UNIVERSITÀ DEGLI STUDI DI BARI ALDO MORO
PhD School in Physics XXXII Cycle

Activities report of the III years

The CMS RPC system upgrade project for HL-LHC

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Bari, 18 October 2019

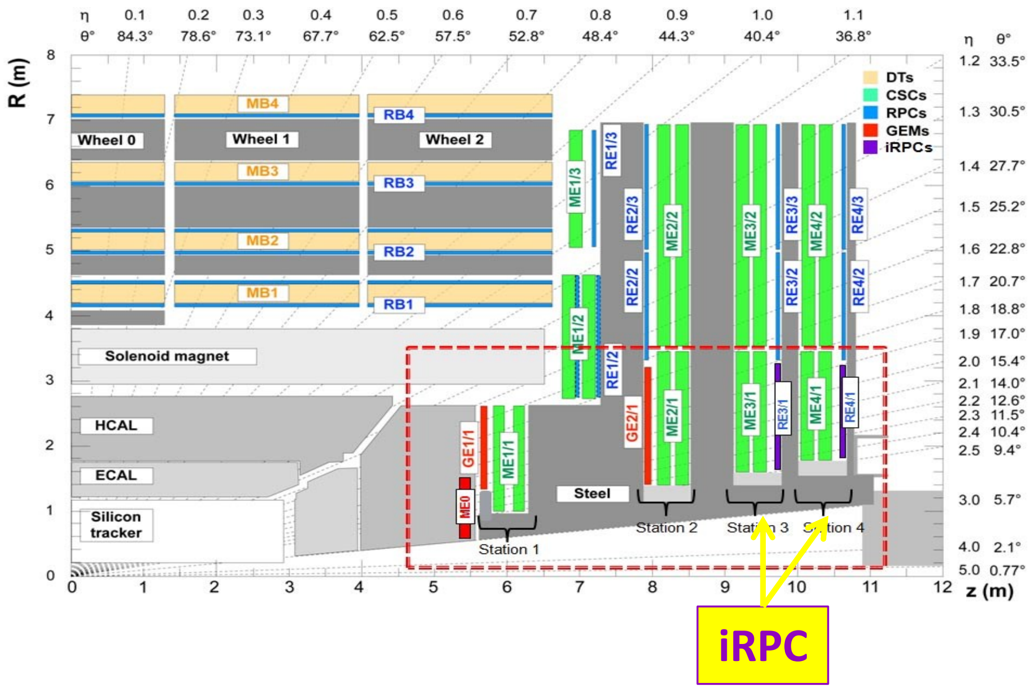
Activities of the III years

- ***CMS RPC system upgrade project for HL-LHC***

  1. **Aging studies of:**
     - **the CMS RPC system during Run-II**
     - **the CMS RPC system for HL-LHC**
  2. **RPC system extension at the high η region:**
     - **background estimation**
     - **performance study**
     - **aging studies**
  3. **Search for RPC eco-friendly gas mixture**
  4. **L1 Muon trigger study**

- **Schools, conferences and publications**

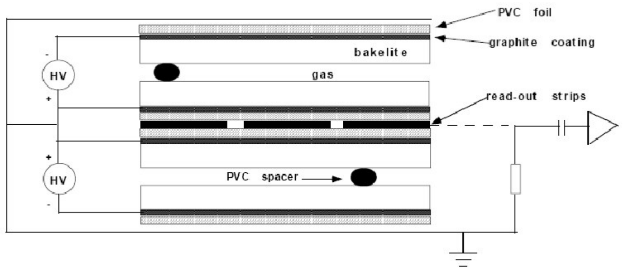
The CMS-RPC system



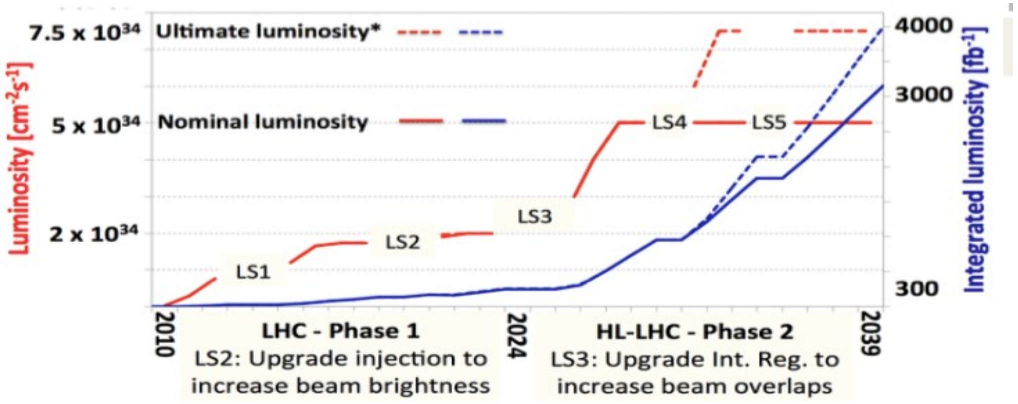
- RPC system covers $0 < |\eta| < 1.9$
- 1056 chambers: 480 in Barrel & 576 in Endcap

- Double gas-gaps RPC
- HPL bulk resistivity: $\rho = 1 - 6 \cdot 10^{10}\ \Omega\text{cm}$
- 2 mm gas gap and electrodes thickness
- Gas mixture:

$C_2H_2F_4$	$isoC_4H_{10}$	SF_6
95.2%	4.5%	0.3%



- RPC information used for muon trigger, reconstruction and identification
- RPC designed and certified for **10 years of LHC** (10^{34} $cm^{-2}s^{-1}$)



RPC Upgrade program in view of HL-LHC

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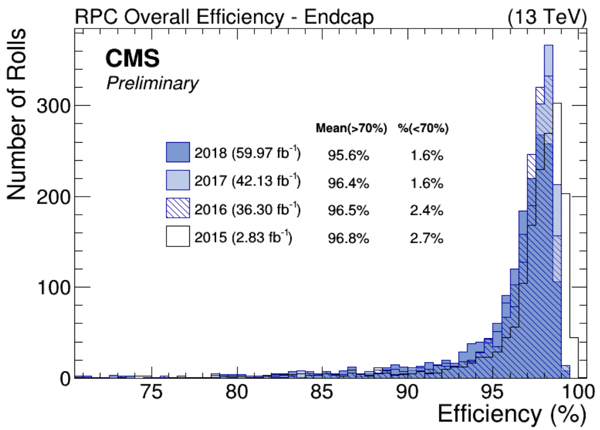
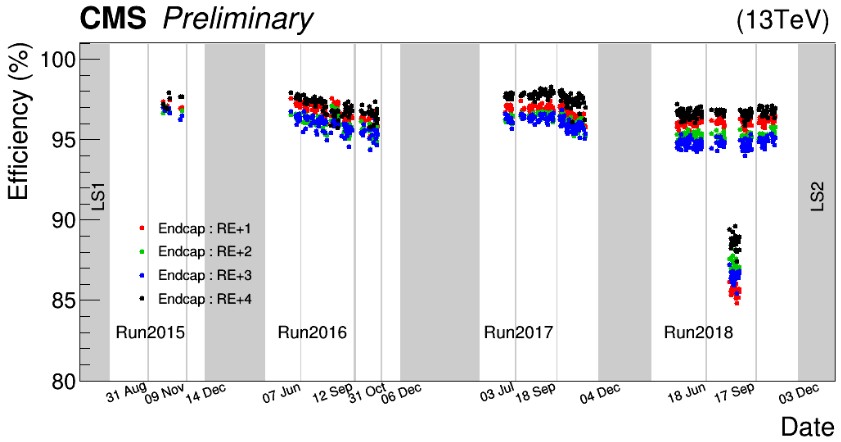
CMS-RPC performance during LHC Run-II

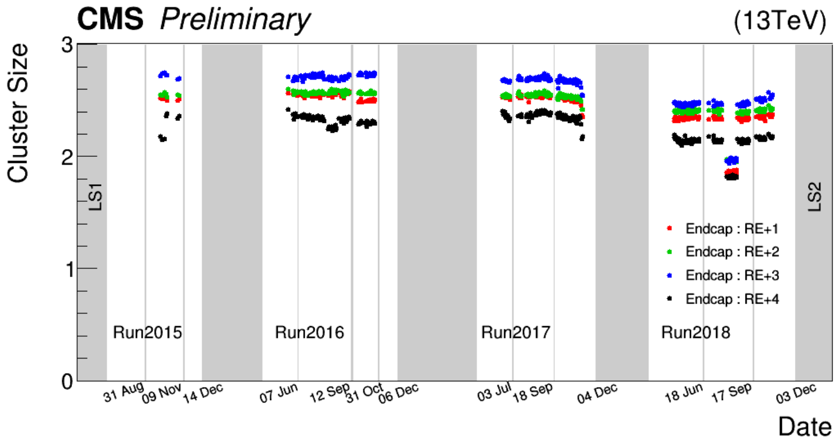
After ~ 7 years operation → ~ 185 fb^{-1} integrated luminosity:

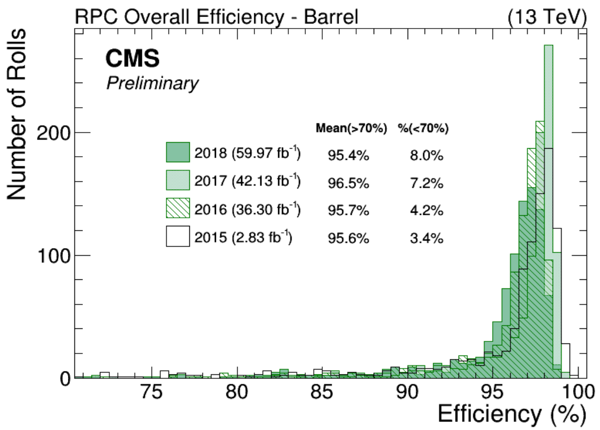
CMS RPC **efficiency >95 % and stable**

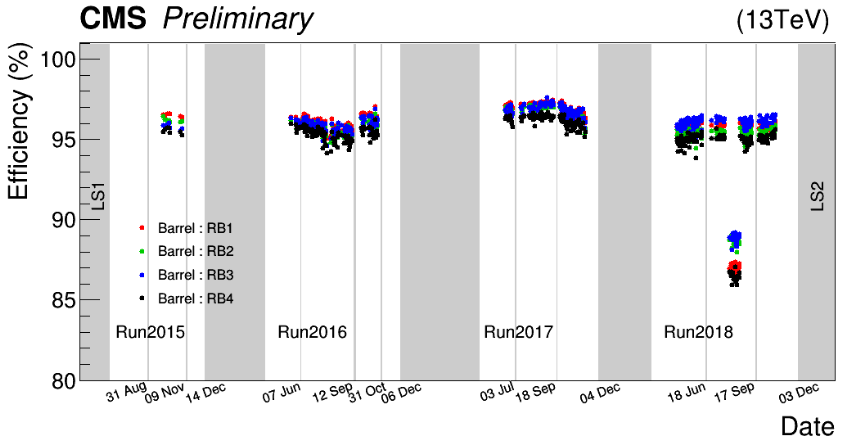
CMS RPC **cluster size stable**

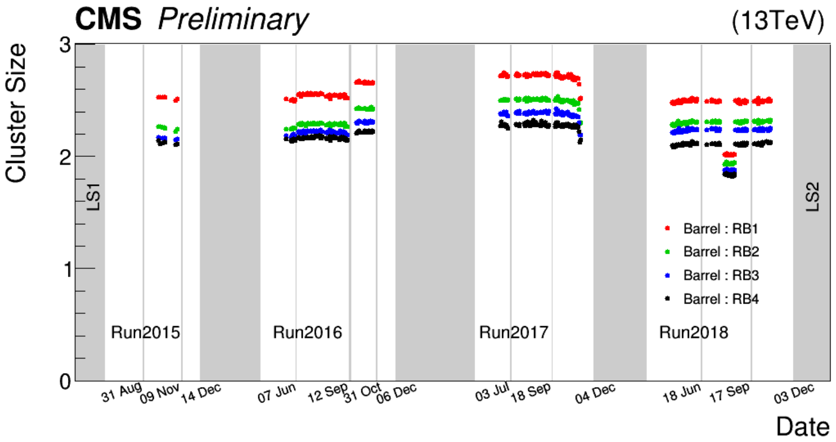






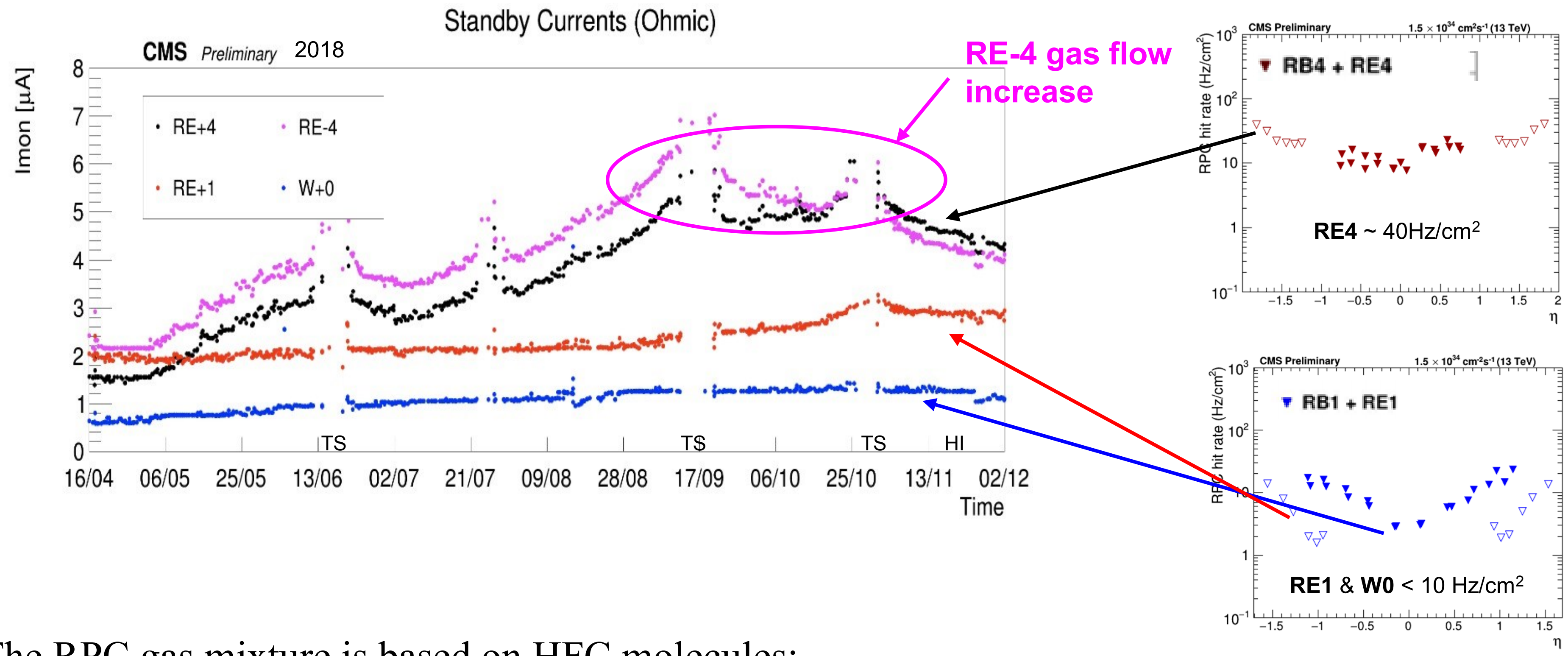






CMS RPC ohmic current monitoring during LHC Run-II

- **Ohmic current increase** in the furthermost parts of the detector (Endcap RE4)
- **Ohmic current decrease** when there is no beam (TS) or the luminosity is very low (HI)



