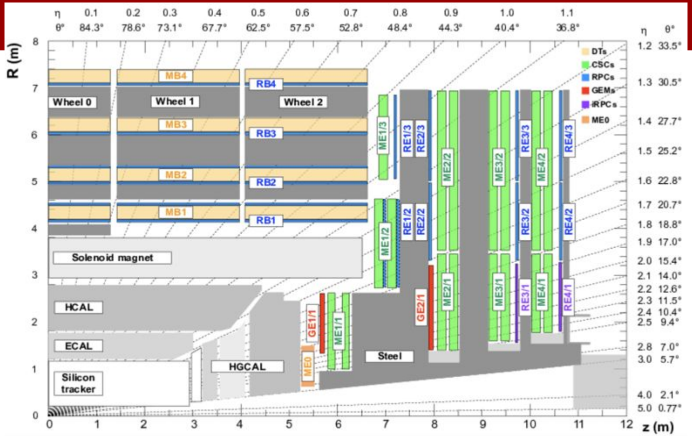
The iRPC project: innovative RPCs for the CMS experience at CERN and COMET at J-Parc

Maxime Gouzevitch for
IP2I, CMS and COMET colleagues

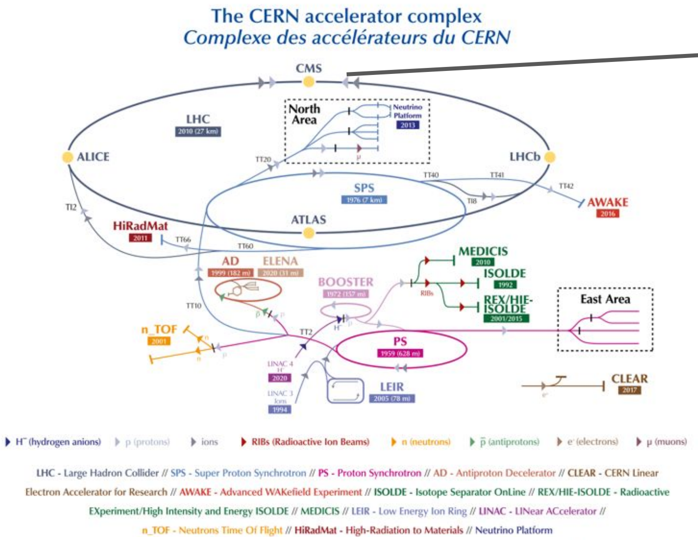
GDR-DI2I
Groupement De Recherche
Détecteurs et Instrumentation pour les 2 Infinis

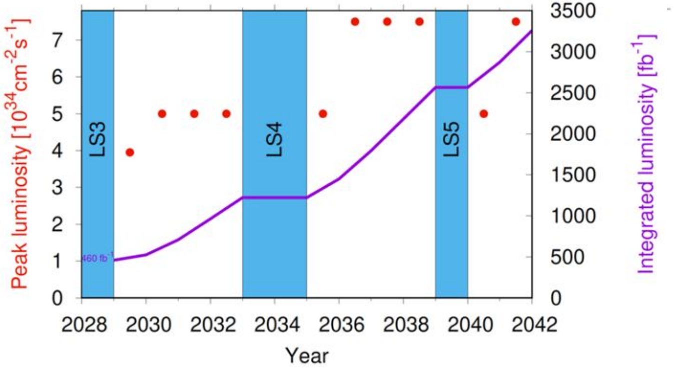
1) iRPC project in CMS
2) Front-End (IP2I - CNRS)
3) Performance
4) Mass production and QC
5) Installation
6) Application to COMET

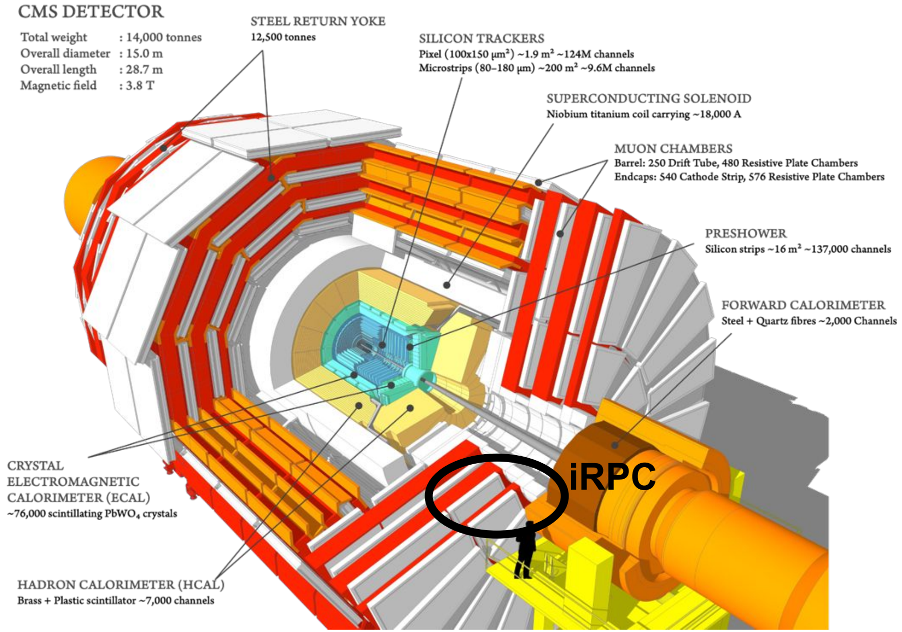
1) iRPC project in CMS



The Compact Muon Solenoid for HL-LHC

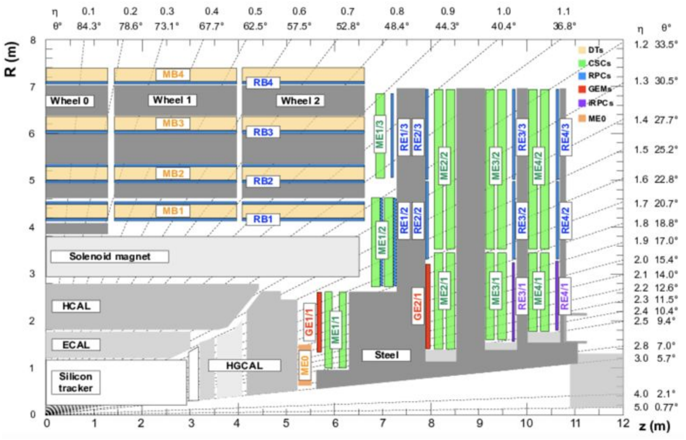






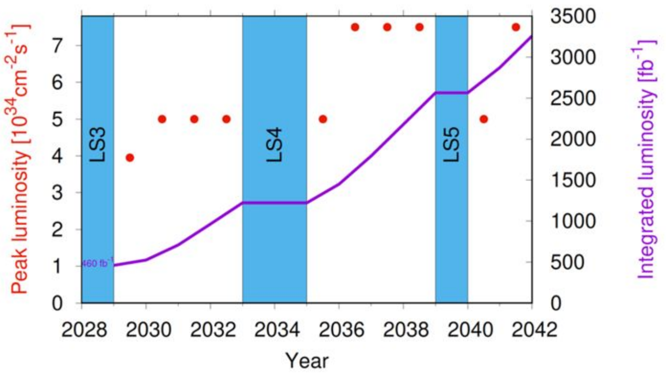
CMS is under Run III data taking and in the process of preparation to extend its sensitivity to new physics searches for the High-Luminosity LHC period starting in 2029, anticipated to feature a higher Instantaneous Luminosity to around 3000 fb^{-1}.

CMS muon LHC phase 2 upgrade



Muon system upgrade for HL-LHC (|η| < 1.8)

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



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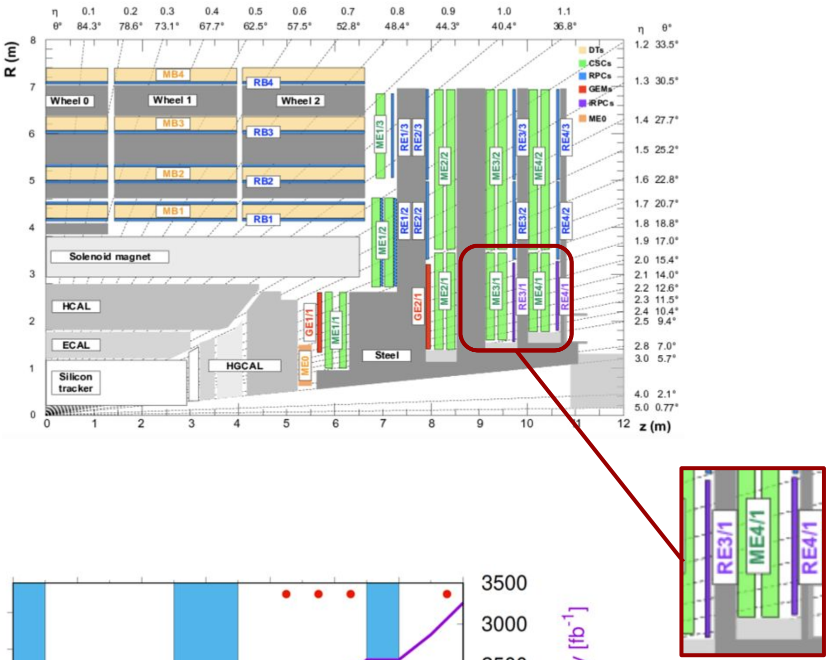

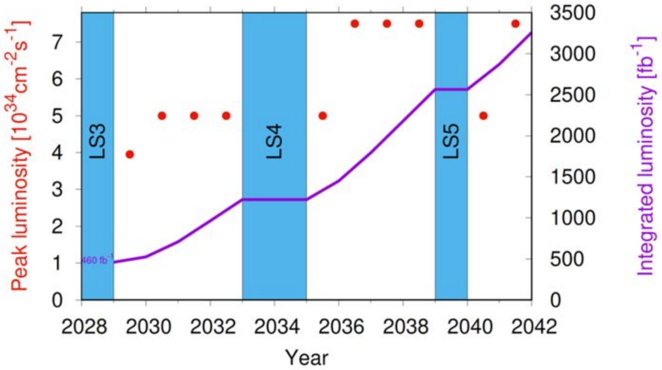

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Installation of new detectors in the forward region

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

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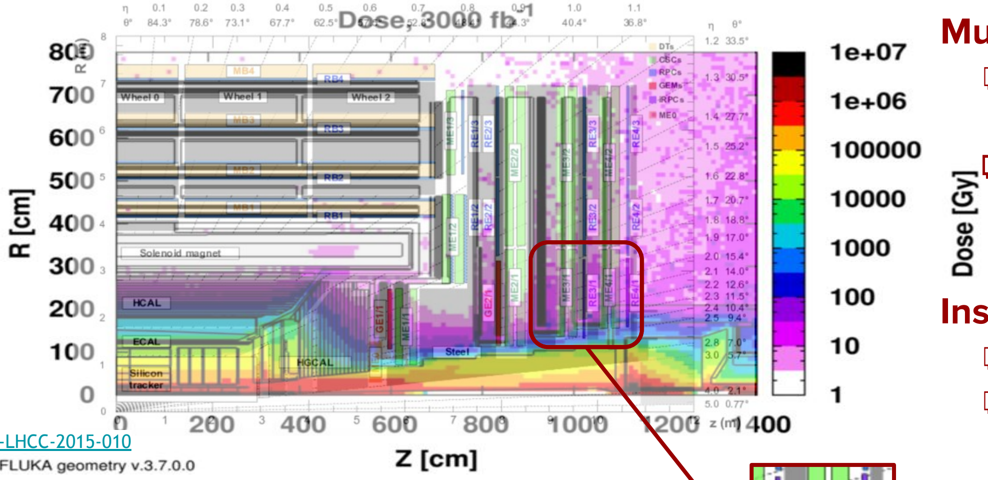
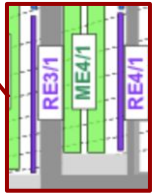
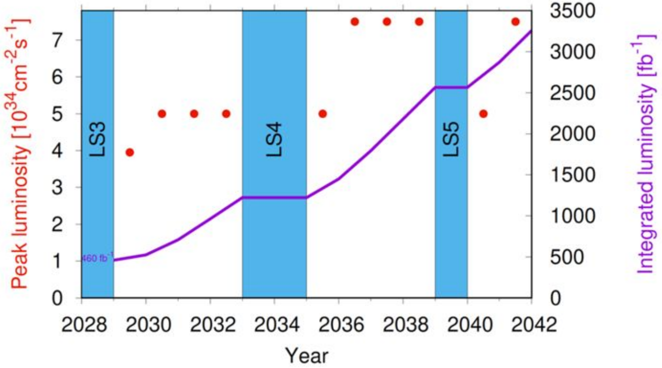


CERN-LHCC-2015-010

CMS FLUKA geometry v.3.7.0.0



max bkg. rate ~700 Hz/cm^2



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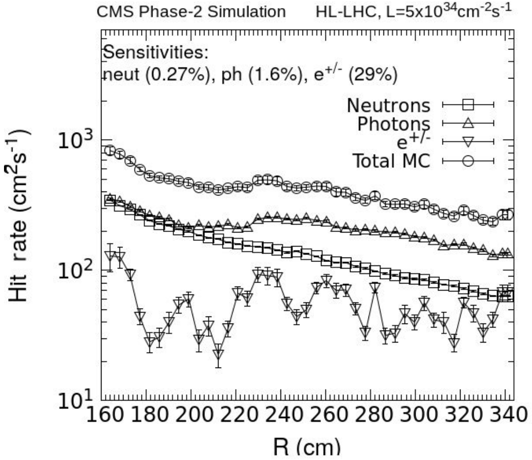