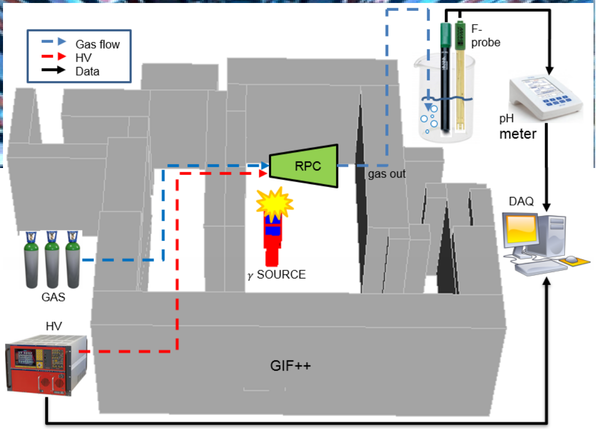
- **Ohmic current** depends on the **background** and **gas flow**

The RPC gas mixture is based on HFC molecules:

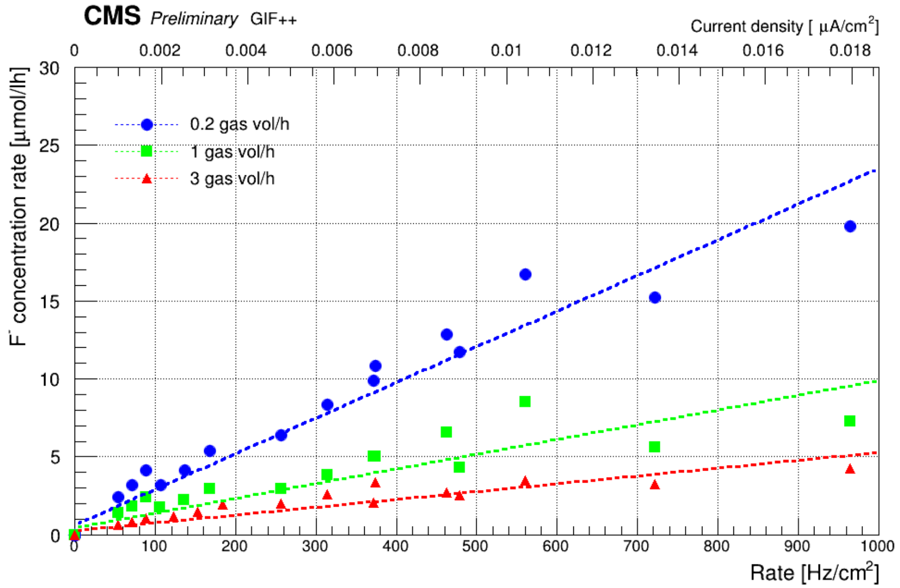
→ HFC decomposition under electrical discharge produces Fluorin iones F^- → **$F^- + H^+$ = HF acid**

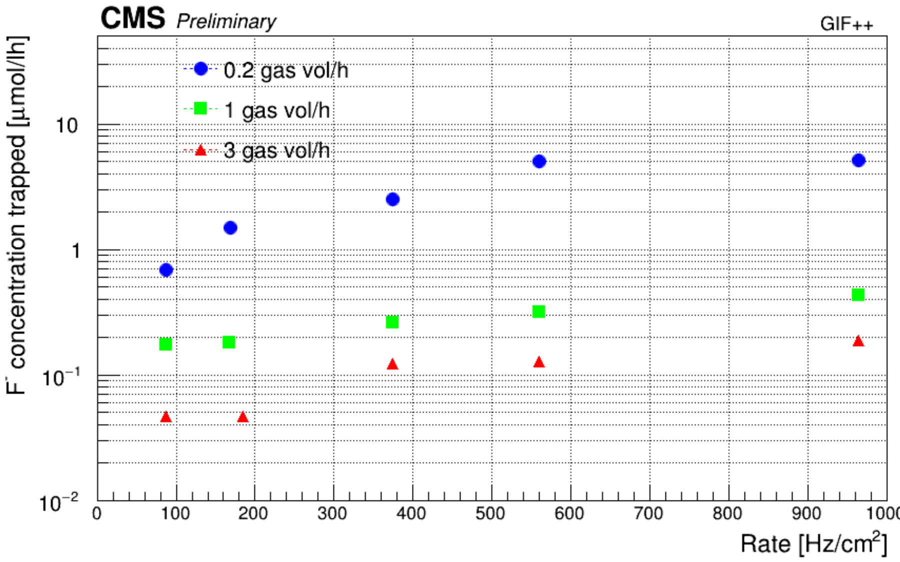
HF represents a possible cause for inner surface damaging due to its high chemical reactivity, especially if it is not efficiently removed by the gas flow and it remains for a not negligible time inside the chambers

HF measurements @ GIF++



1) HF production rate study @ GIF++ as a function of the background rate and gas flow
2) Study the HF production in CMS RPC system





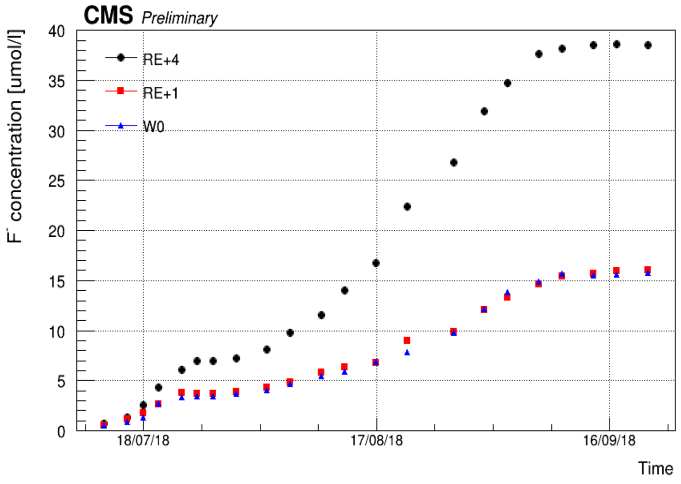
✓ **HF concentration rate depends linearly on the background**
✓ **HF concentration rate slope depends on the gas volumes exchanges**

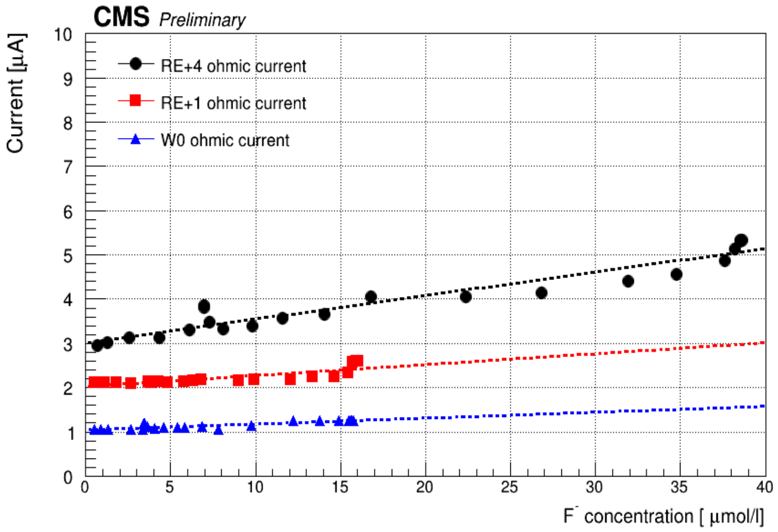
HF trapped within the gas gap depends on:
- background rate
- gas flow
- removable operating the chamber with argon

HF measurements @ CMS

HF measurements performed during run II (July - October 2018) @ CMS:

- Endcap **RE+4** → ~1.1 gas vol/h → ~ 40Hz/cm^2 @ 1.5*10^{34} cm^{-2}s^{-1}
- Endcap **RE+1** → ~0.7 gas vol/h → < 10Hz/cm^2 @ 1.5*10^{34} cm^{-2}s^{-1}
- Barrel **W0** → ~0.6 gas vol/h → < 10Hz/cm^2 @ 1.5*10^{34} cm^{-2}s^{-1}





The ohmic current and the HF concentration are linearly dependent

- W0 & RE+1: lower background → lower HF production → lower current increase
- RE+4: higher background → higher HF production → higher current increase

HF can be the reason of the observed dark current increase

It is necessary to fine tune the gas flow as a function of the background rate so that the HF is efficiently removed

Consolidation of the present RPC system

- The RPC system has been certified for 10 years of LHC (at nominal luminosity of 10^{34} $cm^{-2}s^{-1}$)
- LHC collision data have been used to estimate the **expected** **background rate** and the **integrated charge** at HL-LHC

HL-LHC expected conditions:

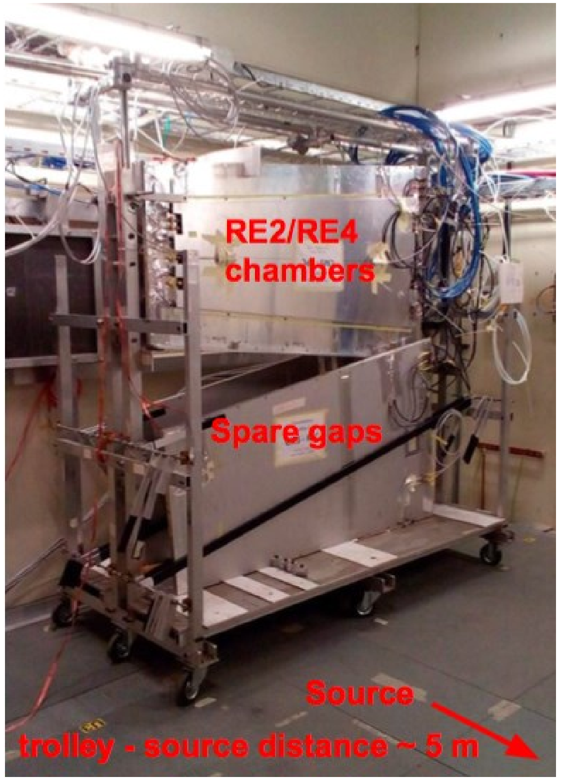
- **Max bkg rate≈ 600 Hz/cm²**

- **Max int. charge ≈ 840 mC/cm²**

(safety factor of 3 included)
* Barrel chambers factor 2 less

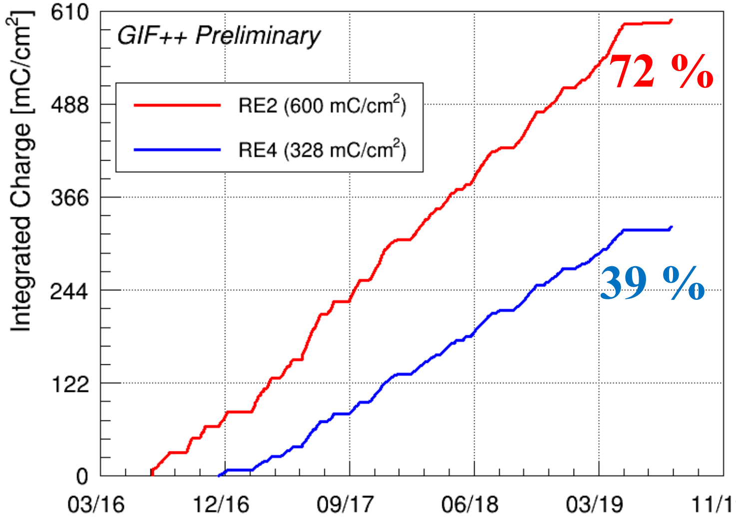
❖ **Setup @ GIF++:**

↦ 2 **RE2** chambers (Irr & Ref)
↦ 2 **RE4** chambers (Irr & Ref)



Longevity procedure:

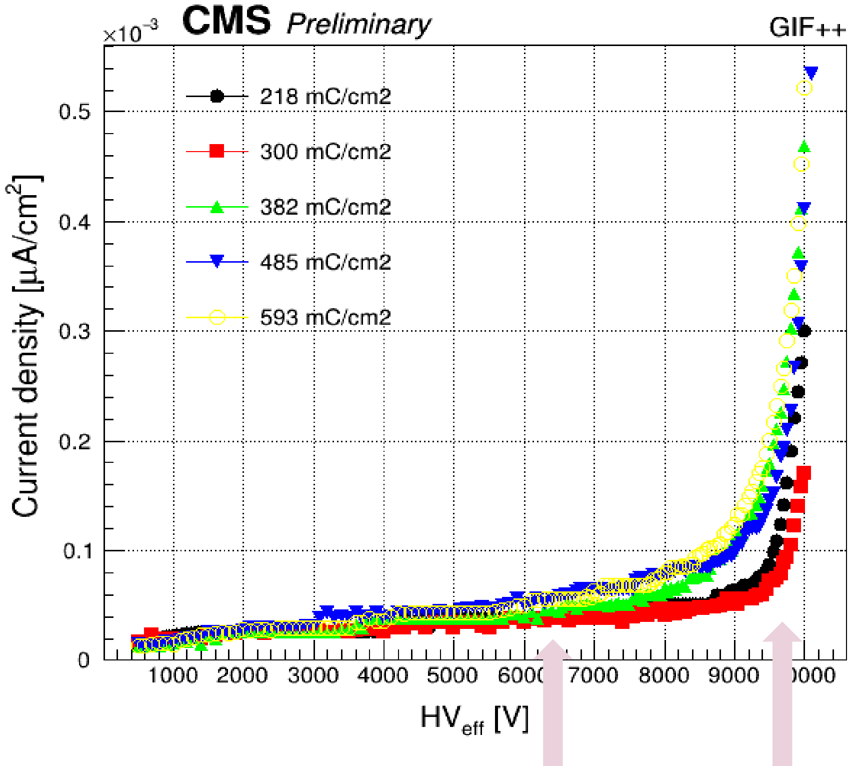
- Irradiation @ ~ 600Hz/cm² (NO AF)
- Constant current measurements
- Current and rate monitoring at different bkg and without background
- HPL resistivity
- Performance monitoring



Dark current & noise rate monitoring

Dark currents & **noise rate** periodically monitored to spot variations of the gas gap surface

RE2/2 IRRADIATED dark current

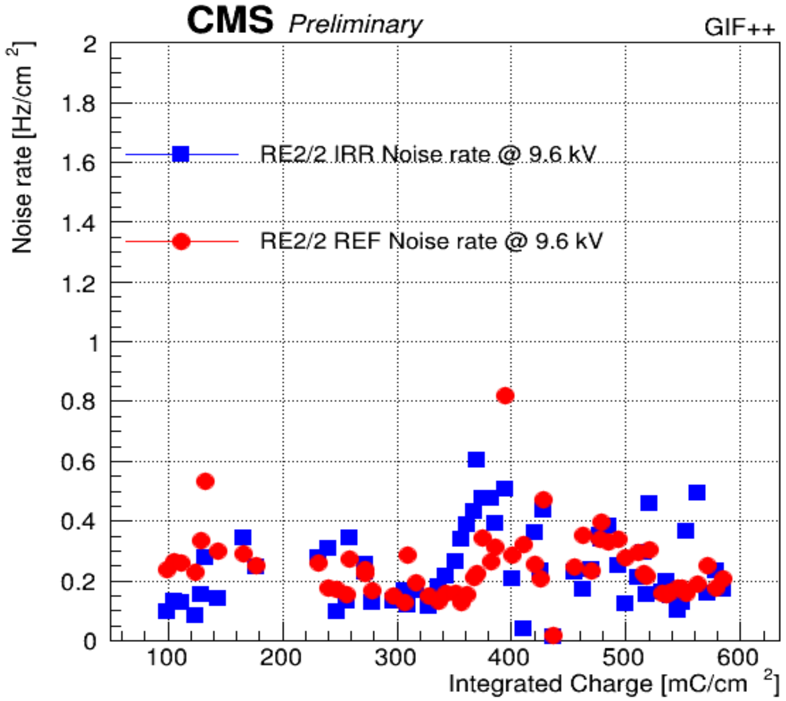


HV = 6.5 kV
Ohmic Current

HV = 9.6 kV
Physics Current

✓ Ohmic and physics current almost stable and in agreement with values before the irradiation

RE2/2 IRRADIATED noise rate

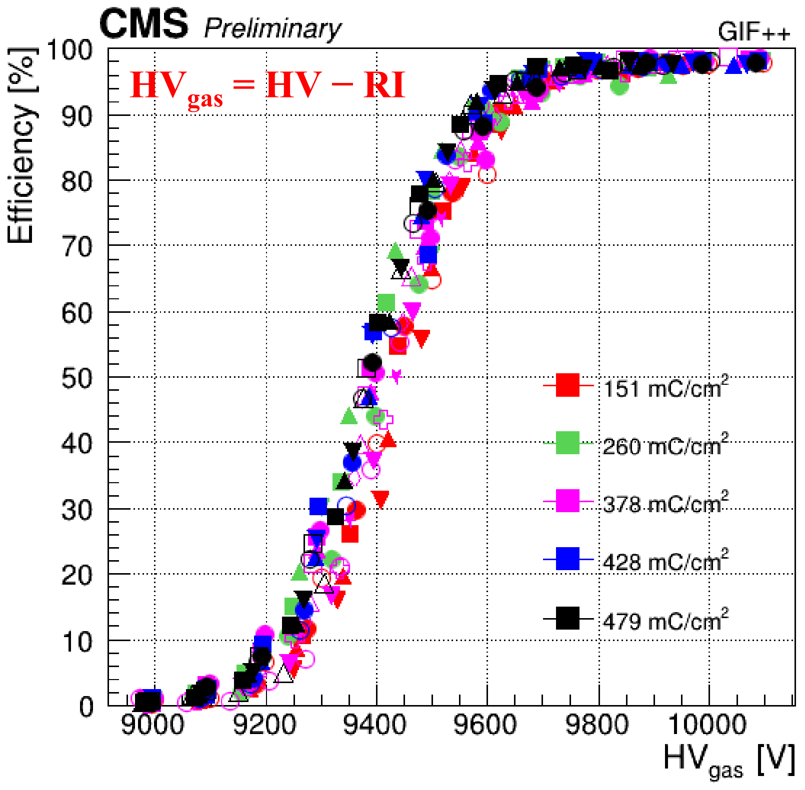


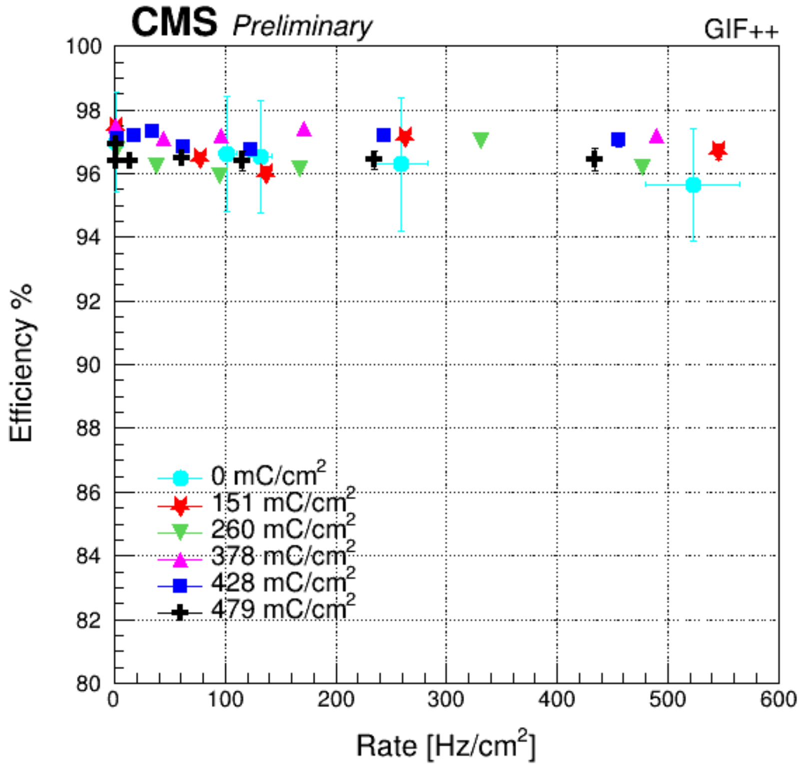
Noise rate & strip profile almost stable in time

Average noise rate less than 1 Hz/cm^2

No noisy strips→ no degradation of the gas gap surface

RPC performance monitoring





- Efficiency at different background and at different integrated charge (different TB) overlap.
- NO any efficiency degradation observed

- Efficiency at WP stable in time
- Efficiency decrease of ~2 % at the highest expected background rate (600 Hz/cm^2)

No evidence of any aging effects has been observed

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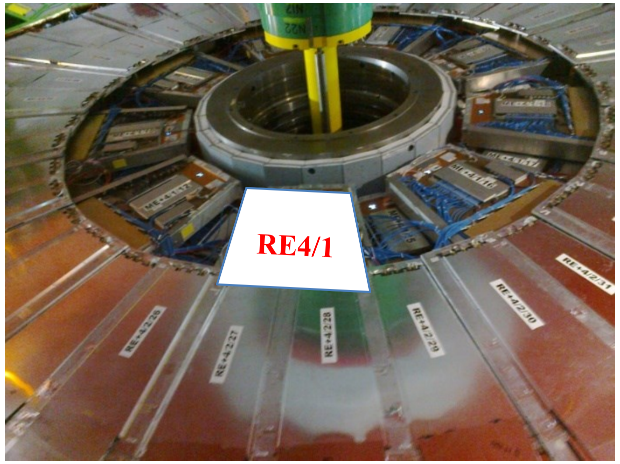
RPC system extension

iRPC will complete the coverage in the RE3/1 and RE4/1 Endcap stations,
$1.8 < |\eta| < 2.4$ **18 chambers per disk (20°) → 72 in total**



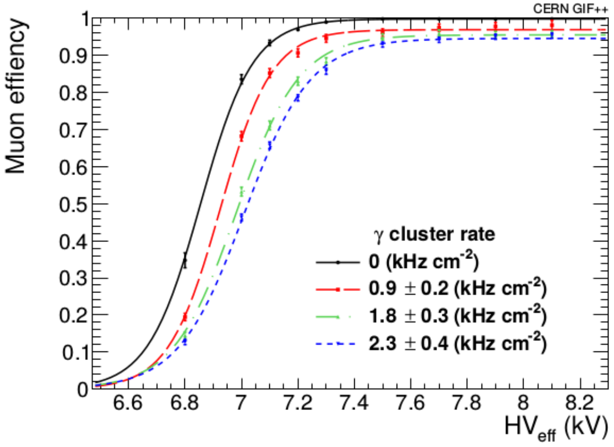
Main requirements:

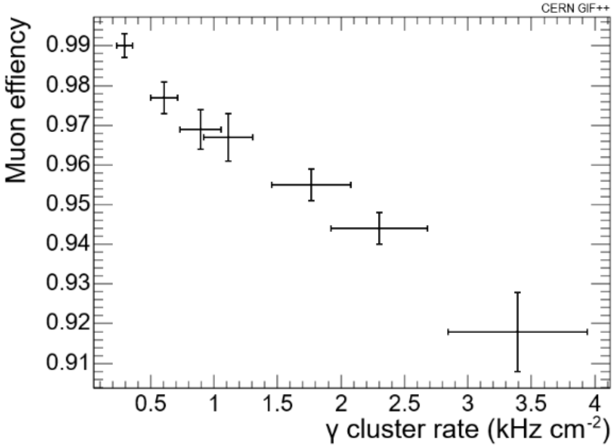
- Rate capability ~**2 kHz/cm²** [1]
- Aging tolerance ~**1 C/cm²** [1]
- Space resolution ~**1 cm**
- Time resolution ~ **1.5 ns**

[1] including safety factor 3

iRPC BASELINE		
	RPC	iRPC
Gas Gap & Electrode width	2 mm	**1.4 mm**
High Pressure Laminate	2 mm	**1.4 mm**
Resistivity (Ωcm)	1 - 6 x 10^{10}	**0.9 - 3 x 10^{10}**

iRPC efficiency equipped with the new FEB
~ 94% at ~2 kHz/cm²

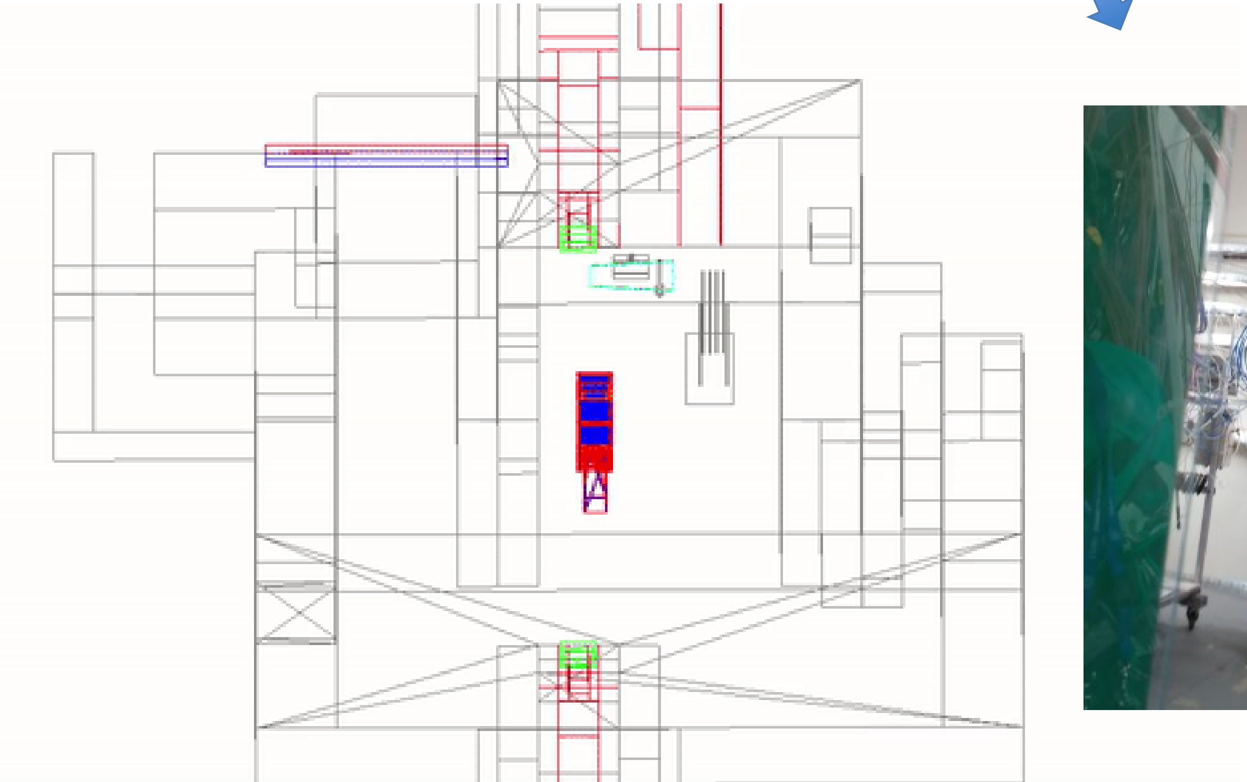




iRPC background rate estimation @ HL-LHC

iRPC sensitivity study: detector geometry simulated with Monte Carlo simulation (GEANT)