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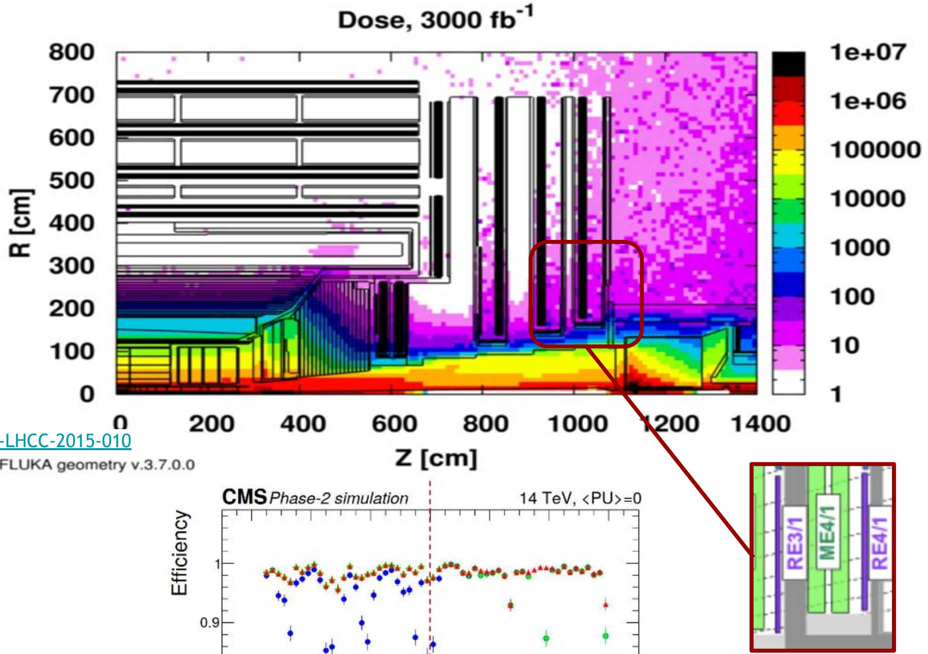

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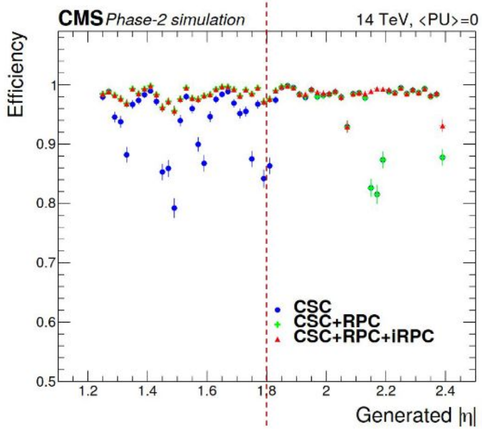

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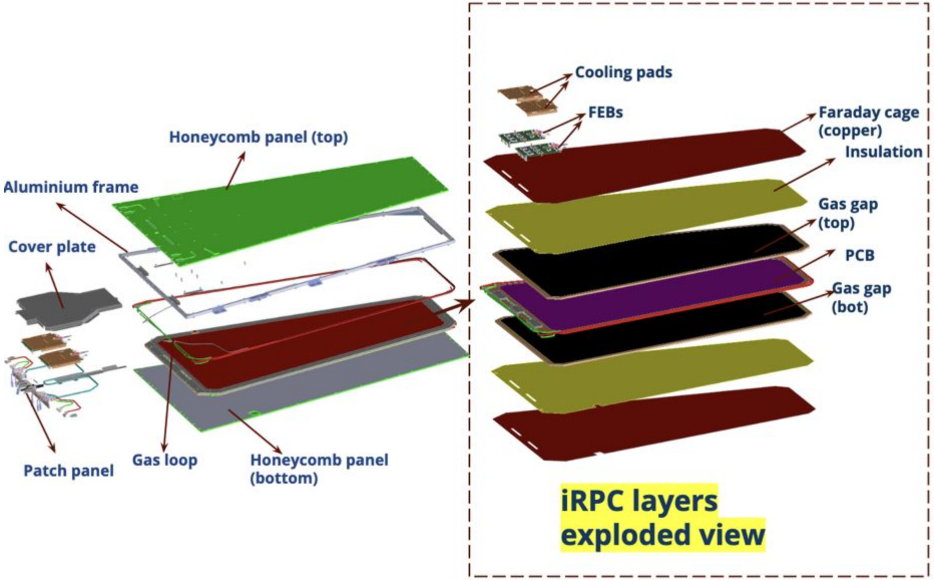
Motivation for iRPC installation of phase 2 upgrade

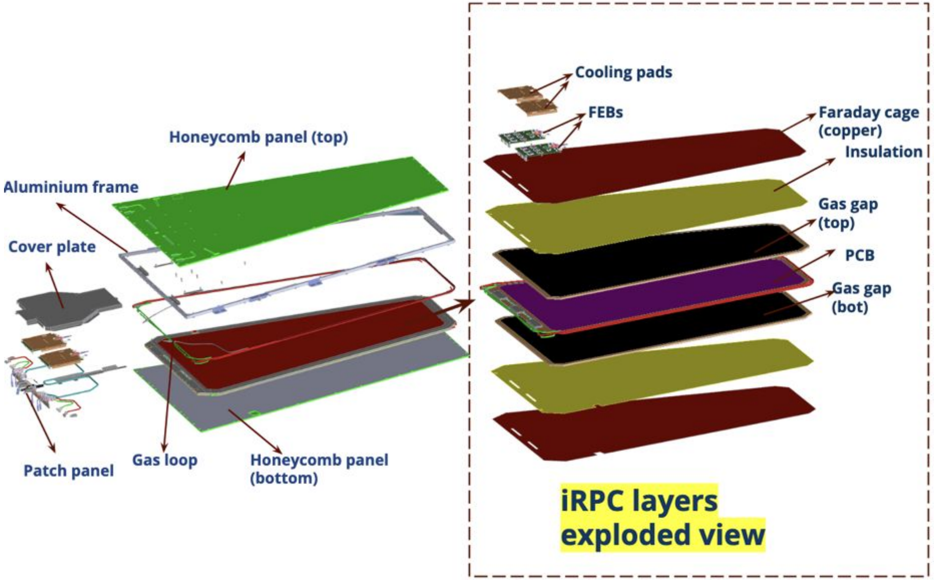
- high particle rate and high pileup environment due to increased luminosity in HL-LHC
- Extension of the RPC coverage in the high η region
  → improved L1 trigger efficiency and rate

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)	$1 - 6 \times 10^{10}$	$0.9 - 3 \times 10^{10}$
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

iRPC: improved resistive plate chamber



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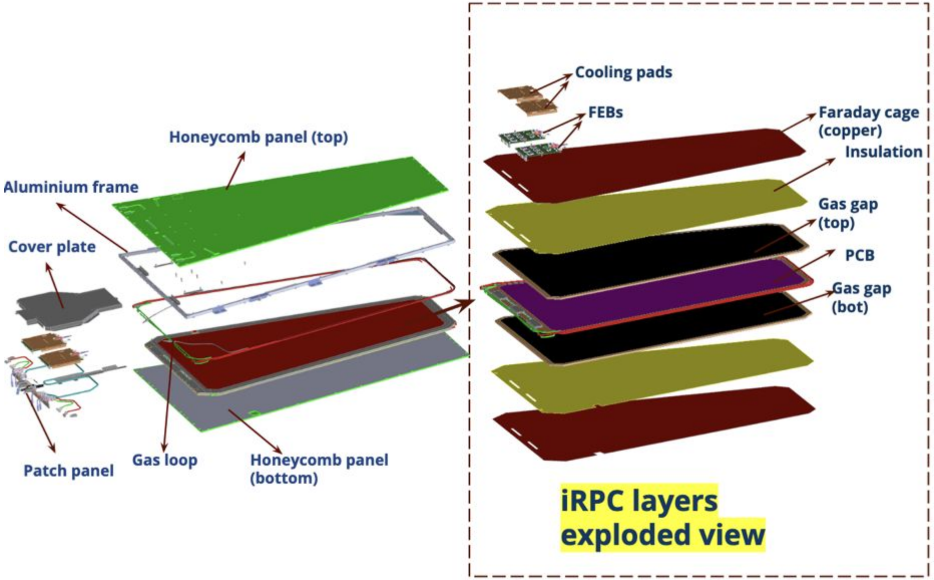

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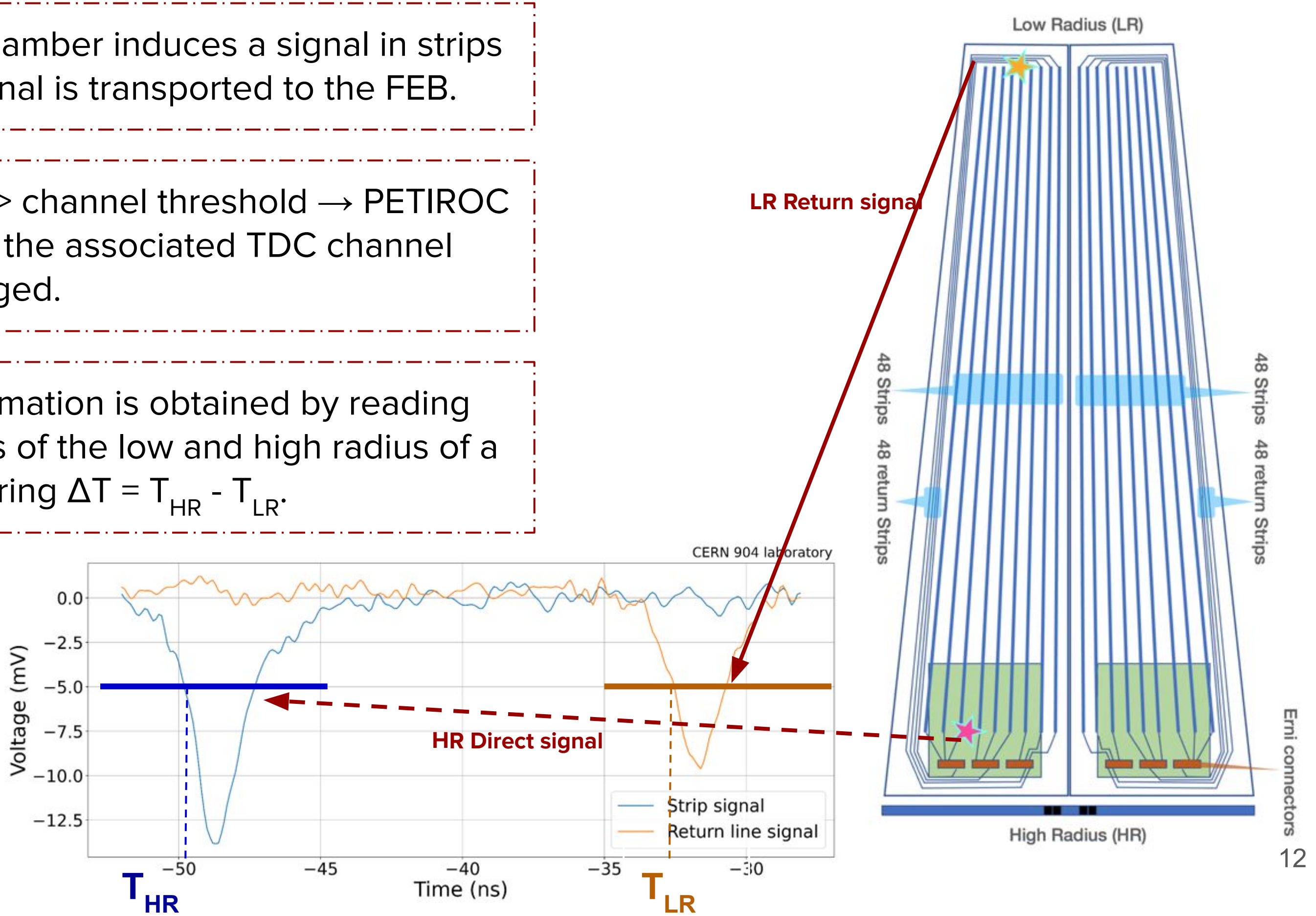
2d readout for iRPC.

iRPC read out principle

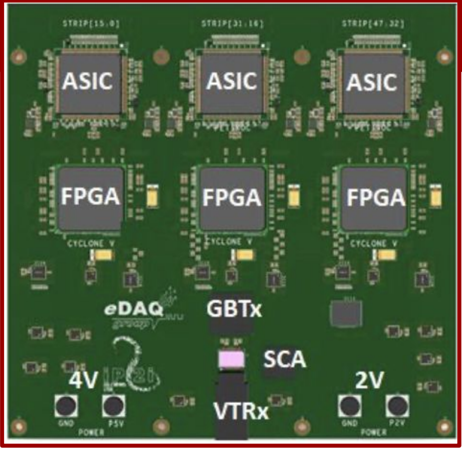
a muon crossing the iRPC chamber induces a signal in strips outside the gaps and the signal is transported to the FEB.

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

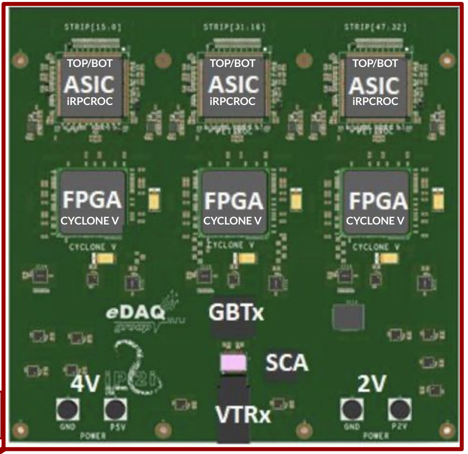
The 2D position information is obtained by reading out the TDC channels of the low and high radius of a strip and then measuring $\Delta T = T_{HR} - T_{LR}$.