Validation of the simulated iRPC geometry:
→ Comparison between simulated and experimental data from GIF++

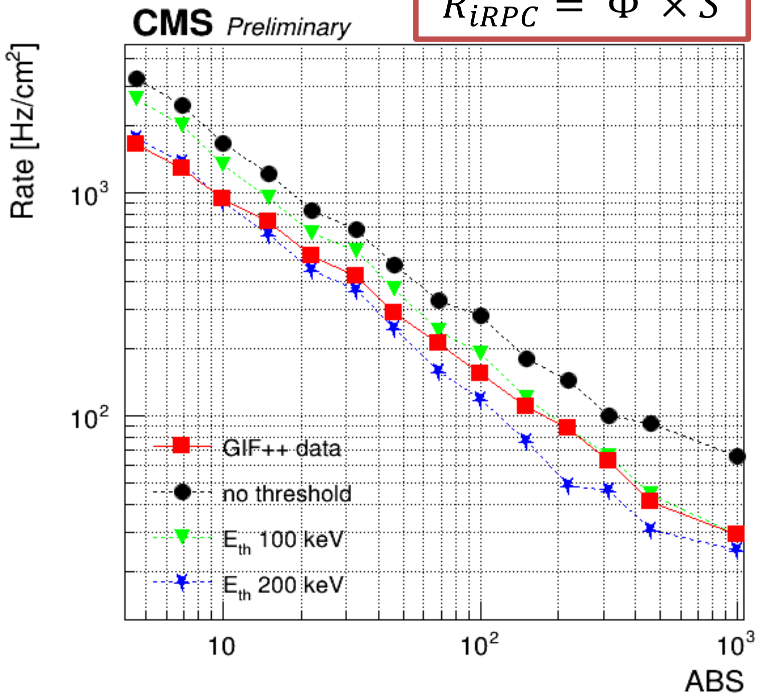


Good agreement between simulated and experimental data:

iRPC geometry validated @ GIF++ ✓

Optimal charged particles $E_{Th} > 100$ keV ✓

$$R_{iRPC} = \Phi \times S$$

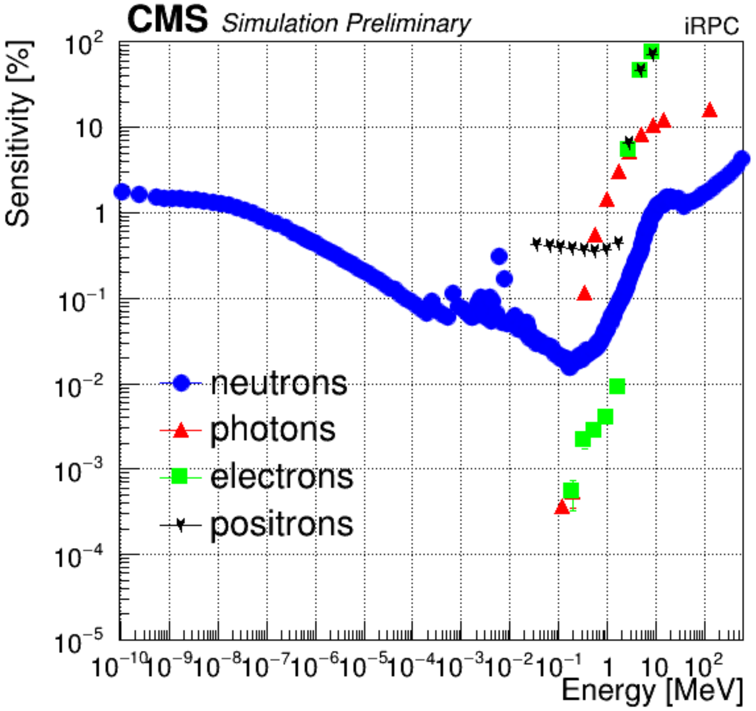


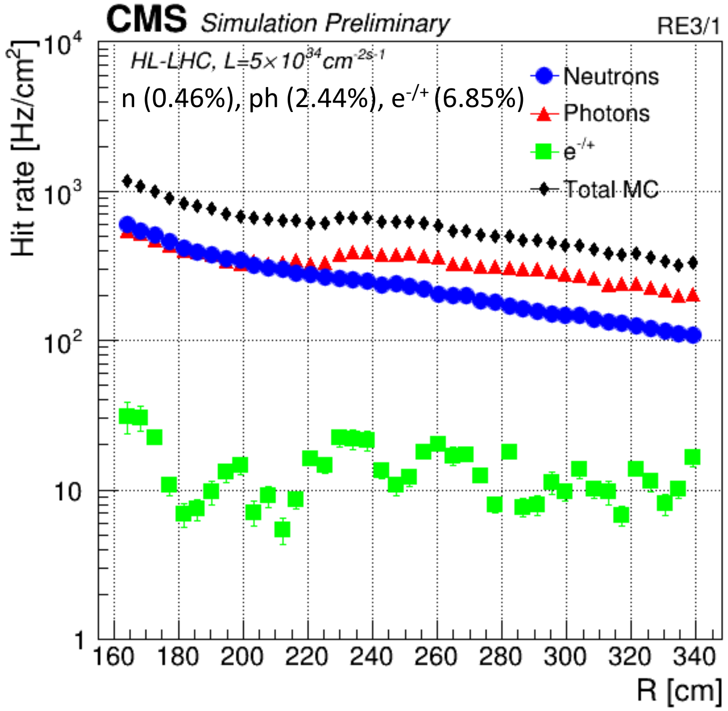
iRPC background rate estimation @ HL-LHC

Convolution of flux and sensitivity → Background rate vs R

iRPC sensitivity

$$R_{iRPC}(E) = \phi_{bkg}^{CMS}(E) \times S(E)$$





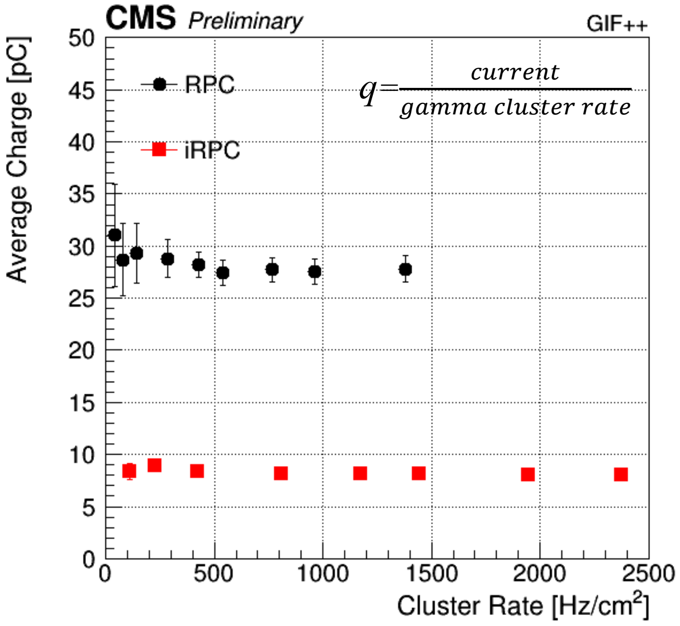
Average background rate of ≈ 600 Hz/cm² indicates the requirement of a minimum rate capability of **≈ 2 kHz/cm²** for the iRPCs when considering a safety factor of 3

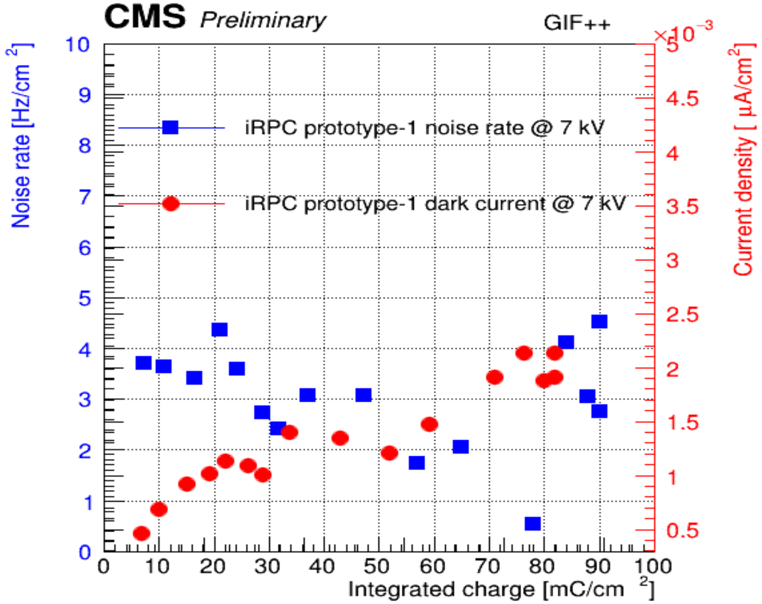
iRPC longevity studies

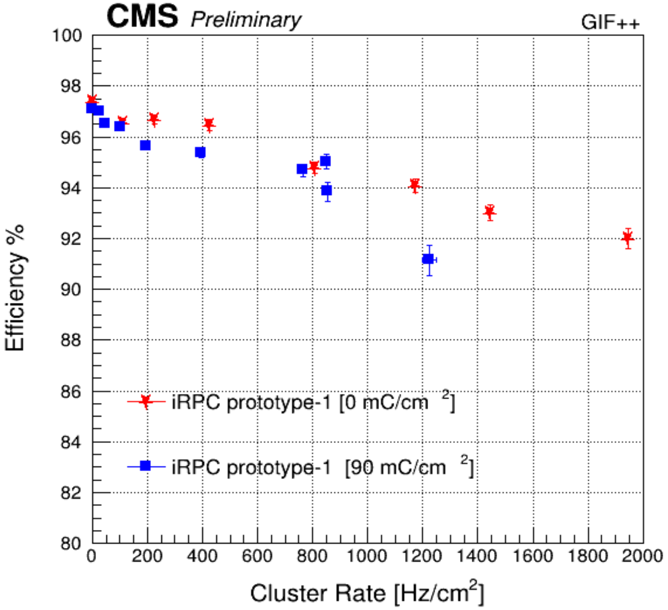
iRPC certification for the equivalent HL-LHC integrated luminosity

Expected simulated integrated charge:
Q = R*q*T = 2 kHz/cm^2 * 9 pC * 6*10^{7}s
≅ **1 C/cm^2** (safety factor 3 included)

Prototype-1: ~90 mC/cm2
- Dark current increase
- Efficiency loss



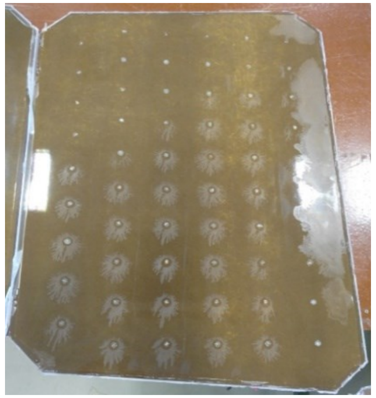




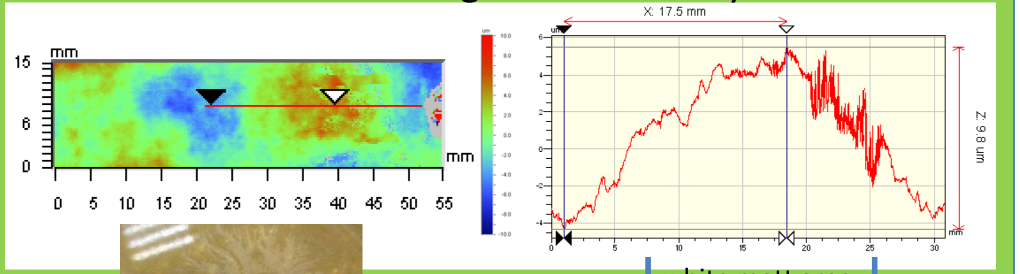
iRPC avalanche charge 3 times lower than RPC