2) FRONT END



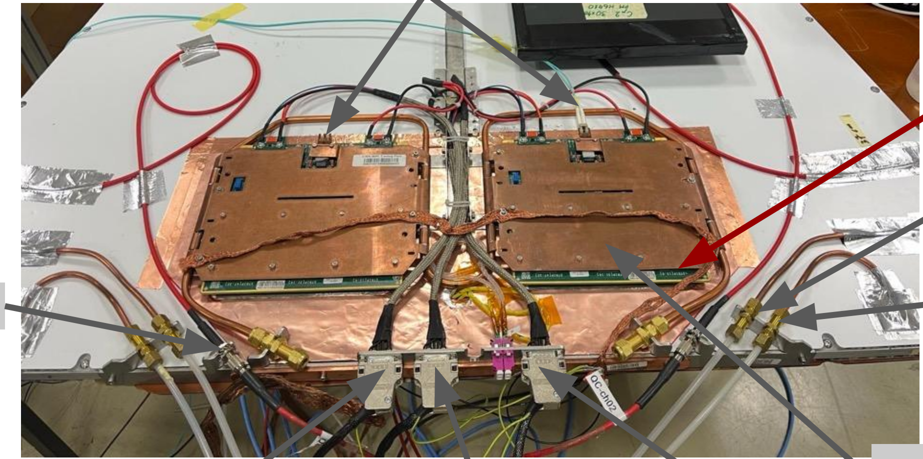
iRPC front-end electronics (FEB)



Feb v2.3 PETIROC 2C

FEB

Fiber readout



Gas supply

Gas return

HV connector

2V for left FEB

2V for right FEB

4V for both FEBs

Cooling plate with thermal pads

History of the FEB at IP2I

First proto

2017

proof of principle for CMS-MUON-TDR-016

2 PetiROC2A
+ FPGA Cyclone II
+ ETHERNET
directly on strip PCB (50 cm)

Feb V0

2018

First FEB (Conf. note)

1 PetiROC2A + MEZZANINE with FPGA Cyclone II
+ ETHERNET

Feb V1

2019

FEB without mezzanine

2 PetiROC2B
+ FPGA Cyclone V
+ ETHERNET

Feb V2_1,2

2021

Non-rad hard for iRPC Demo

6 PETIROC2C
+ 3 FPGA Cyclone V

Feb V2_3

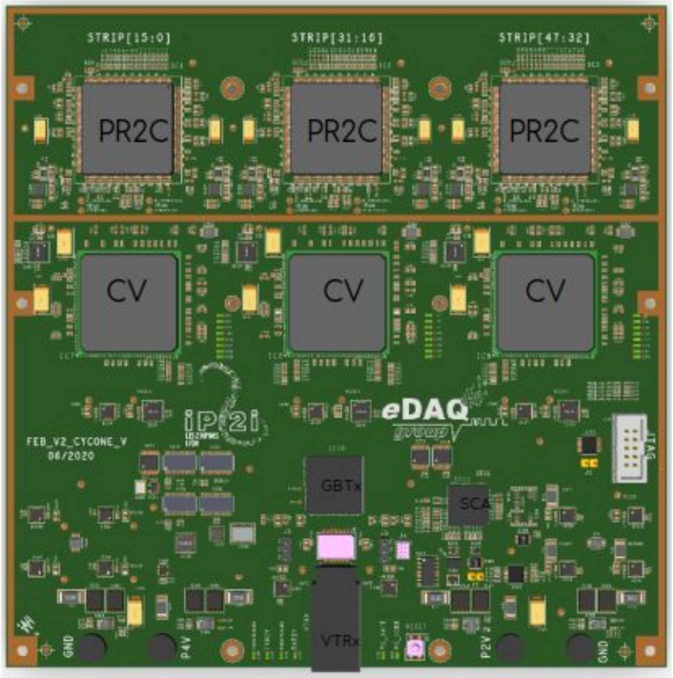
2023

Mass production prototype

FEBv2_1 + firmware update feature by optical GBT

FEB design

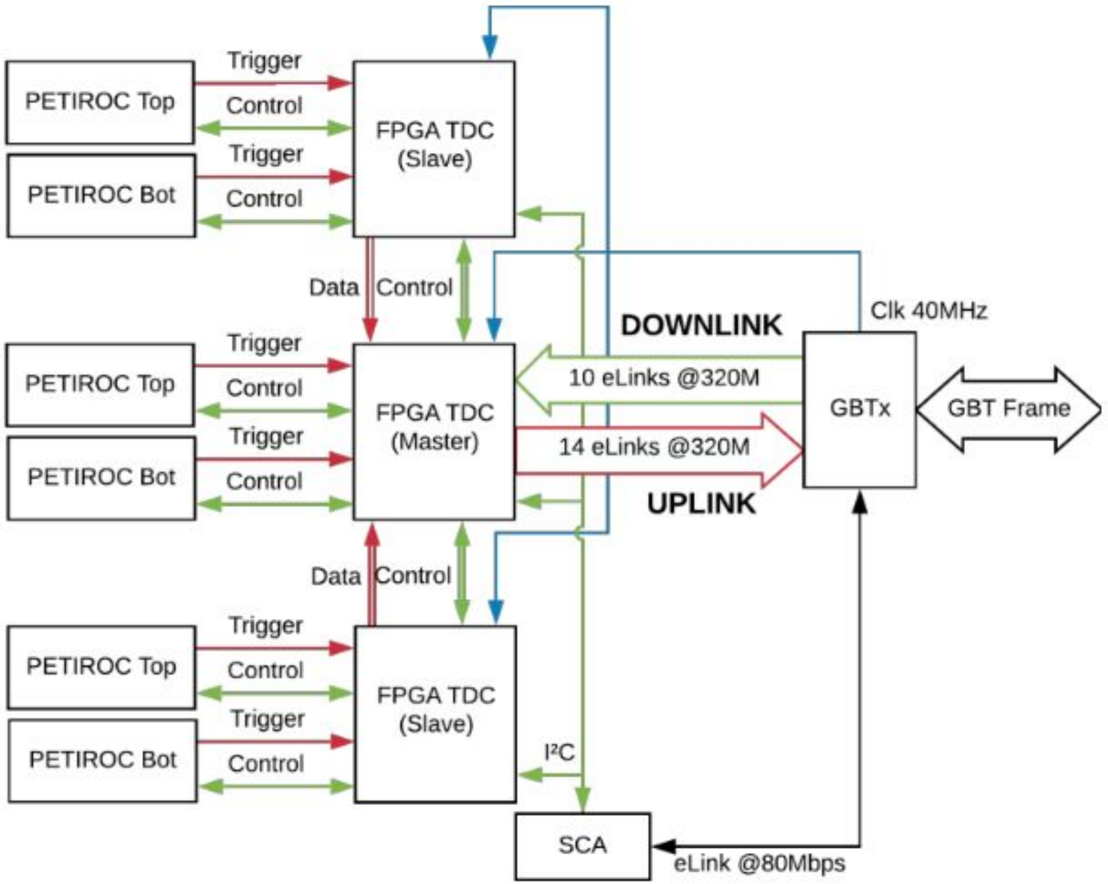
- 2 FEBs / Chamber → 144 (+16 spares) FEBs in total
- 3 Erni connectors with 32 channels each.
- 6 ASIC PetiROC2C (PR2C):
  - Specially designed by OMEGA group for CMS RPC project based on Petiroc2A
- 3 FPGAs (96 + 6 TDC channels)
  - FEBv2: CYCLONE V (non rad-hard)
- CERN ASICS: GBTx + GBT-SCA + VTRx
  - for the communication ald slow control
- Separated 2V and 4V power zone for Analog and Digital components. Latchup protection (Overcurrent detection).



4V zone with regulators

2V zone with regulators

FEB design


PETIROC Top
PETIROC Bot
PETIROC Top
PETIROC Bot
PETIROC Top
PETIROC Bot
Trigger
Control
Trigger
Control
FPGA TDC (Slave)
FPGA TDC (Master)
FPGA TDC (Slave)
Data
Control
DOWNLINK
UPLINK
10 eLinks @320M
14 eLinks @320M
Clk 40MHz
GBTx
GBT Frame
I²C
SCA
eLink @80Mbps

ASIC Petiroc

PETIROC2A designed for PET

- High frequency preamp
- Thr > 60 fC
- Time resolution < 100 ps

Limitations: low rate expected

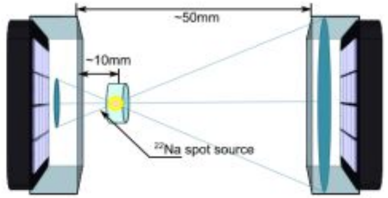


Figure 2. Setup structure used during the experiments.

https://dx.doi.org/10.1109/NSSMIC.2018.8824464

PETIROC2A for RPC :

- Retriggering and inter-channels cross-talk
- Thr > 100 fC
- Time resolution < 200 ps

PETIROC2B modif for iRPC :

- Reduce preamp. frequency
- Thr ~ 100 fC
- 10-20 ns / ASIC dead time introduced to remove retriggering

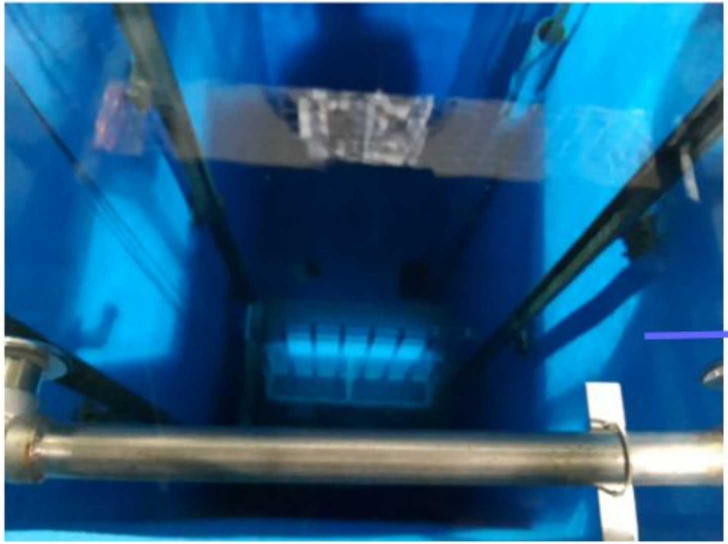
→ 2-3% efficiency loss / chamber

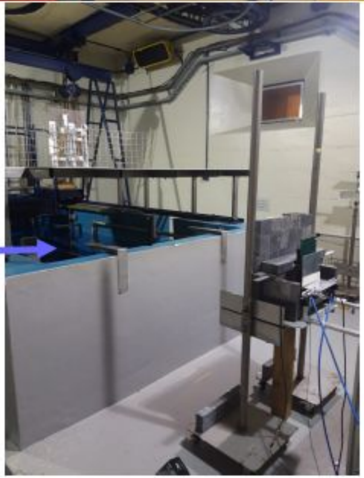
iRPCROC (PETIROC2C) :

- Removed useless components from PR2A.
- Thr < 50 fC
- 40 ns auto-reset / channel te remove retriggering.
- 960 required, a set of 1300 available with uniform behaviour.

Radiation tolerance

Validation en radiation gamma





Caliope a ENEA Casaccia a côté de Rome

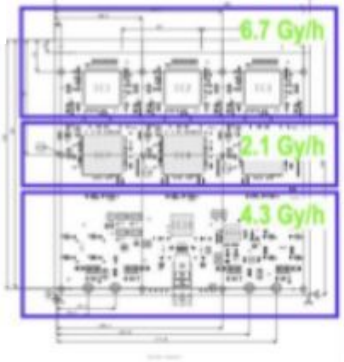
Radiation tolerance

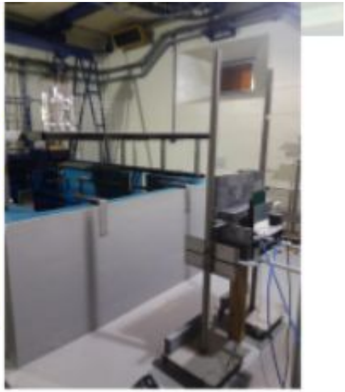
1) TID (γ's) -- Facility ENEA Casaccia Calliope ^{60}Co July 2022

Requested: 17 Gy

Certified:

- FPGA Cyclone V (50 Gy):
- Petiroc (160 Gy);
- Power supply zone (100 Gy)
- **Safety Factor: 3 - 9**





2) TNID (neutrons) - Facility FNG Frascati, with support from RADNEXT March 2022

Requested: 6e11 neq1MeV/cm^2:

Certified: 25e11 neq1MeV/cm^2:

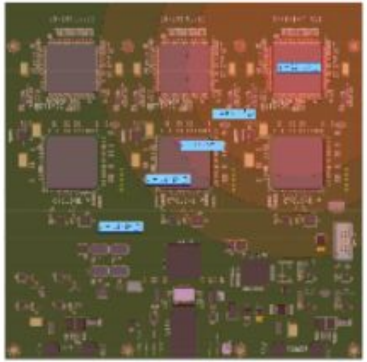
SF: 4

3) Neutron flux -

Requested: 10e3 neq1MeV/cm^2/s

Certified: 450e3 neq1MeV/cm^2/s

SF: 45



Radiation tolerance

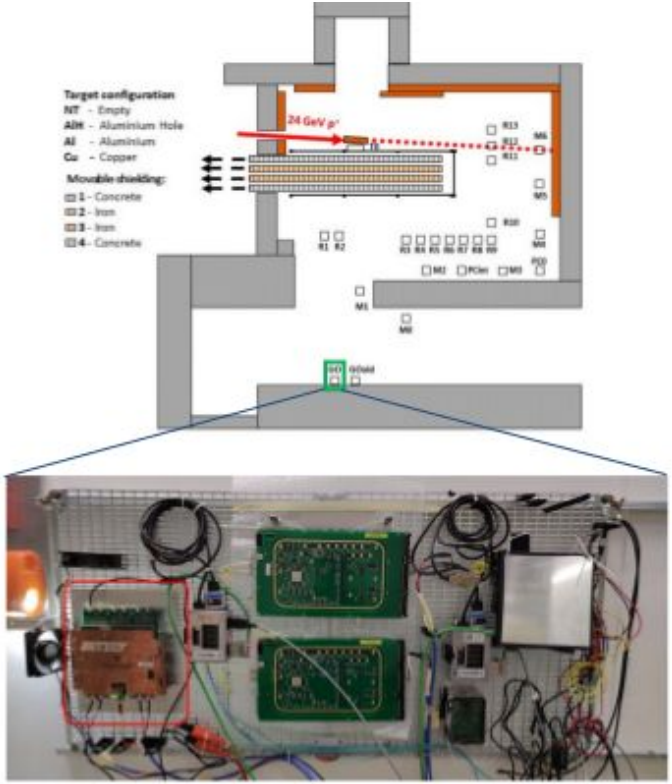
1) TID (charged hadrons, thermal neutrons)
in CHARM, CERN

Dose Requested: 17 Gy
Certified: ~ 57 Gy
SF: 3.3

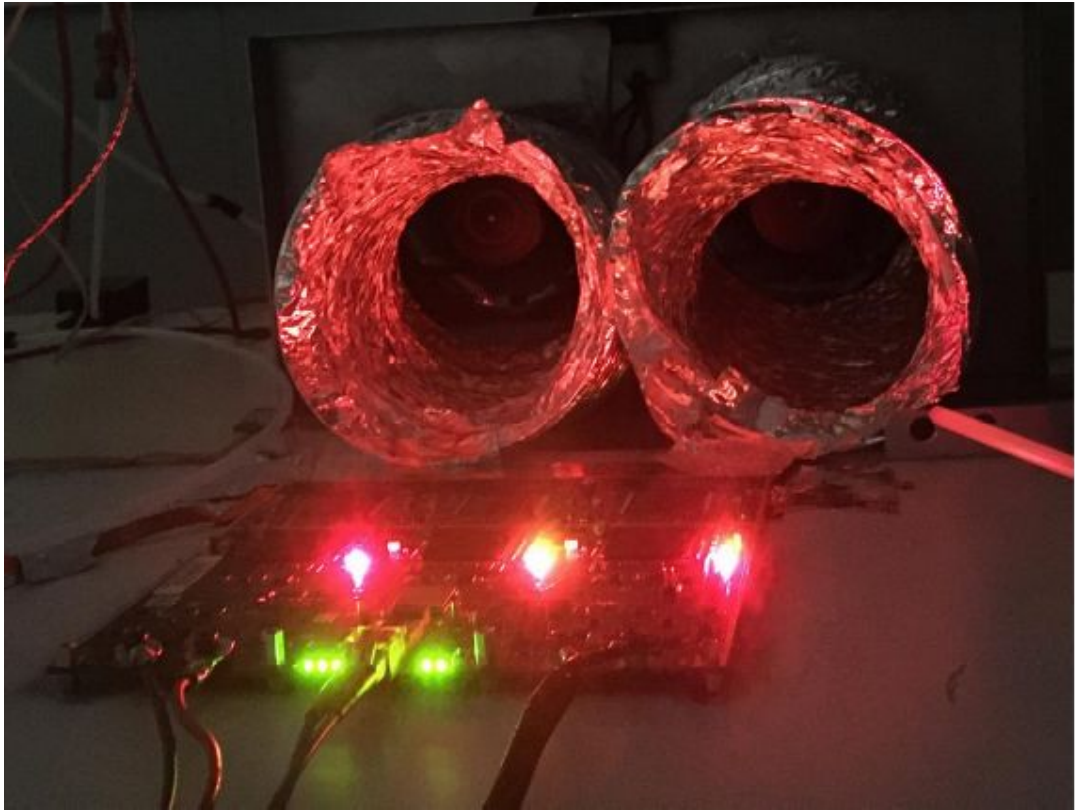
Fluence Requested: 0.9e11 HEH/cm2; 2.7e11 ThN/cm2
Certified: ~ 1.6e11 HEH/cm2; 3.3e11 ThN/cm2
SF: 1.8; 1.2

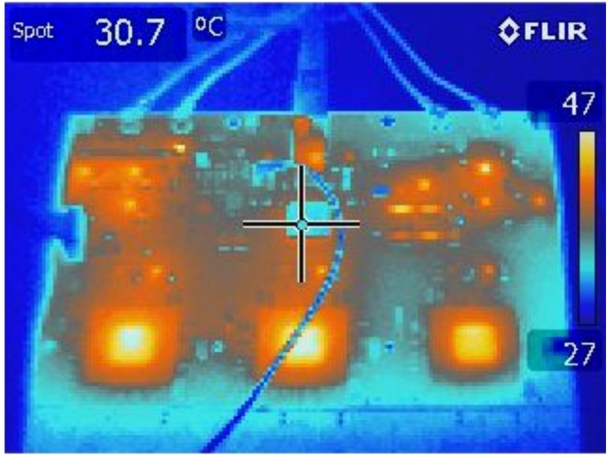
2) SEU (charged hadrons, thermal neutrons)
in CHARM, CERN

Flux Requested: 1.4 kHEH/cm^2/s; 4.2 kThN/cm^2/s
Certified: 140 kHEH/cm^2/s; 280 kThN/cm^2/s
SF: 100; 67



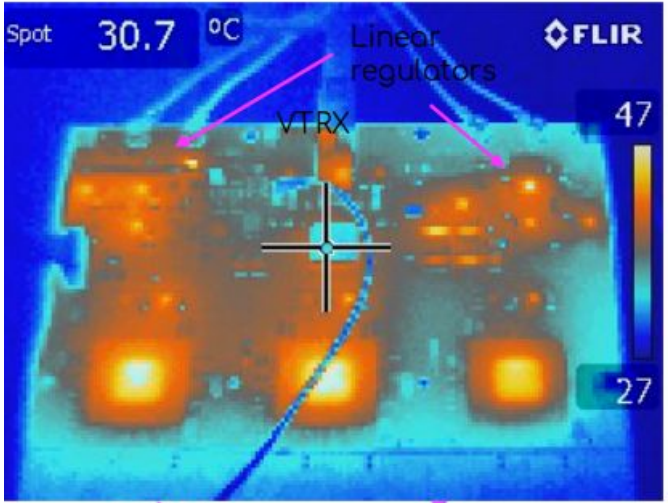
Cooling





Cooling

Total consumption: 2V*6.3A+4V*2.3A = 22 W



FPGA

Hottest elements:

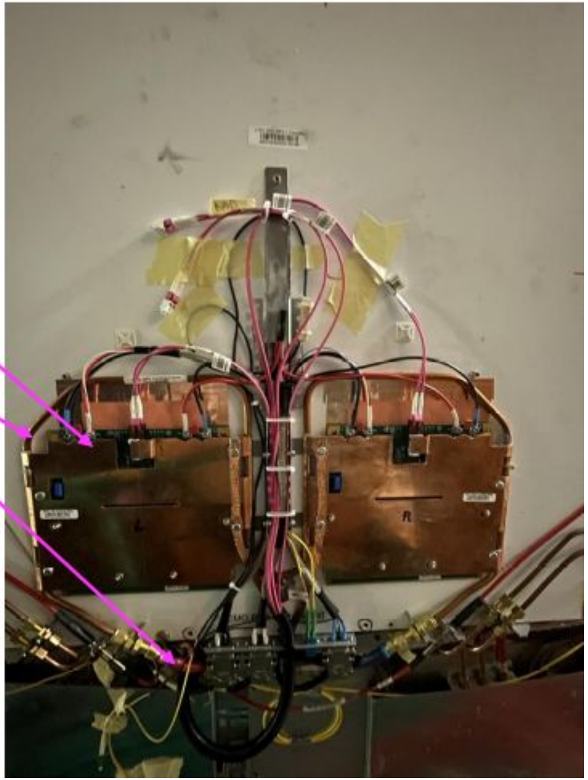
- linear regulators - Ohmic effect
- Optical communication
- FPGA - logic

Cooling system

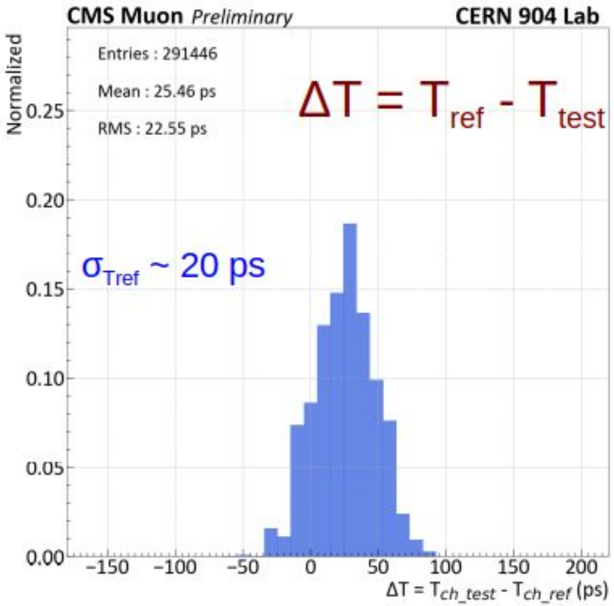
1) Thermal pads + copper plate
2) Cooling pipe
3) Cool water: 15 C

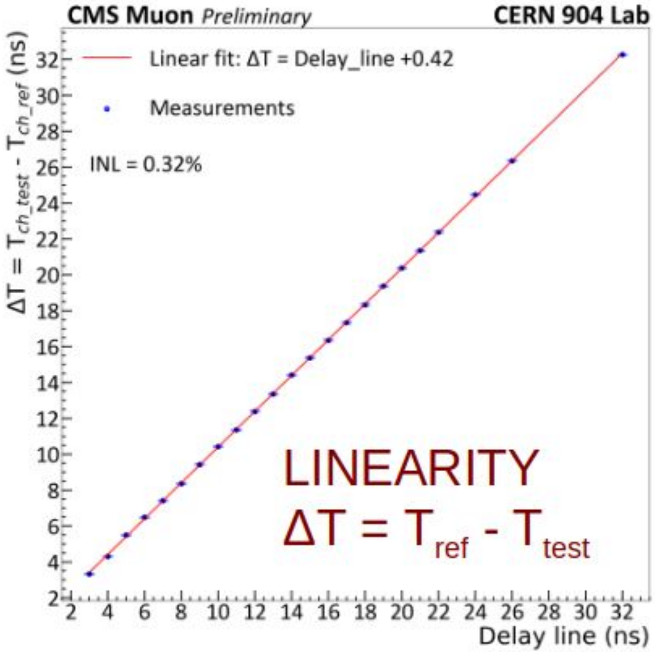
Max temperature < 50 C

Play also the role of grounding plane



Time resolution and linearity





Pure TDC time resolution was measured using 2 channels test and a reference

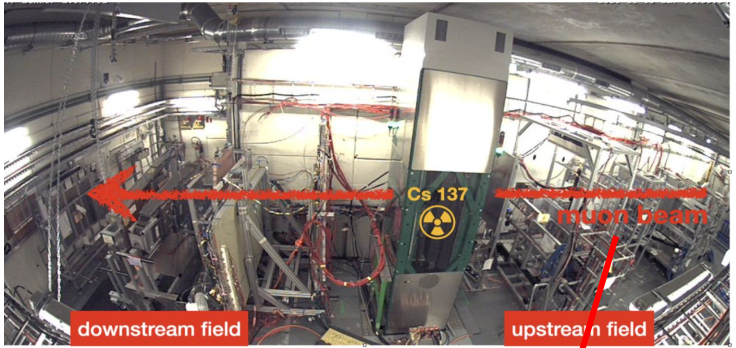
3) PERFORMANCE

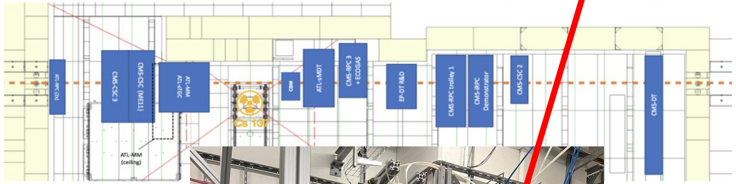
iRPC performance under gamma background

Gamma irradiation facility (GIF++)

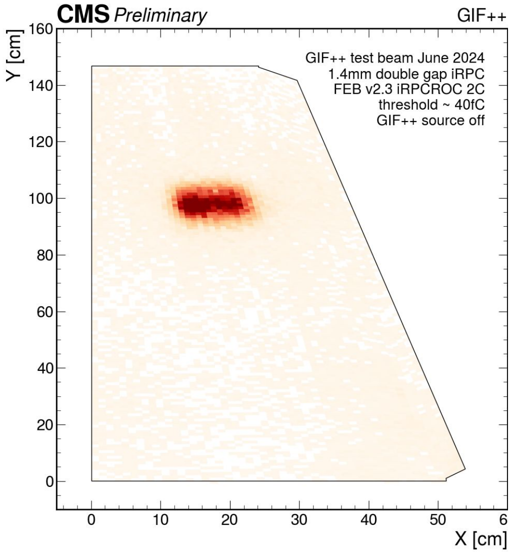
- ❏ 12 TBq ^{137}Cs gamma source 662 KeV
- ❏ Muon beam ~ 150 GeV/c