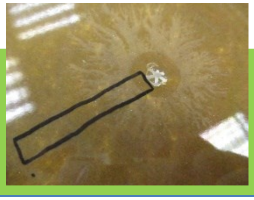
Inner-gap surface analysis

iRPC protype-1 surface analysis



Vertical Scanning Interferometry

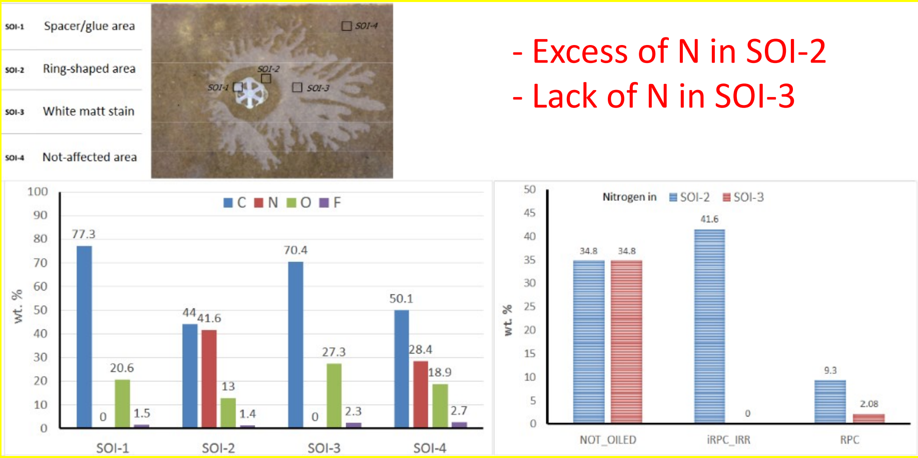




white matt area

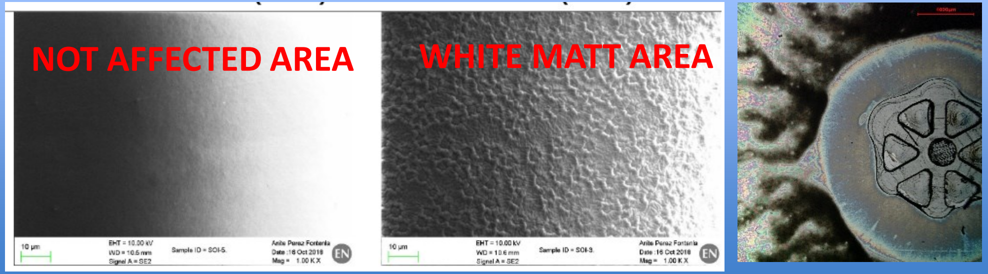
surface profile → not uniform

Energy Dispersive Spectrometer



- Excess of N in SOI-2
- Lack of N in SOI-3

Scanning Electron Microscope



- Not uniform and thinner oil layer
- Lack of oil around the spacers
- White matt area around the spacers and the edges

→ **not polymerized linseed oil**

- **Lower HPL roughness wrt RPC**
- **Different spacers wrt RPC**

Oiling procedure improvements:

- Smaller spacers
- Oil dry time increased
- “Fast double” oil coating
- More dense oil 50-50 (oil - heptane)

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Search for RPC eco-friendly gas mixture

In view of the Green-House-Gases (GHGs) usage limitation, **an extended R&D program** has been started in collaboration with ATLAS, ALICE and EP-DT groups, to find a new RPC ecogas mixture

RPC gas mixture Global Warming Potential GWP ~ 1433

95.2% $C_2H_2F_4$ (tetrafluoroethane): GWP = **1430**

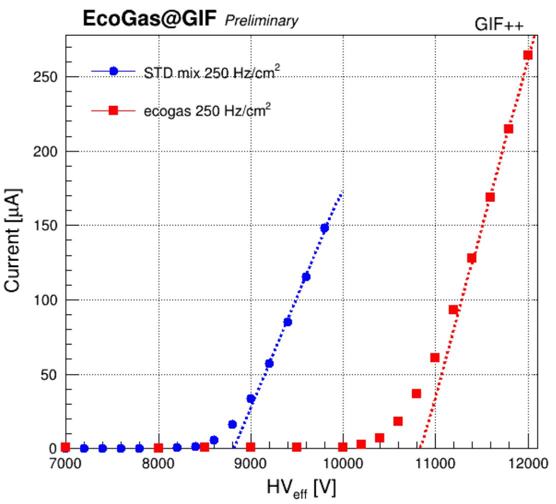
PROMISING ECOGAS MIXTURE:

HFO 45%, CO2 50%, isobutane 4%, SF6 1%

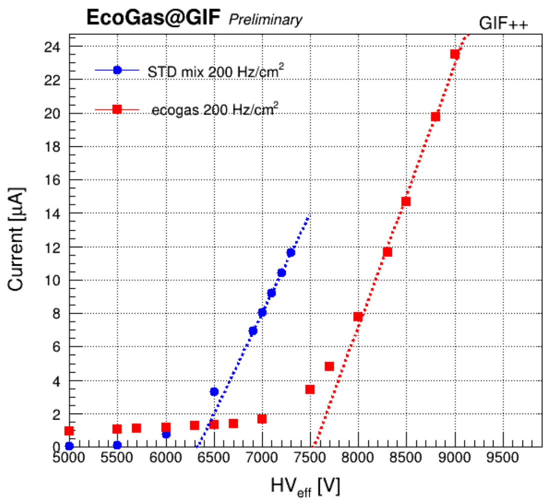
HFO 1234ze ($C_3H_2F_4$) → GWP = 6

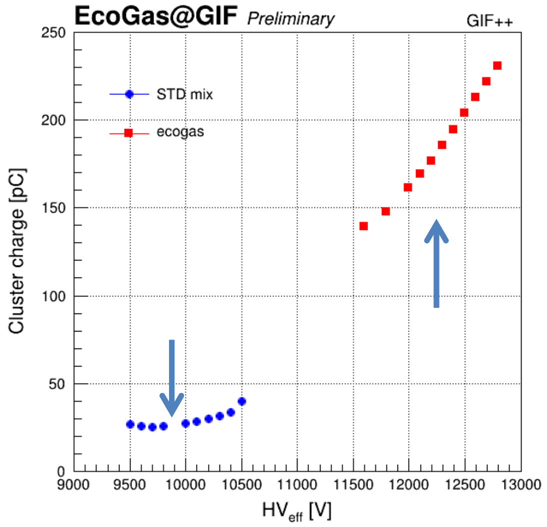
Ecogas mixture characterization @ GIF++

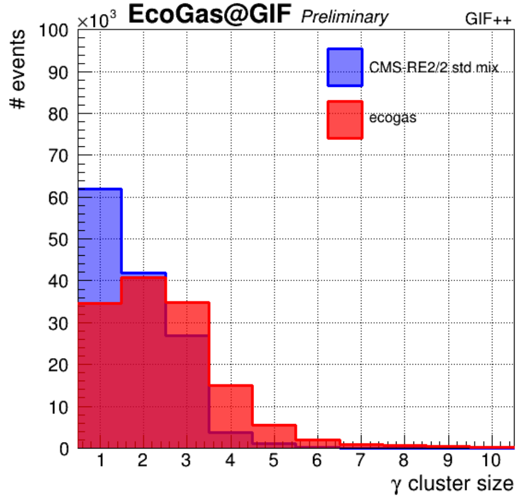
RPC: ~ 2 kV of HV shifts



iRPC: ~ 1.2 kV of HV shifts







- **Average charge ~ 5 time higher:** ≈ 27 pC for STD mix and ≈ 150 pC for ecogas
- **Average Cluster size at WP:** 1.9 strips for CMS and 2.6 strips for eco-gas

Search for RPC eco-friendly gas mixture

Irradiation test @ GIF++ using ecogas mix
~ 800 Hz/cm², 1 gas vol/h

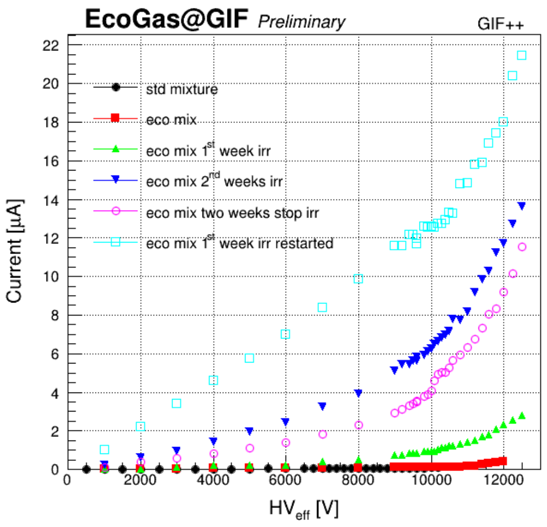
General dark current increase for all the tested chambers

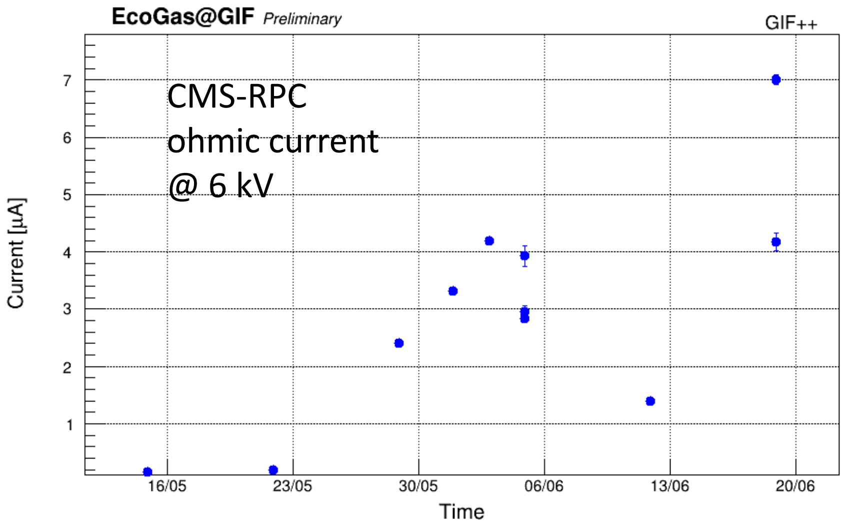
- Chamber off allows the current recovery
- At the irradiation restart, the dark current increase again

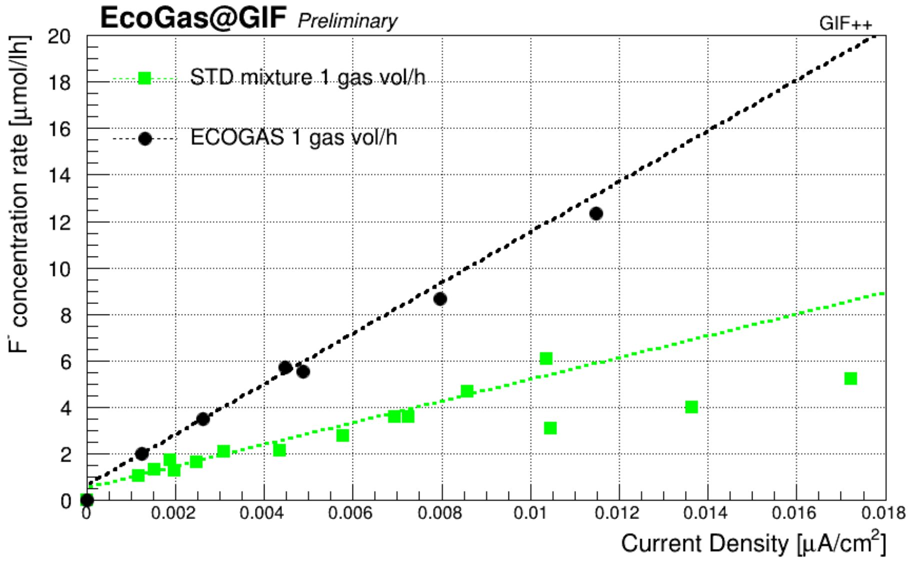
HF measurements using ecogas mix:

✓ **The HF concentration depends linearly on the current**

✓ **HF concentration: factor 2.5 higher with ecogas**







Plan: fine tune the gas mixture in order to:

- optimize the detector performance under irradiation
- mitigate the irradiation effect (HF production)

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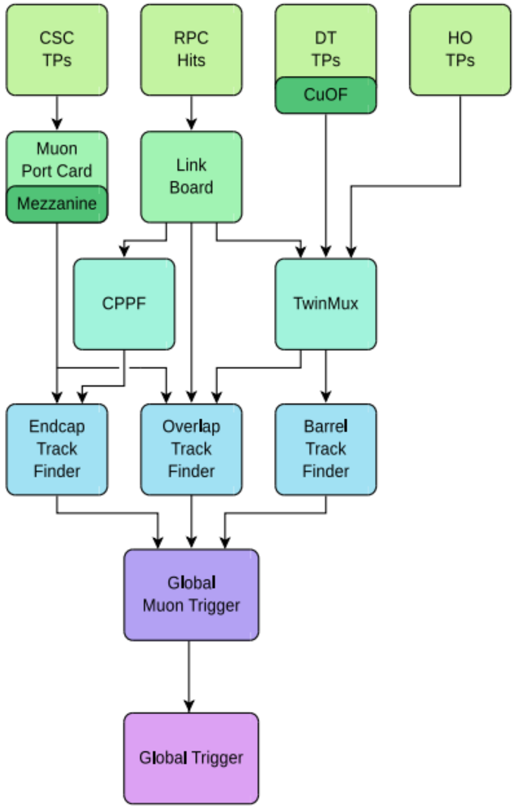
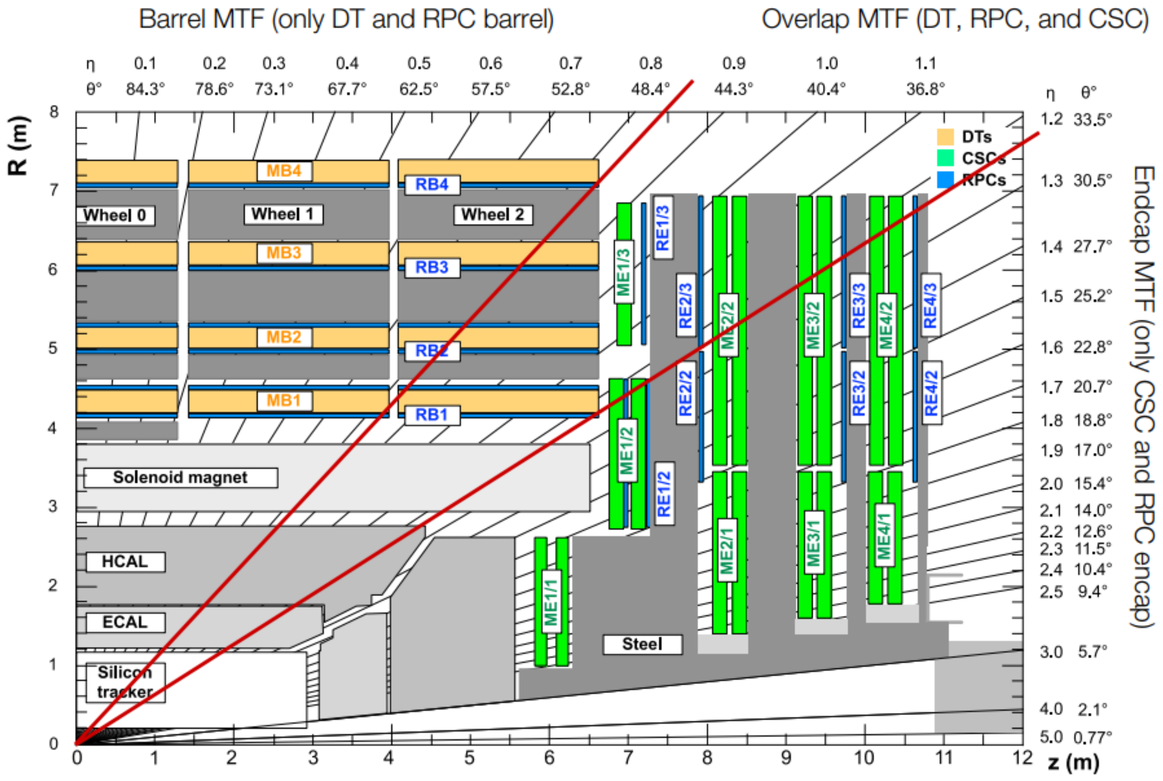
L1 muon trigger study