→ Test iRPC performance in HL-LHC background conditions

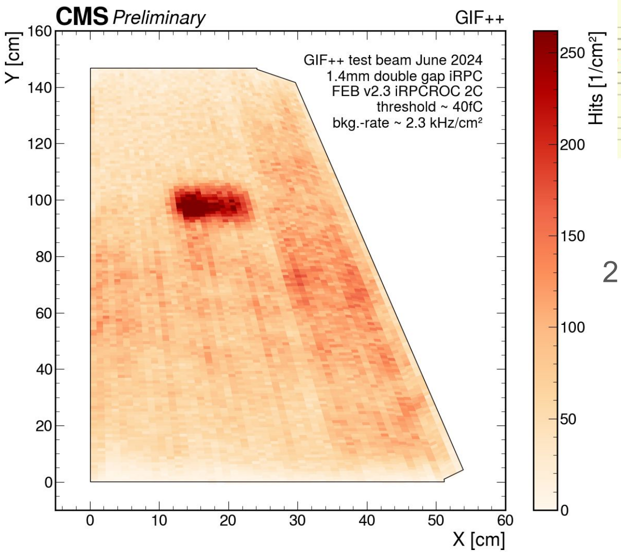




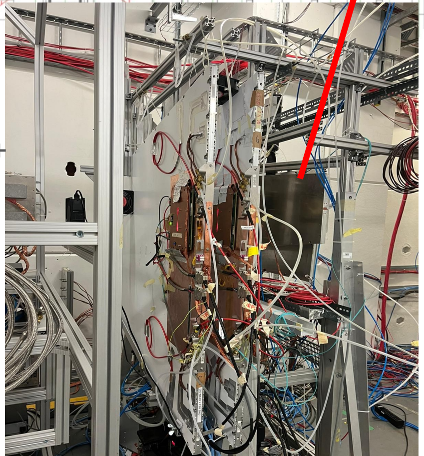
GIF++ source off



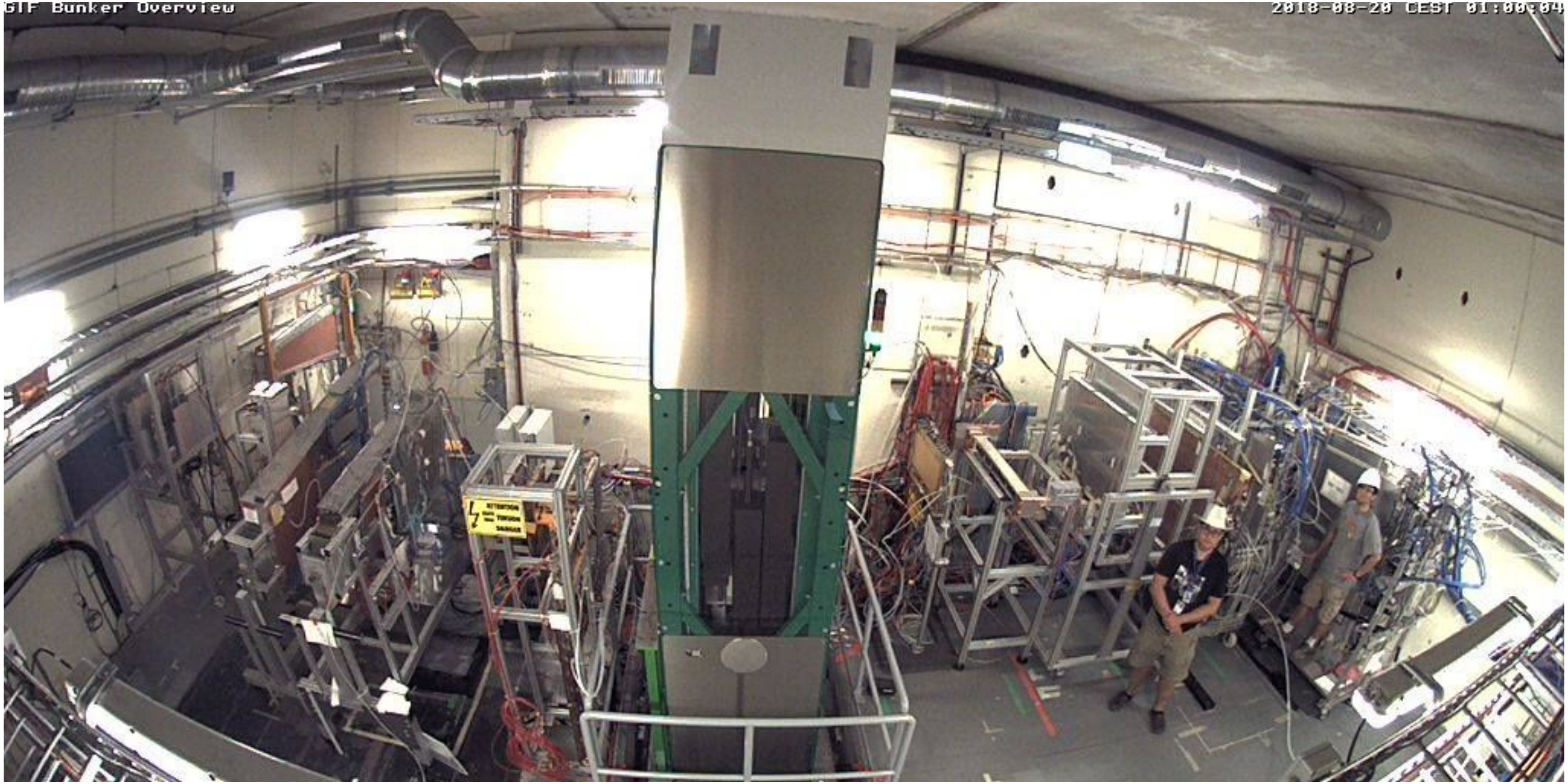
bkg. rate ~ 2.3 kHz/cm^2



2 iRPC in Gif++



Polergeist



iRPC performance under gamma background

Gamma irradiation facility (GIF++)

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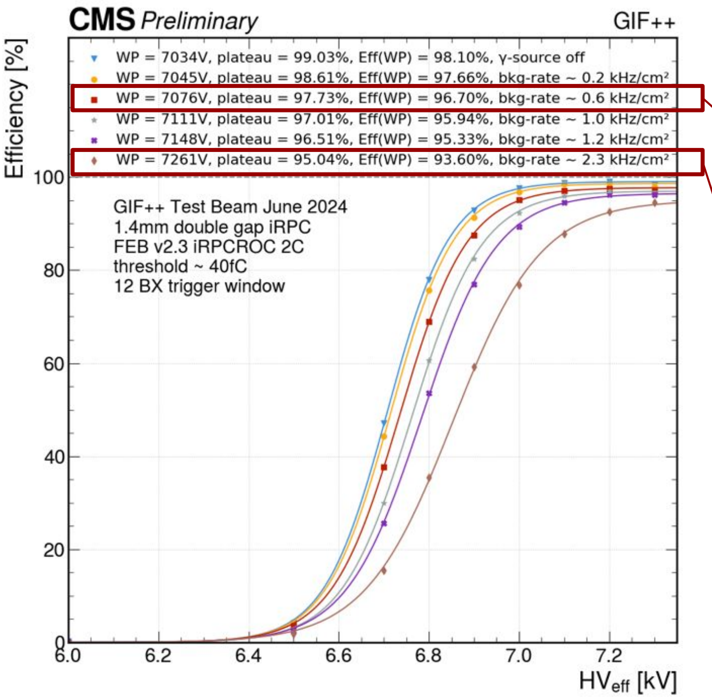
- Muon beam ~ 150 GeV/c

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

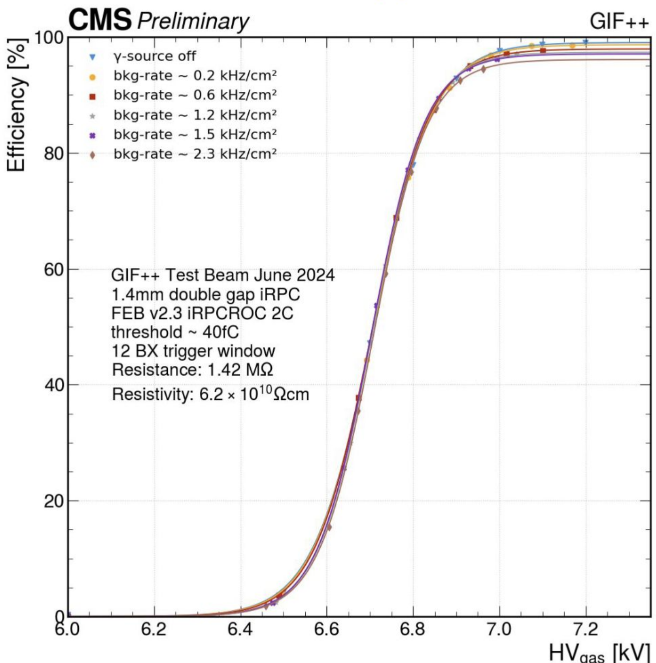
→ Test iRPC performance in HL-LHC background conditions



@ 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

$$HV_{gas} = HV_{eff} - RI$$



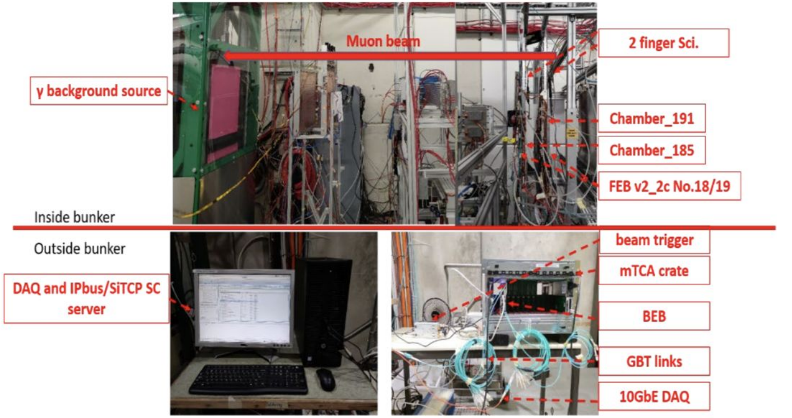
IP2I team debugging during COVID at CERN

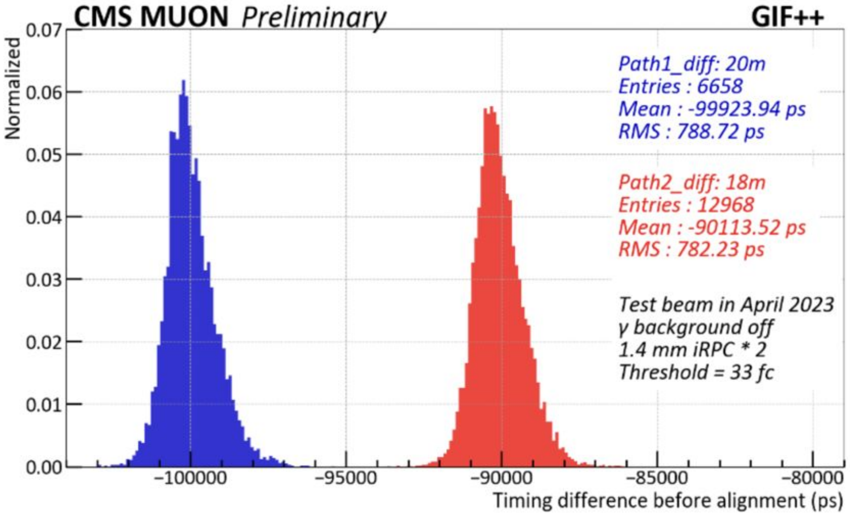
iRPC time resolution

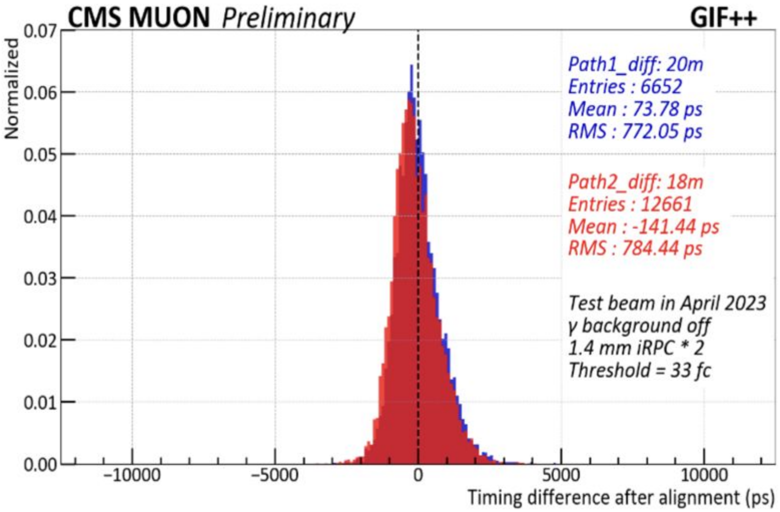
time resolution measurement at GIF++

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

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







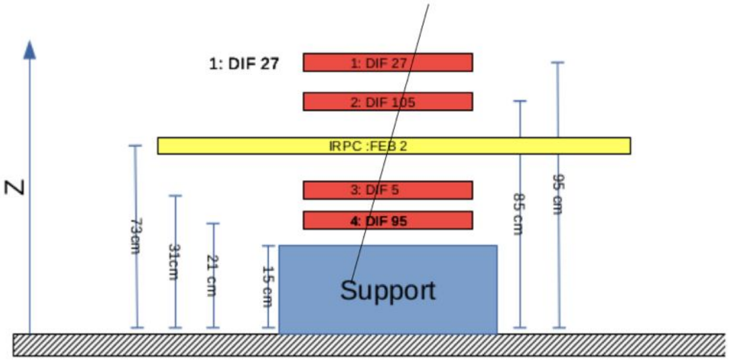
iRPC space resolution

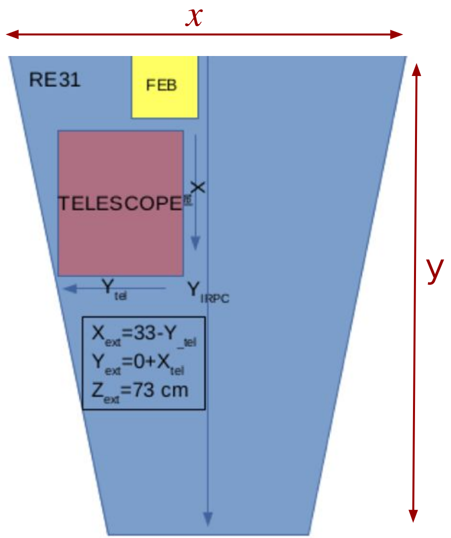
Cosmic muon telescope in Lyon University IP2I

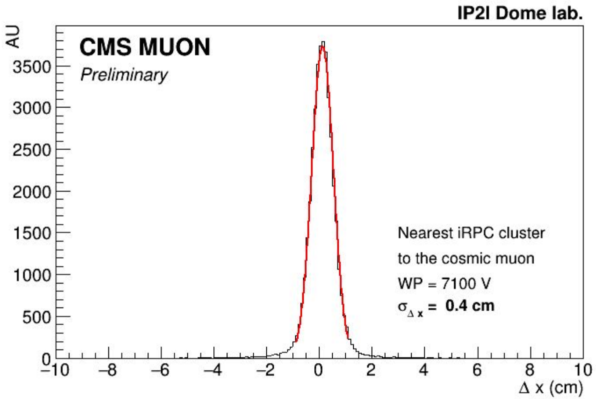
- 4 control RPC-chambers
- space resolution measurement of iRPC:

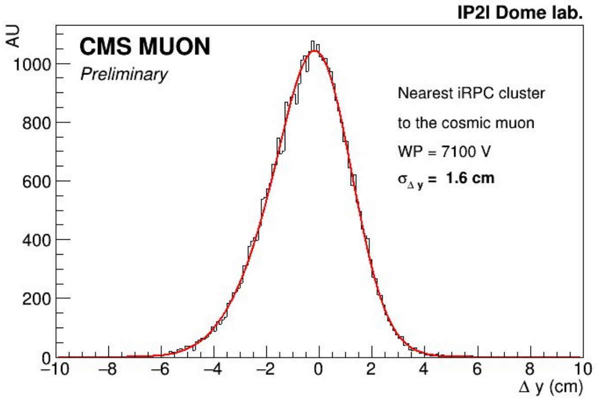
  σ_x = 0.4cm (depends on **strip pitch** in the telescope region)

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









4) MASS PRODUCTION and QC

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** laboratory in KOREA (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

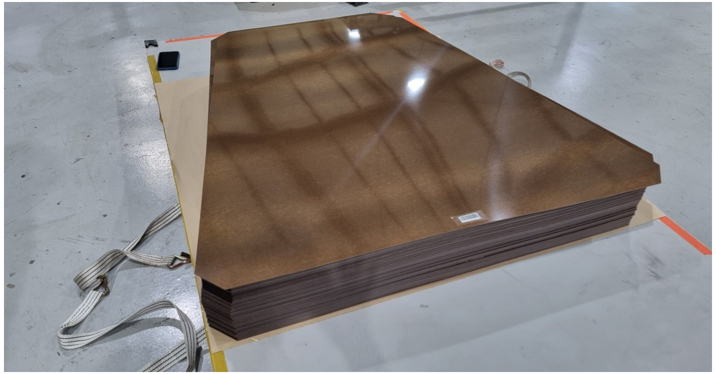
- QC3.1 Chamber Assembly Tests: Visual test, Gas Leak test
- QC3.2 Chamber Cosmic Tests with 1 portable FEB (noise, eff, cluster size, HV), Connectivity Test, Dark Current Test (DC1)