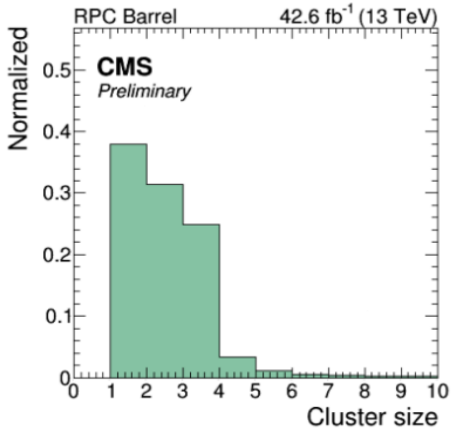


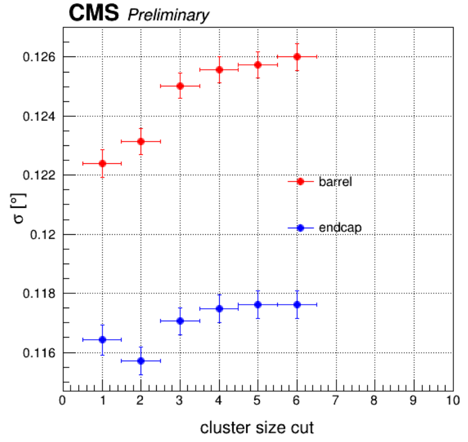
RPC participate in the three L1 Muon Track Finders' η regions:

- ➢ **BMTF** (DT+RPC): assign bunch crossing of low-quality DT segments & only segments (MB1 and MB2) if no DT segment
- ➢ **OMTF** (DT+RPC+CSC): 8 RPC layers are also used for position information
- ➢ **EMTF** (RPC+CSC): RPC hits are used in case of CSC segment absence

RPC cluster size cut optimization

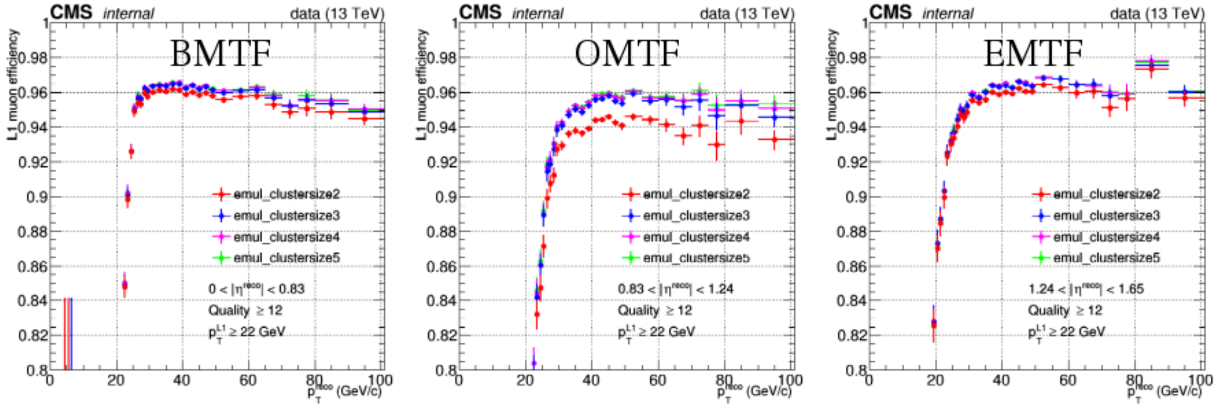
- RPC hits are clustered in Trigger Primitive (TP) before to be used by L1 Muon Track Finders
- Only TP <=3 strips are used at L1 muon trigger (average RPC TP CLS = 2)
- Not negligible fraction (~4%) of muon hit have cluster size higher than 3

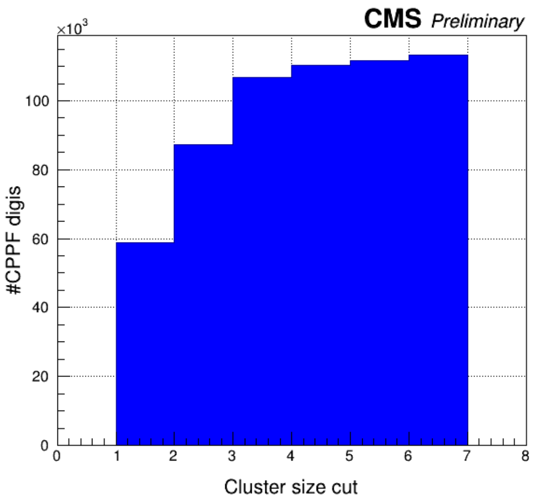


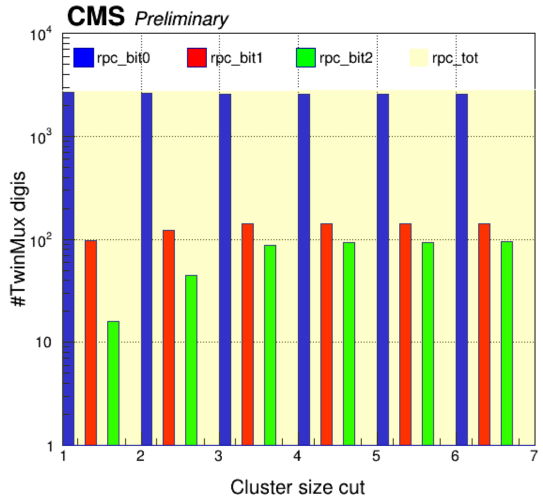


Optimization study: CLS cut 3 → 4

- spatial resolution (Φ) is not degraded
- CPPF TP: +~3%, TwinMux TP +~0.2% (+~7% "RPC only")
- MTFs muon efficiency +~0.5% in OMTF







OMTF decided to apply CLS cut = 4 for the future runs

EMTF and BMTF are evaluating to increase the CLS cut to 4

Conclusions

- **Longevity study for the CMS RPC system**:
  - Stable performance and high efficiency
  - Ohmic current increase correlated with background rate and gas flow
  - HF study performed @ GIF++ & in CMS: HF can be the reason of the dark current increase
- **RPC longevity study for HL-LHC @ GIF++:**
  - ~ 72% of the expected integrated charge has been accumulated
  - Stable detector parameters and performance → no any evidence of aging effect was observed
- **Extension of the RPC system at the high eta region (RE3/1 & RE4/1 stations):**
  - iRPC technology development + new FEB
  - Monte Carlo simulation to study the detector sensitivity and to estimate the expected background rate
  - iRPC performance study
  - iRPC longevity study: oiling problems, several surface analysis, oiling procedure improvements
- **Search for RPC eco-friendly gas mixture:**
  - Ecogas mixture characterization in presence of background: higher HV, charge and CLS
  - Longevity studies: dark current increase → HF ~ 2.5 times higher wrt the standard mixture
- **L1 muon trigger study:**
  - RPC CLS cut optimization → spatial resolution, TP rate, RPC efficiency, MTF trigger efficiency and rate
  - OMTF increased the RPC cluster size cute at 4 in view of the next runs

Attended schools

Schools:

- International School Of Trigger and Data AcQuisition (ISOTDAQ), London (UK), 3-12 April 2019.
- CMS Machine Learning workshop, 2-4 July 2018, CERN, Switzerland
- XXX National seminar of nuclear and subnuclear physics, 5-12 June 2018, Otranto, Italy
- First International RPC detector school, 14-17 February 2018, Mexico City, Mexico
- RD51 Gaseous detectors lectures, 11-15 December 2017, CERN, Switzerland
- “CMS Physics Object School POS”, Bari, Italy, September 2017, participating as facilitator and giving a lesson about the introduction of “GEANT4” and a short exercise
- “XIV Seminar on Software for Nuclear, Subnuclear and Applied Physics”, Alghero, Italy, June 2017

Teaching activity

- Attività didattico-integrative per l’insegnamento di “Fisica Generale” A.A 2017/18 della durata di 40 ore @ Politecnico di Bari, responsabile Prof.ssa Pugliese. & Prof. Maggi

Time abroad

1 year simil-fellow at CERN: from June 2018 to June 2019

Contribution presented at conferences

- **European Physical Society Conference on High Energy Physics (EPS2019),** Ghent (Belgium), 10-17July 2019.

Oral presentation: ”Fluoride production in CMS Resistive Plate Chambers (RPC) and aging studies”.

- **Students' Poster Session at the 2019 Winter LHCC meeting (Posters@LHCC),** CERN, 27 February 2019.

Poster: ”improved-RPC for the CMS muon spectrometer upgrade for HL-LHC”.

- **2018 IEEE Nuclear Science Symposium and Medical Imaging conference (IEEE 2018),** Sydney (Australia), 20-27 November 2018.

Oral presentation: ” Long-term aging studies on Resistive Plate Chambers (RPC) of the CMS muon system for HL-LHC”.

- **Incontri di Fisica dele Alte Energie IFAE 2018,** 4-6 April 2018, Milano, Italy.

National conference, oral presentation: ”RPC upgrade project for CMS Phase II”.

- **14th Pisa Meeting on Advanced Detectors PM2018,** 27 May - 2 June 2018, La Biodola, Isola d’Elba, Italy.

Poster: ”Background rate study for the CMS improved-RPC at HL-LHC using GEANT4”.

- **XIV Workshop on Resistive Plate Chambers and Related Detectors (RPC 2018),** 19-23 February 2018, Puerto Vallarta, Mexico.

Oral presentation: ”Longevity studies for the CMS-RPC system”

"**Upgrade of the RPC system of the CMS Muon Spectrometer**", ”2017 Fall Meeting of the Korean Physical Society”, Gyeongju-si, Republic of Korea, October 2017

- "**Upgrade of the RPC system of the CMS Muon Spectrometer**", ”SIF2017: 103-esimo congresso nazionale società italiana di fisica”, Trento, Italy, September 2017

Publications

CMS Publications:

CMS Collaboration Author since 11th November 2017: 196 papers

CMS Collaboration, *"The Phase-2 Upgrade of the CMS Muon Detectors",* CERN-LHCC-2017-012. CMS-TDR-016

First author publications:

- A. Gelmi et al. [CMS Muon Collaboration & CERN-EP-DT group], "*Fluoride production in CMS Resistive Plate Chambers (RPC) and long-term aging studies*", EPS 2019 proceeding submitted.
- A. Gelmi et al. [CMS Muon Collaboration], "*Long-term aging studies on Resistive Plate Chambers (RPC) of the CMS muon system for HL-LHC*", IEEE Xplore, 2019. doi: 10.1109/NSSMIC.2018.8824516.
- A. Gelmi et al. [CMS Muon collaboration], *"Background rate study for the CMS improved-RPC at HL-LHC using GEANT4",* Nucl. Instrum. Meth. A, 2019, doi: 10.1016/j.nima.2018.10.046,
- A. Gelmi et al (CMS RPC group)., *"Longevity studies for the CMS-RPC system",* JINST, JINST-017P-0818, 2018.

Publications

RPC group & Ecogas collaboration publications:

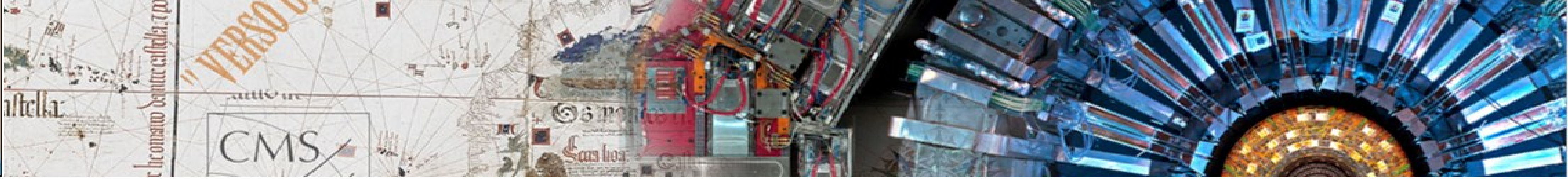
- "*CMS RPC system operation and performance during LHC Run II data-taking*", CMS RPC group, to be submitted 2019.
- "*Studies of RPC operations with ecological gas mixture under irradiation at GIF++*", G. Rigoletti et al. (Ecogas Collaboration), EPS 2019 proceeding submitted.
- "RPC upgrade project for CMS Phase II", M.I. Pedraza et al. (CMS RPC group), JINST, 2018.
- "R&D results of iRPC tested at GIF++ for CMS Phase II upgrade", J. H. Lim et al. (CMS RPC group), JINST, 2018.
- "Fast timing measurement for CMS RPC Phase II upgrade", C. Combaret et al. (CMS RPC group), JINST, 2018.
- "RPC Radiation Background Simulations for the High Luminosity Phase in the CMS Experiment", B. Carpinteyro et al. (CMS RPC group), JINST, 2018.
- "High rate, high time precision RPC detector for LHC", F. Lagarde et al. (CMS RPC group), JINST, 2018.