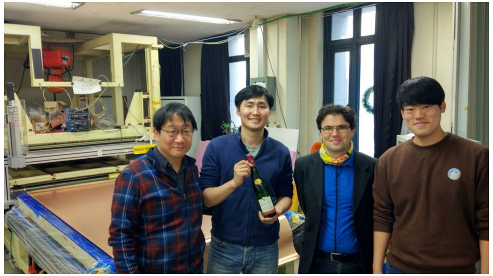
QC4 - Final Chamber Validation @ CERN 904

- 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)

Bakelite production (INFN) and gaps (KOREA)

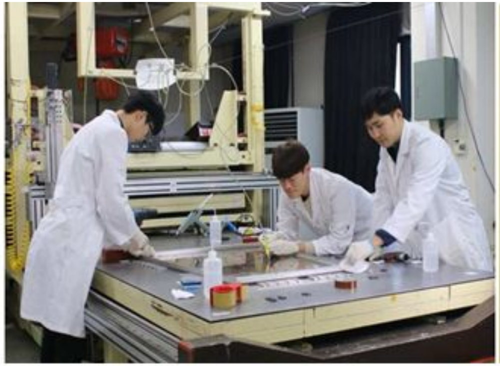
HPL @ Firm under INFN Pavia supervision





Gap production in Korea

Gluing tables and pressure devices



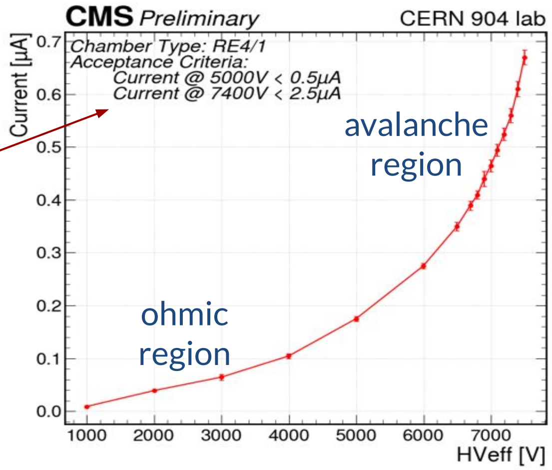
Gap validation *@ production & assembly sites*

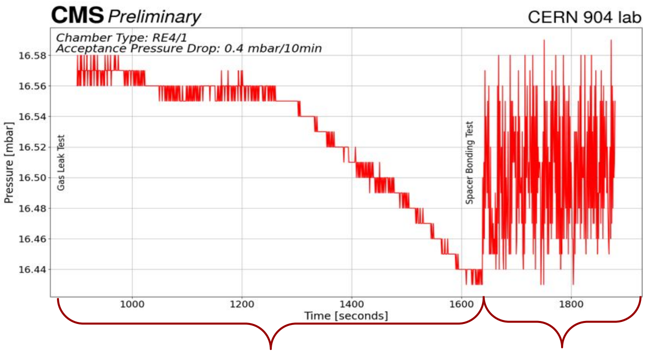
Gap pressure and spacer bonding test

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

dark current test

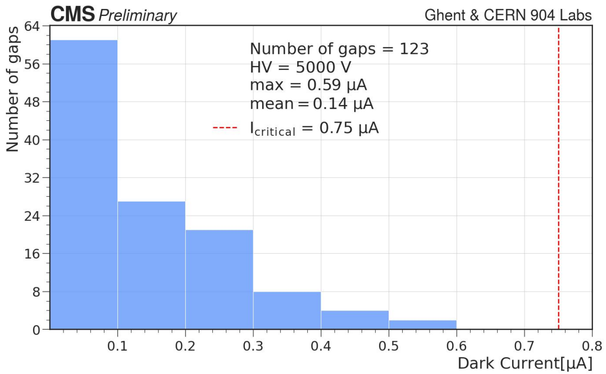
- ❏ monitor gap current over high voltage range
  → current acceptance criteria to validate gaps

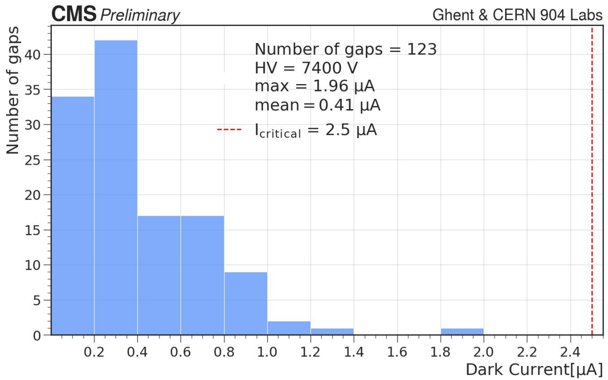




Leak test (drop < 0.4 mbar/10 min)

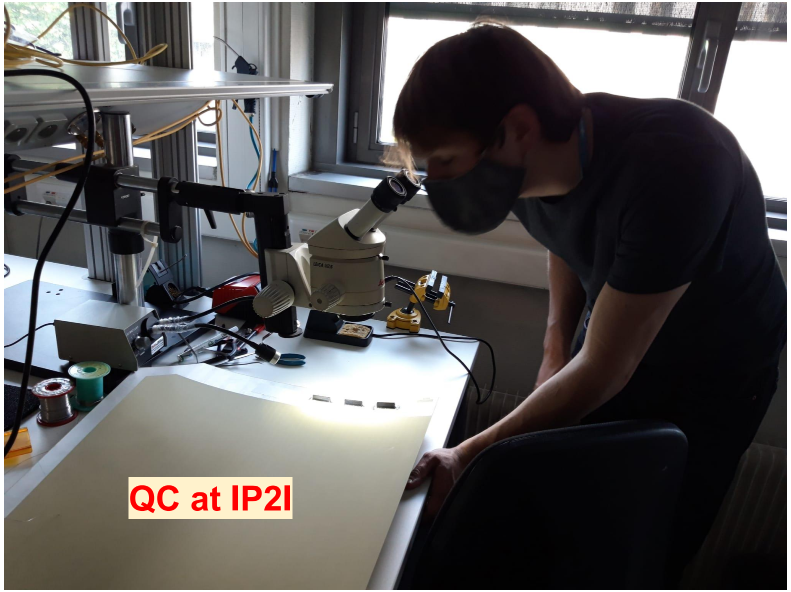
Spacer bonding test

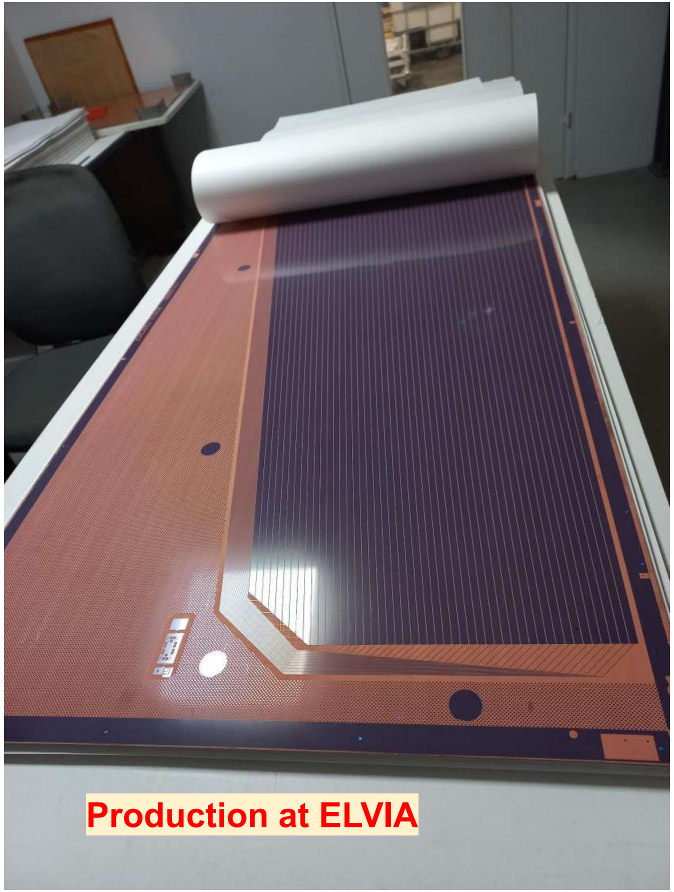




Strip PCB production

1) ELVIA in Normandy
can produce 0.6 m * 1.5 m, 2-3-4 layers PCBs.
2) Very large size with a precision of O(10 %) in thickness. CMS RPC PCB - 350 µm





FEB production and quality control

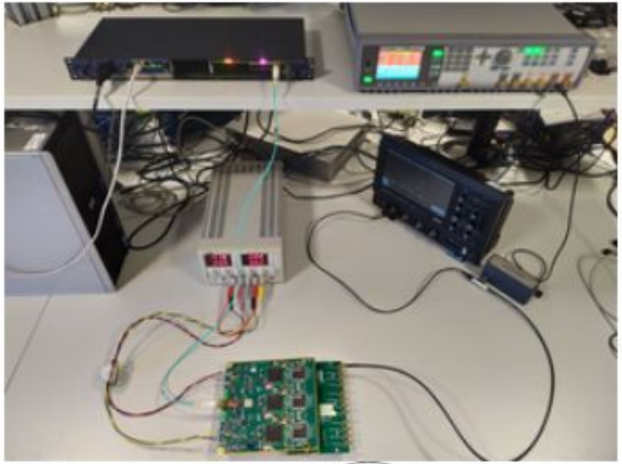
Production of 160 is done by French company FEDD in 2023-2025 :

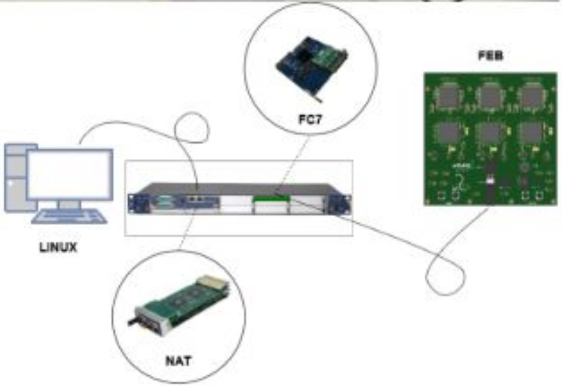
1) PCB production : Italian company SOMACIS

2) Stuffing + QC factory : FEDD

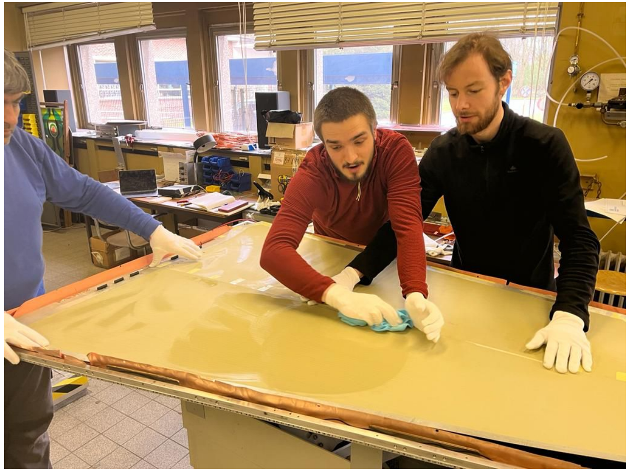
3) Functional QC1 at IP2I on test bench

4) QC on final chamber at CERN





iRPC construction overview



Construction sites:

GHENT UNIVERSITY

CERN

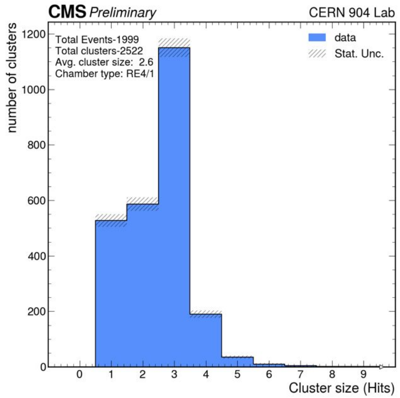
QC3: chamber quality control

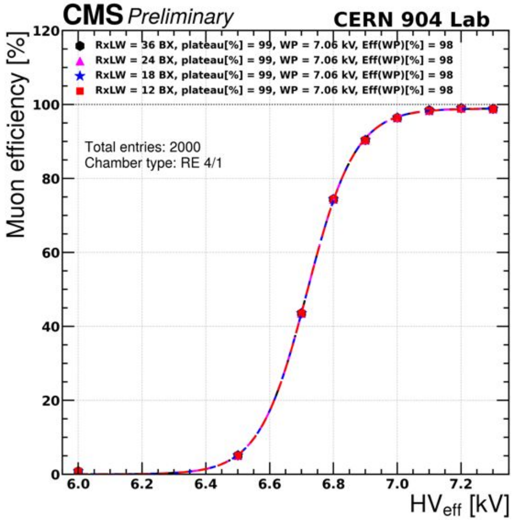
QC3.1 Chamber Assembly tests

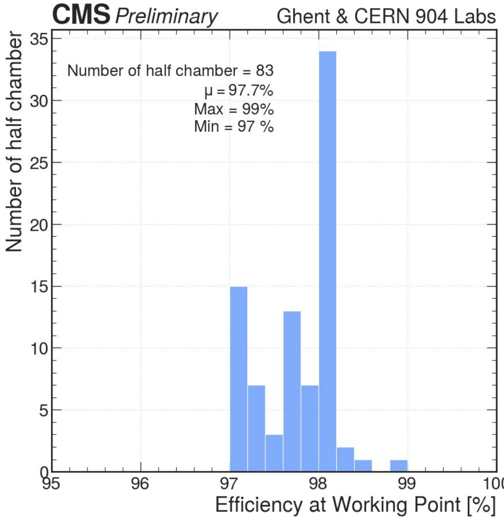
Visual test. Connectivity test, Gas leak test, dark current test

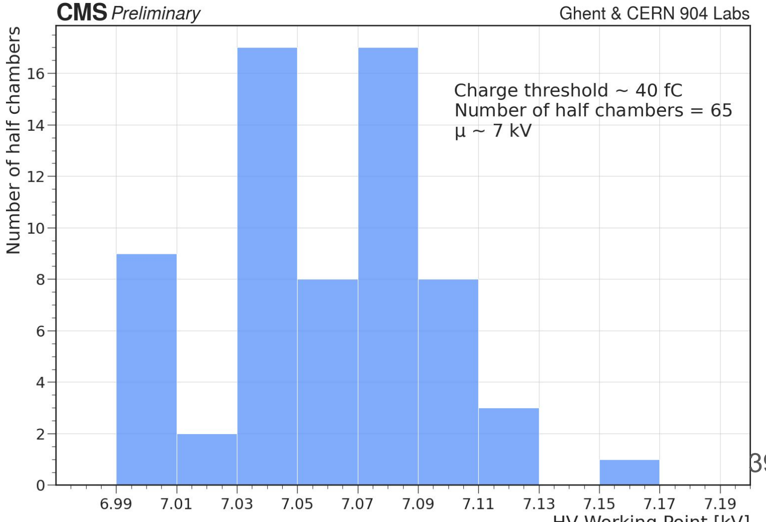
QC3.2 Cosmic efficiency test

- 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

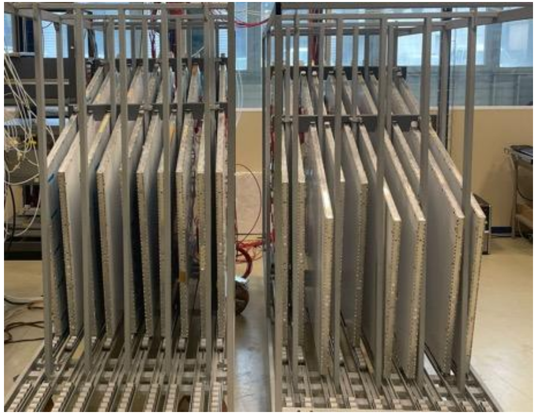
quality control after final chamber assembly with final FEBs (v2.3)

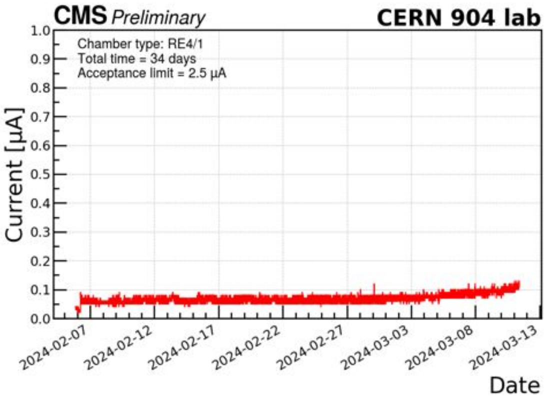
QC4.1 Cooling & Gas leak test

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

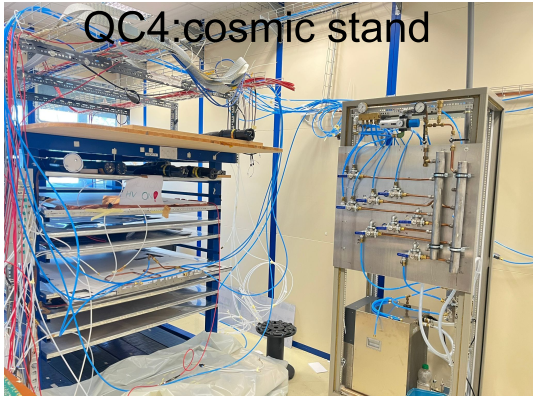
QC4.2 HV current stability

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

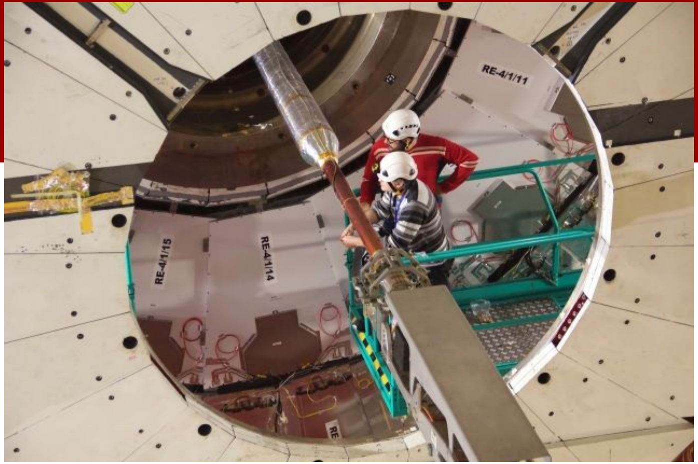




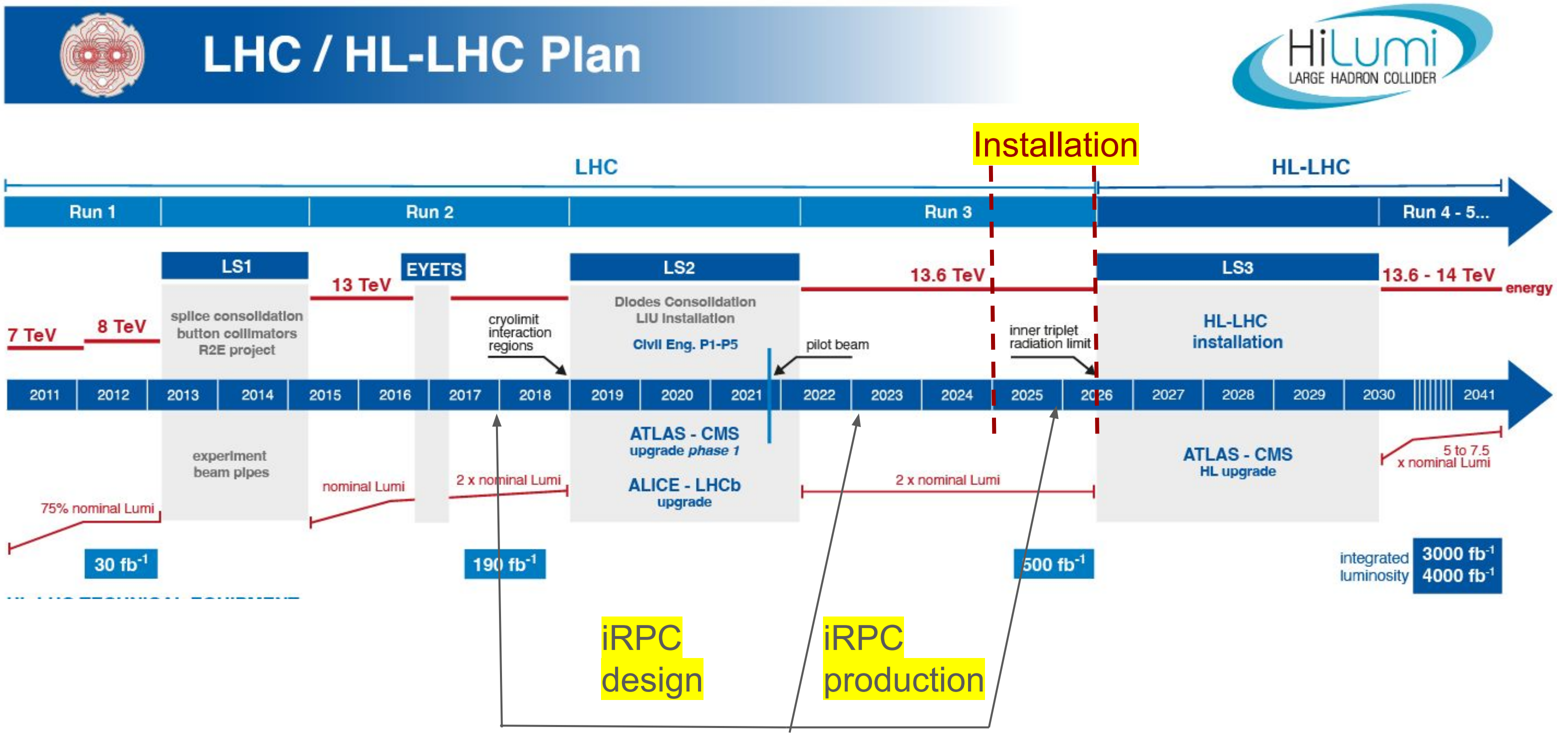
QC4.3 Final cosmic test in CMS like conditions



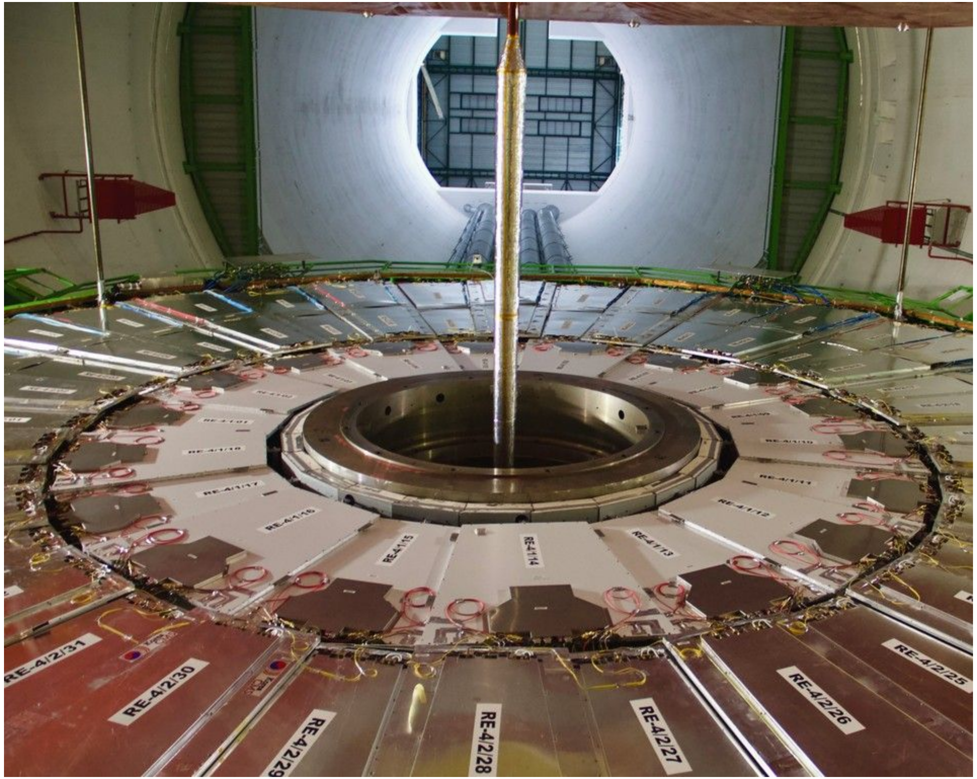
5) INSTALLATION



Installation of full project



Installation of 1 station: RE41-

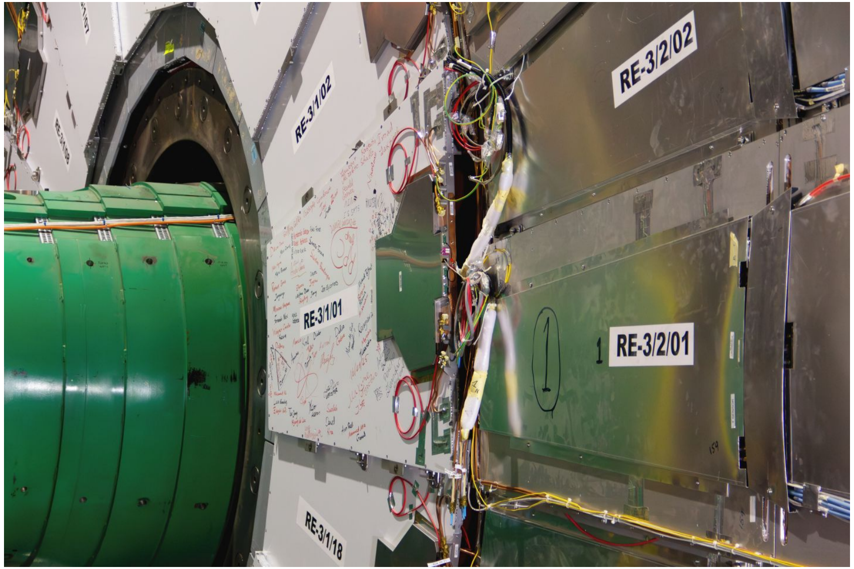


Requires opening of CMS detector → Complex operation
2 days of installation
2 weeks of QC in situ

Installation

- First 2 stations (36 chambers) over 4 installed in Winter 2024/2025
  - Comissionned and tested with real data during 2025 run.
- Remaining to be installed in Winter 2025/2026 and/or start of LS3

https://cds.cern.ch/record/2922015?ln=en



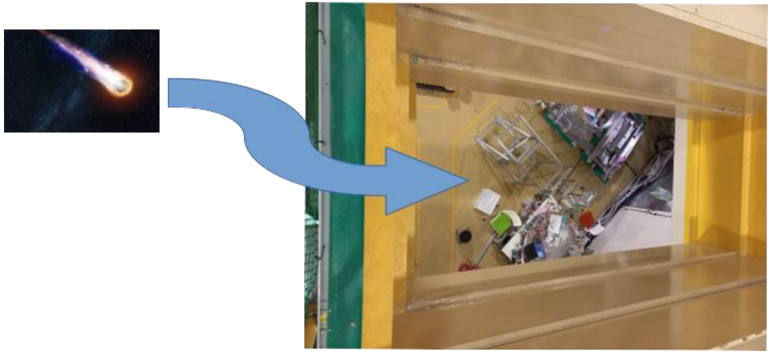
https://cds.cern.ch/record/2925269?ln=en

CONCLUSION for CMS

- The iRPC was a 10 years long adventure reaching its end
- ½ of the system is installed
- ½ is produced ready to install
- The performance of the big size gas detectors is well within specifications:
    - 0.5 ns time resolution
    - ~1 cm space resolution
    - 2 kHz rate capability with efficiency above 95%
    - Uniformity of the response over the surface
- It is a beautiful international collaboration uniting the expertise from many countries and in particular Italy and France

Excellent detector to be used in other experiments. Below the example of application to COMET experiment in J-Parc

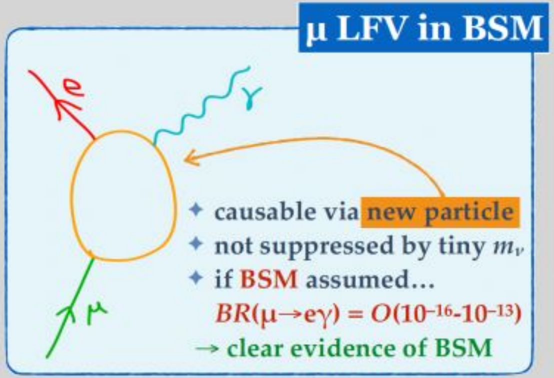
6) APPLICATION TO COMET EXPERIMENT



An alternative experiment for the use of RPC chambers : The COMET Experiment

A search for muon to electron conversion at J-Parc

- Observation of neutrino oscillations confirms the existence of neutrino mass and neutral lepton flavour violation.
- The neutrino mass terms predict charged lepton flavour violation (CLFV) at loop level
  - These processes are highly suppressed due to the tiny values of neutrino masses.
- Many beyond the SM physics models predict sizeable CLFV that may well be accessible experimentally.