Publications

- "The CMS RPC Detector Status and Operation at LHC", M.Shah et al. (CMS RPC group), JINST, 2018
- "Test of a real-size Mosaic MRPC developed for CMS muon upgrade", Y. Yu et al. (CMS RPC group), JINST, 2018.
- "CMS RPC efficiency measurement using the Tag and Probe method", J. Goh et al. (CMS RPC group), JINST, 2018
- "CMS RPC Integrated Charge", M. Cecilia et al. (CMS RPC group), JINST, 2018.
- "CMS RPC background studies during LHC run II", R. Trejo et al. (CMS RPC group), JINST, 2018.
- "The CMS RPC system calibration", R. Reyes et al. (CMS RPC group), JINST, 2018.
- "RE3/1 and RE4/1 chambers integration with Forward region of CMS Muon spectrometer", E. Voevodina et al. (CMS RPC group), JINST, 2018.
- "CMS RPC Condition Data Automation", O. M. Colin et al. (CMS RPC group), JINST, 2018.
- "Search for Heavy Stable Charged Particles in the CMS Experiment using the RPC phase II upgraded detectors", G. Sanchez et al. (CMS RPC group), JINST, 2018.

Thanks

for your attention



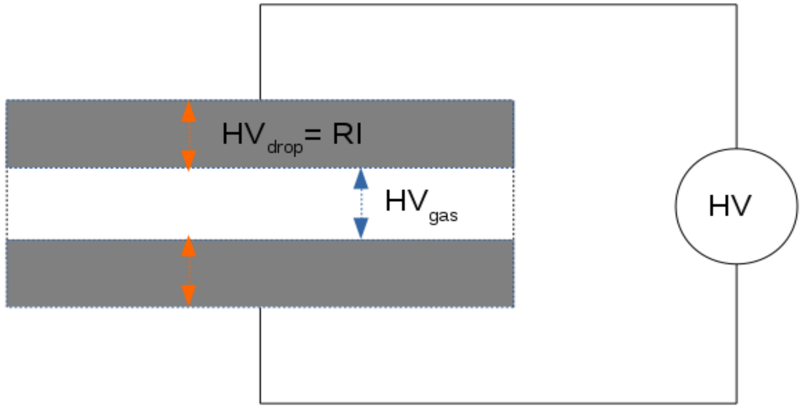
Back up

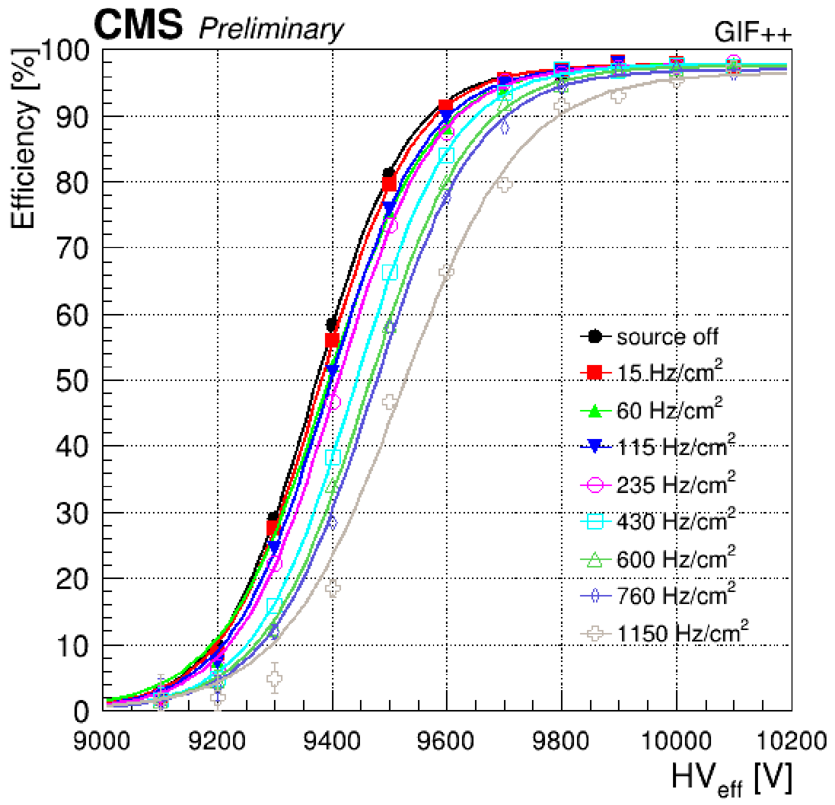
HV correction

- The effective voltage applied to the gas volume (**HV_{gas}**) is reduced by the voltage drop (**HV_{drop}**) across the electrodes:

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

Where **R** the bakelite resistance and **I** is the current produced by the ionizing particles.

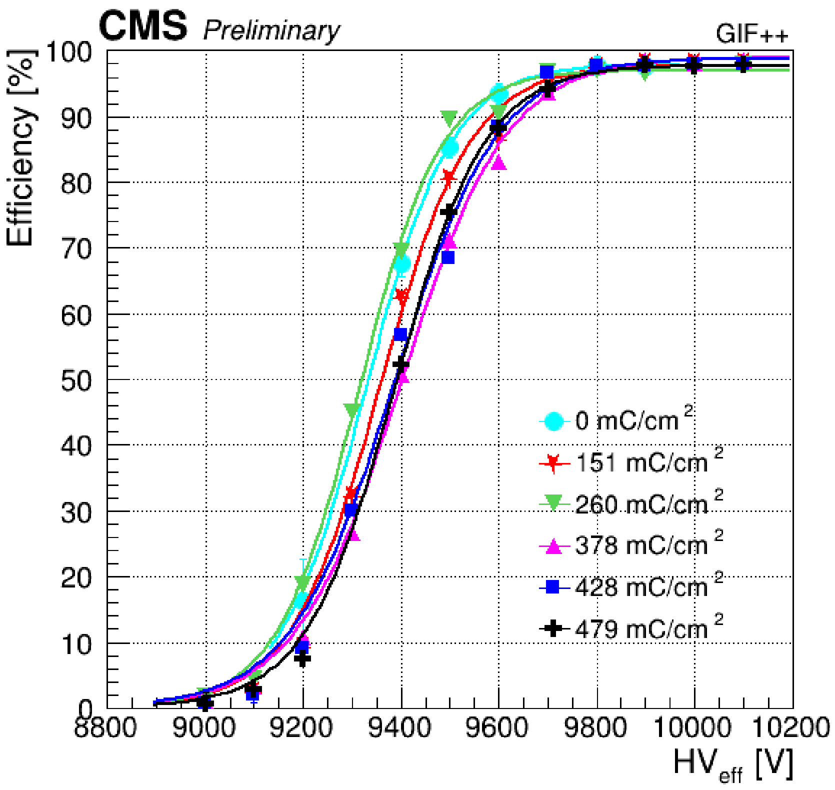


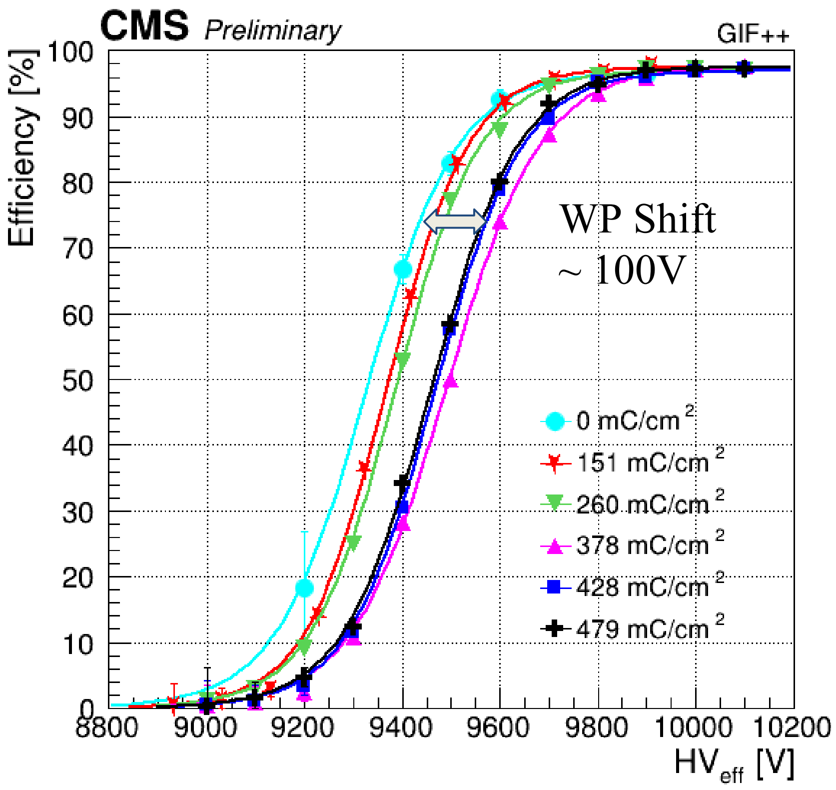


- The efficiency plotted as a function of HV_{gas} does not depends on the background conditions.

G. Pugliese et al., *"Aging study for resistive plate chambers of the CMS muon trigger detector"*
G. Aielli et al., *"Further advances in aging studies for RPCs"*

RPC performance monitoring





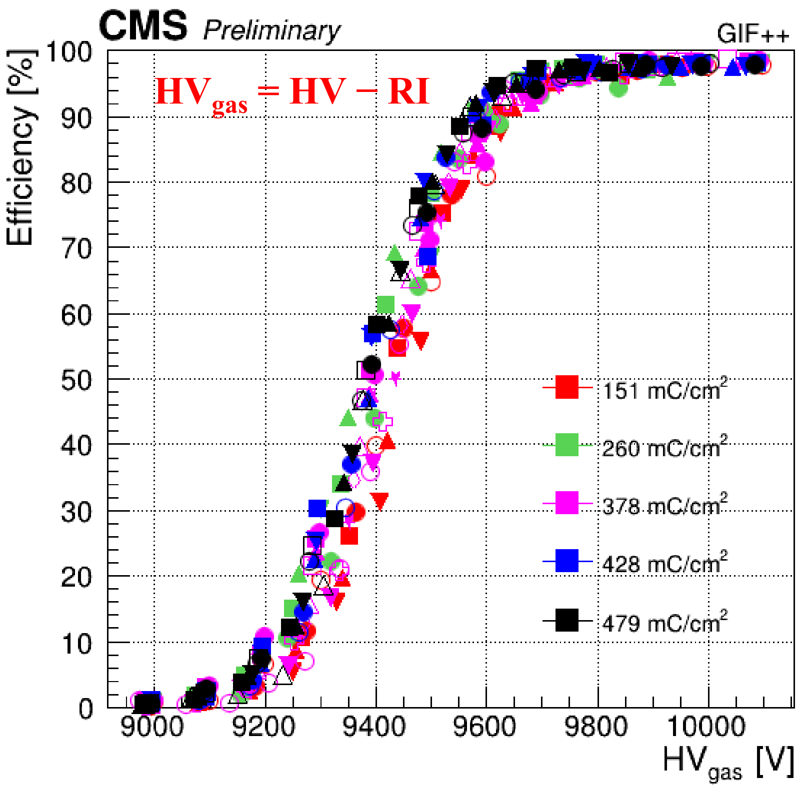
Efficiency vs HV$_{eff}$ measured without background

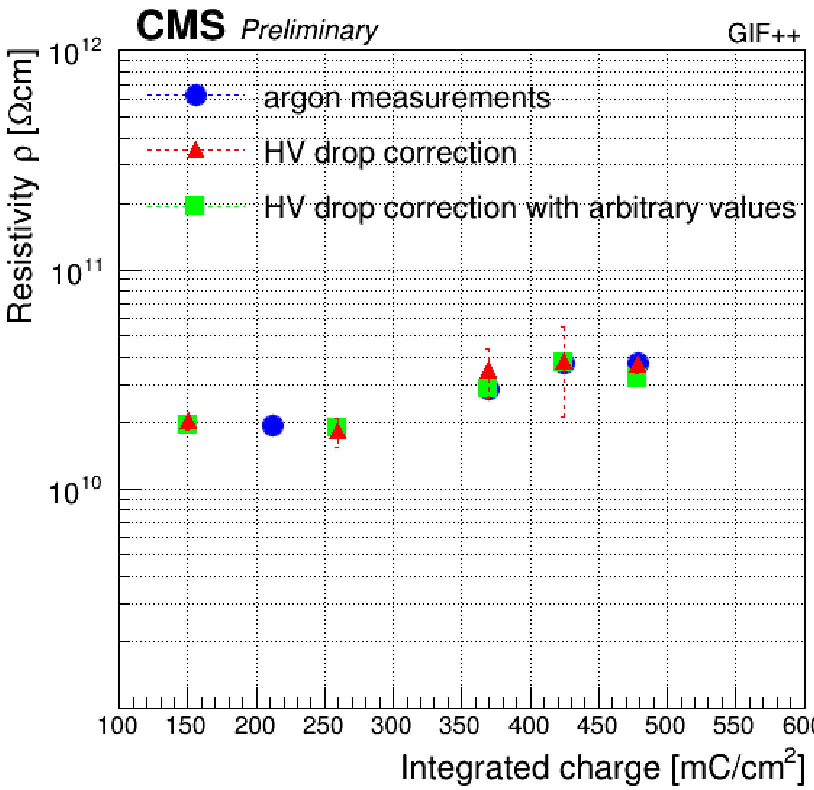
- ★ Stable performance: stable WP and efficiency

Efficiency vs HV$_{eff}$ measured with background (600 Hz/cm^2)

- ★ Stable performance
- ★ WP shift of ~ 100 V (after 378 mC/cm^2)