One of the most interesting CLFV processes which can occur is the transition of a muon to an electron in the presence of a nucleus $\mu N \to eN$.

The image is from Hajime NISHIGUCHI Talk in ICHEP 2024

7

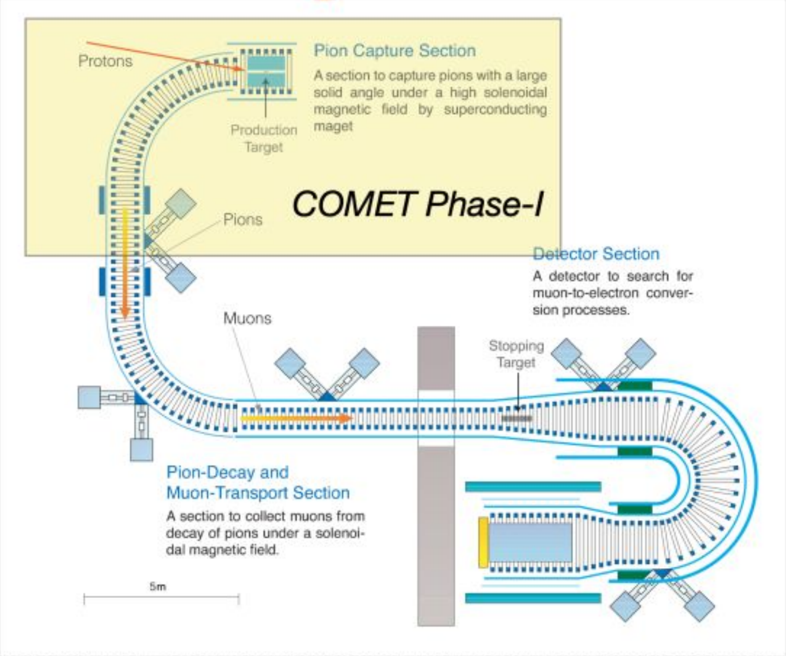
An alternative experiment for the use of RPC chambers : The COMET Experiment

COMET Phase-I

- Construct up to first 90° bend and place detector.
- Perform direct beam measurement
  - No backward σ_π data so far
  - No real background data so far
- Perform μ-e search with an intermediate sensitivity ($O(10^{-15})$)

COMET Phase-II

- Complete all transport
- Perform μ-e search with a full sensitivity ($O(10^{-17})$)



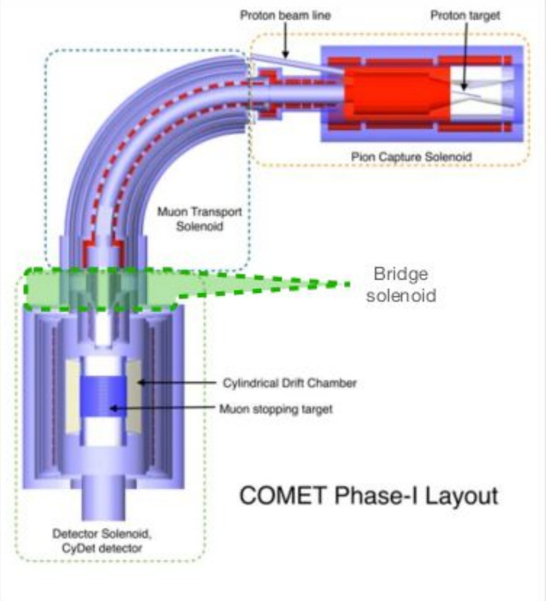
The content is from The COMET Experiment TDR

8

An alternative experiment for the use of RPC chambers : The COMET Experiment

Cosmic Ray Veto

- Cosmic Ray muons can decay in flight or interact with the materials around the area of the muon-stopping target and produce signal-like electrons in the detector region.
- The region around the BS that requires active shielding has a surface of 4.5 x 4.5 m².
- Simulations show a large neutron contamination hit rate of the order of kHz.
- Thin detectors,
  nanosecond time resolution,
  operated at efficiencies better than 95% is proposed.



COMET Phase-I Layout

In the TDR originally a glass RPC was envisaged,
iRPC proposes a "turn key" solution.

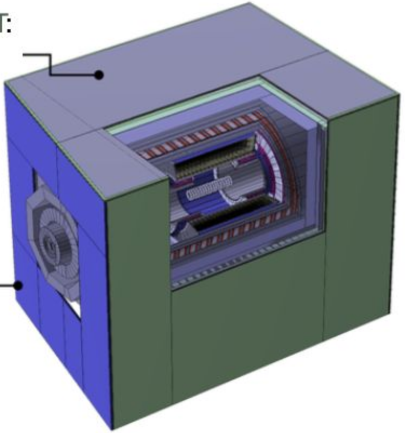
The content is from the COMET Experiment TDR

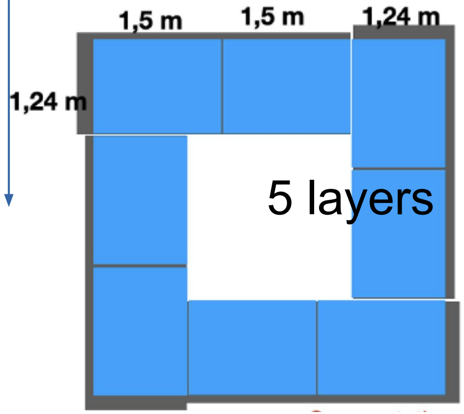
10

COMET

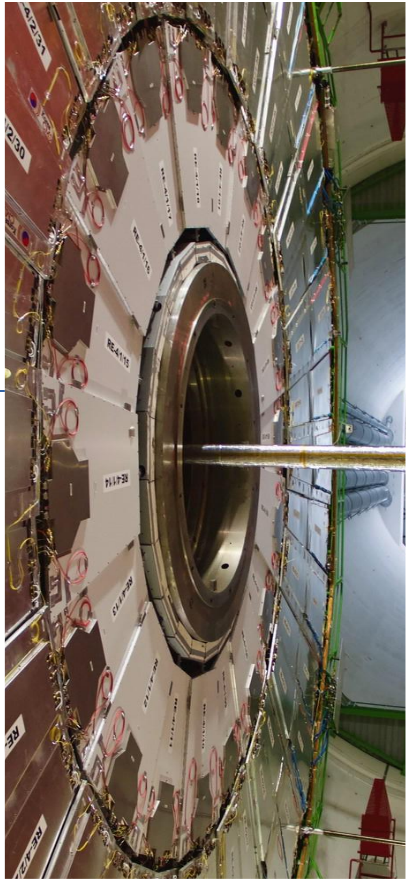
TOP, LEFT, RIGHT:
Scintillators

UPSTREAM:
RPCs





CMS



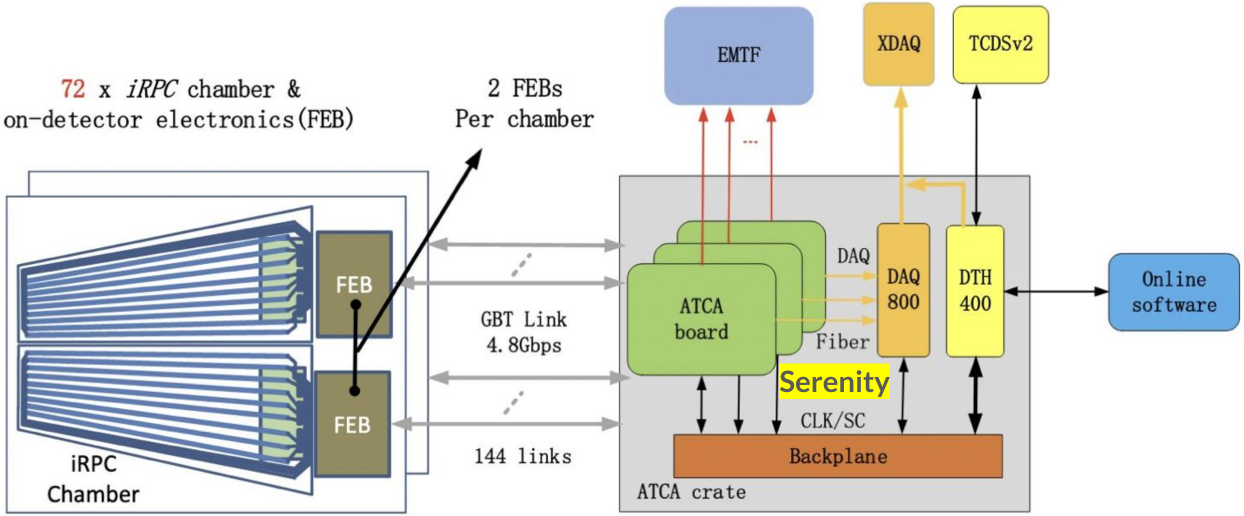
Outlook for COMET

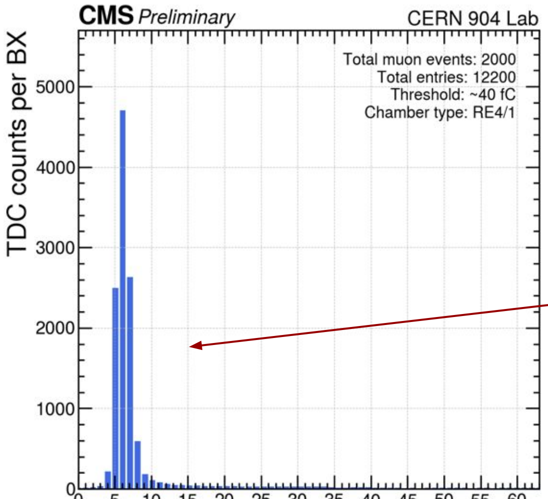
- The iRPC project for COMET represents ~ ½ of the CMS RPC project.
  - The idea is to modify as little as possible the initial project
  - We are looking for fundings to produce Bakelite in Italy; Reproduce gaps in Italy or Korea; Replicate the electronics in France or Asia.
  - The main funding and support of the project is still open and collaborations ate welcome.
- First test with a stack of 4 iRPC chambers (maximal that can be readout by the available BEB) is foreseen end of 2026 during the low Intensity run.

Thanks for your attention

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

uTCA crate with BEB

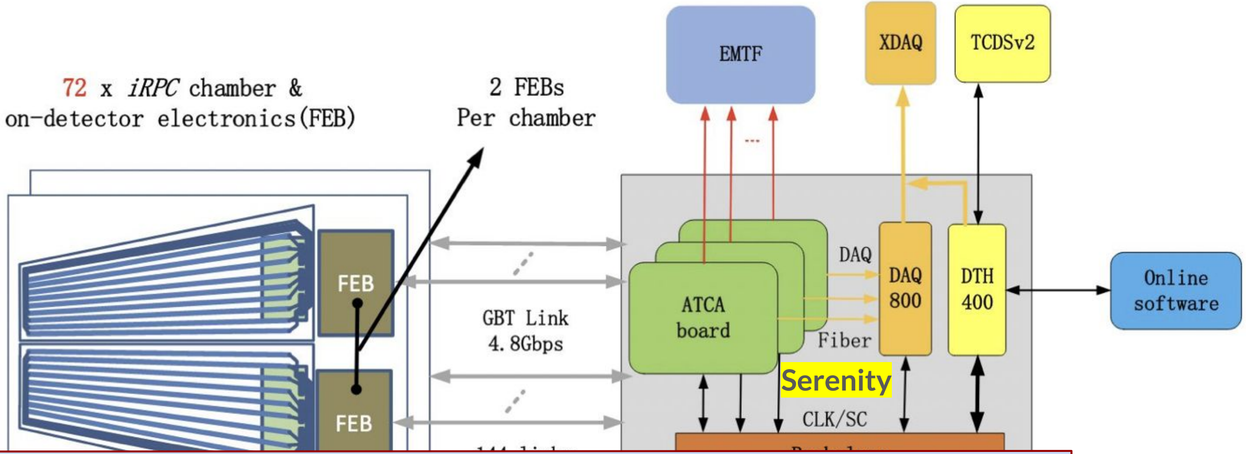
FEB TDC data recorded in few BX,
well inside the 20 BX trigger latency

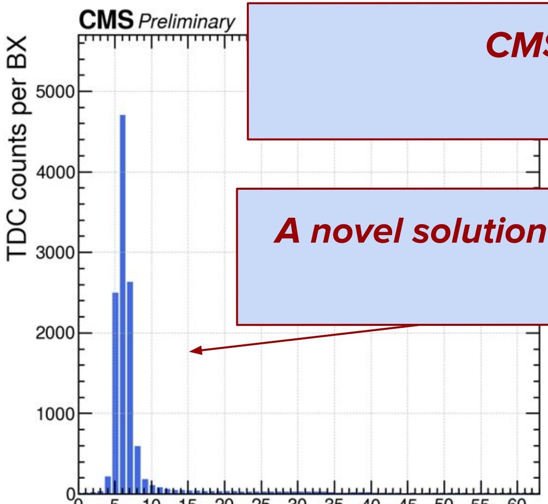
Data transmission delay properly adjusted by Back-end

iRPC back-end electronics

Back-end functions

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



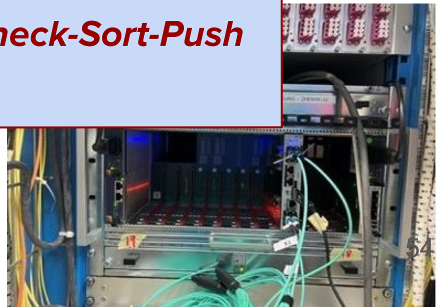


CMS iRPC cluster finding algorithm in Backend electronics

Poster by Qingfeng Hou

Currently we are using uTCA based BE setup

uTCA crate with BEB



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

Poster by Weizhuo diao

Data transmission delay properly adjusted by Back-end