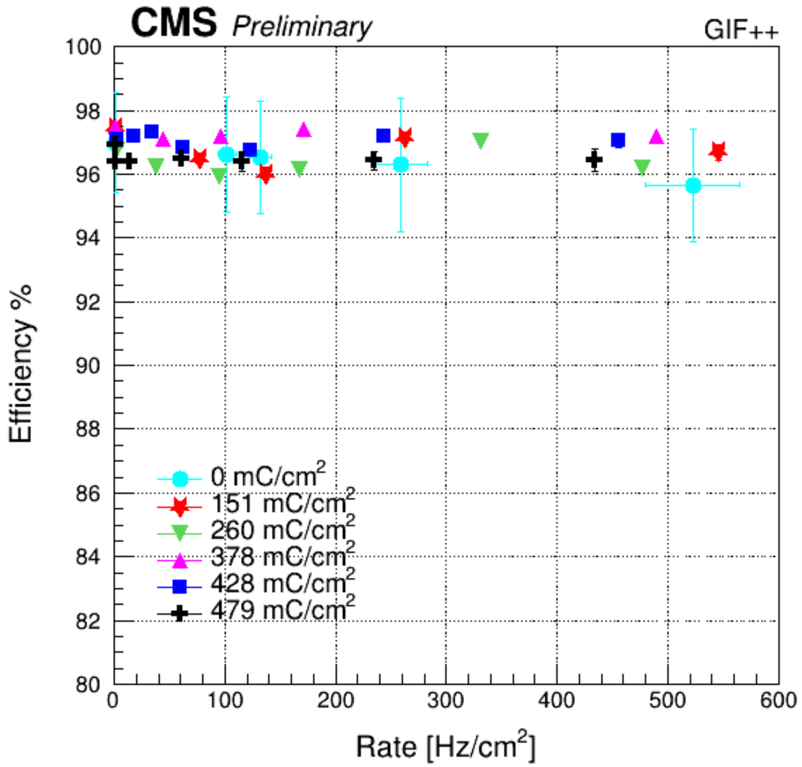
RPC performance monitoring

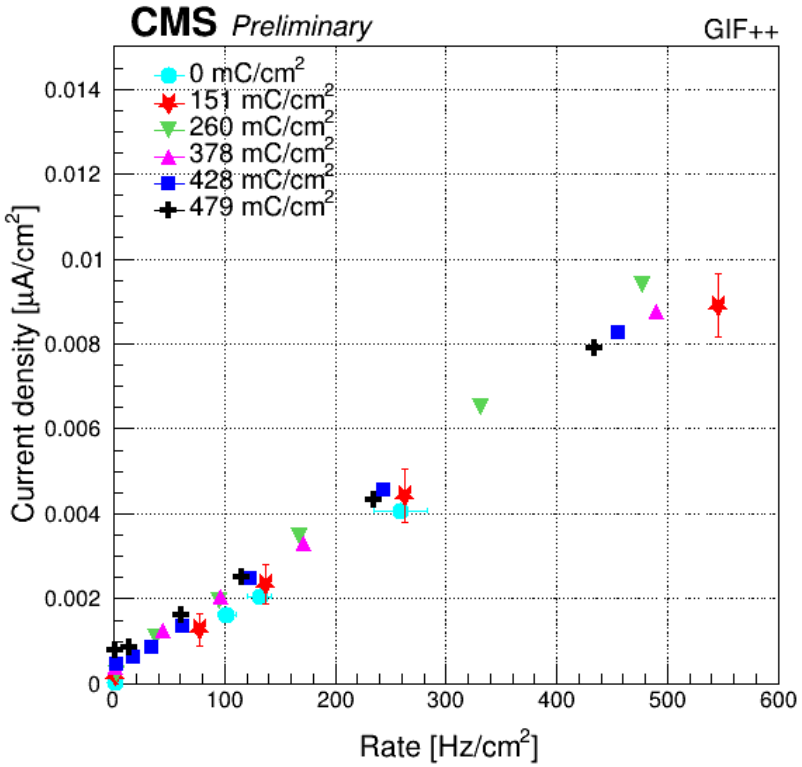


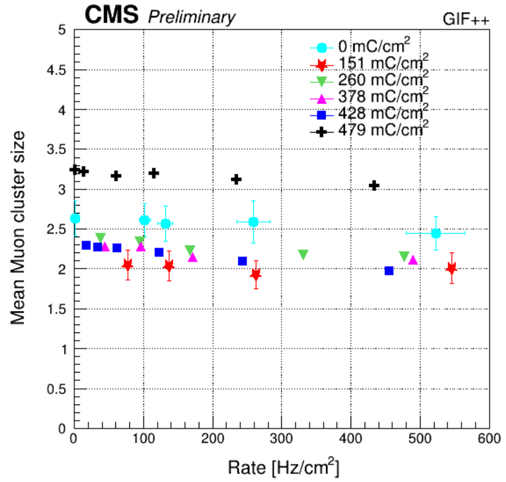


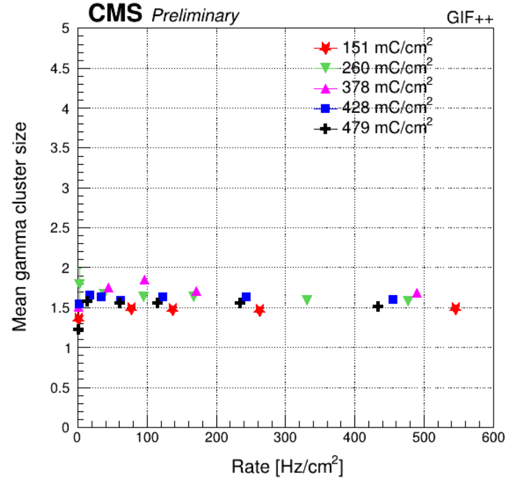
- ➢Efficiency at different ABS and at different Integrated charge (different TB) overlap.
- ➢NO any shift observed vs time and up to background rate of 600 Hz/cm^2.
- ➢Rescale method confirmed by the resistivity measurements

RPC performance monitoring









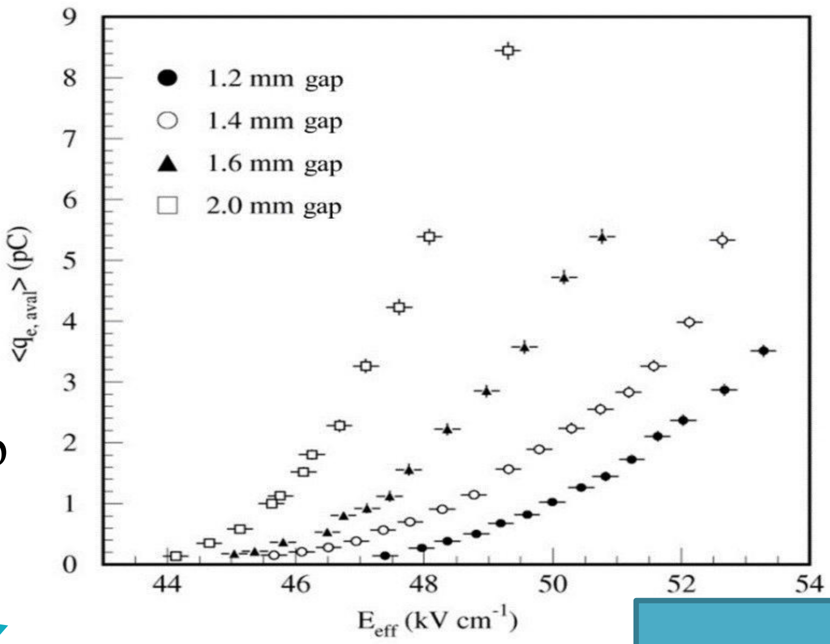
- ★ Efficiency at WP remains stable in time up to the maximum expected rate (600 Hz/cm^2)
- ★ A decrease of about 2% of the efficiency at the highest expected background rate (600 Hz/cm^2)
- ★ Stable deposited charge
- ★ Stable gamma and muon cluster size

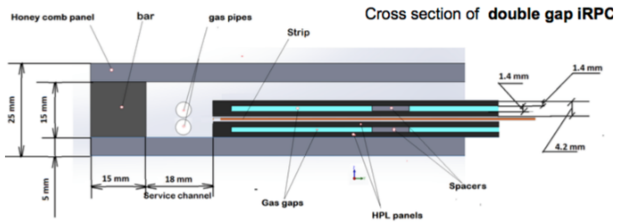
improved-RPC (iRPC) technology

- **Resistivity of the HPL**
  from 1-6·10^10 Ωcm → 0.9-3·10^10 Ωcm
  - Enhance the rate capability

- **Electrodes thickness**
  from 2.0 mm → 1.4 mm
  - Recovery time reduced
  - Efficiency of extracting the pickup charge from the avalanche charge

- **Gap thickness**
  from 2.0 mm → 1.4 mm
  - retards the fast growth of the pick up charge
  - reduce of the operational high voltage
  - reduce aging effect





Move part of the signal amplification from the gas gap to the electronics

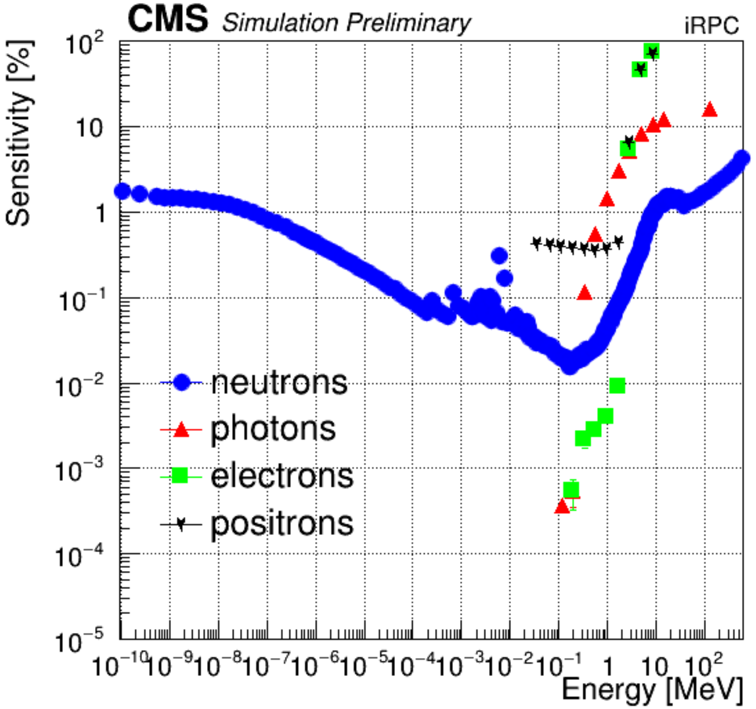
iRPC BASELINE

	RPC	iRPC
Gas Gap & Electrode width	2 mm	**1.4 mm**
High Pressure Laminate	2 mm	**1.4 mm**
Resistivity (Ωcm)	1 - 6 x 10^10	**0.9 - 3 x 10^10**

iRPC background rate estimation @ HL-LHC

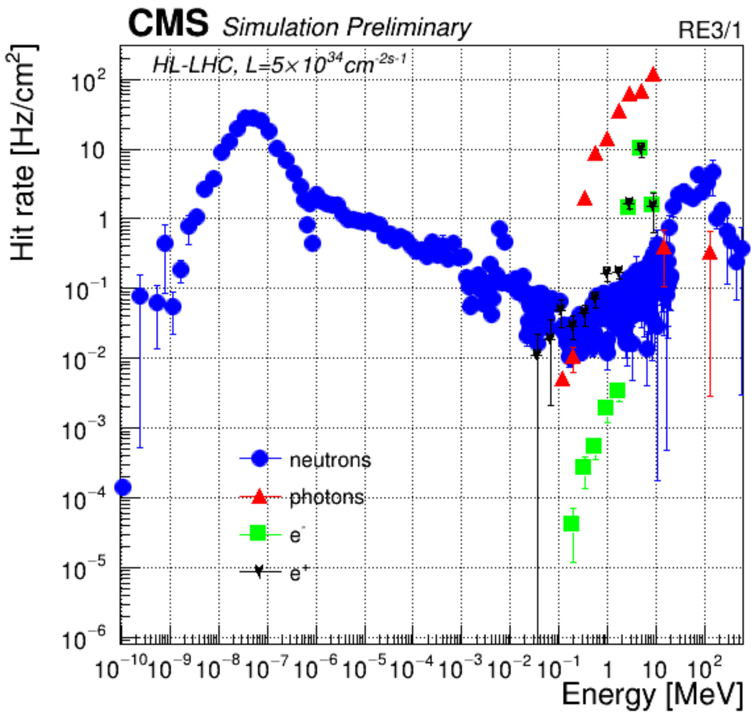
iRPC sensitivity @ HL-LHC particles spectra

$$S(E) = \frac{R_{iRPC}}{\phi_{bkg}^{CMS}}(\mathrm{E})$$

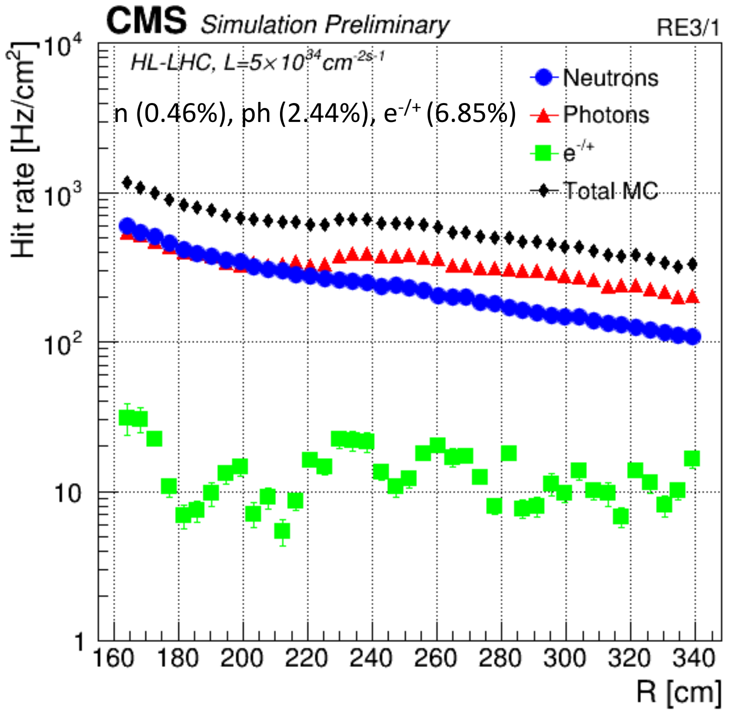


Convolution of flux and sensitivity

$$R_{iRPC}(E) = \phi_{bkg}^{CMS}(E) \times S(E)$$



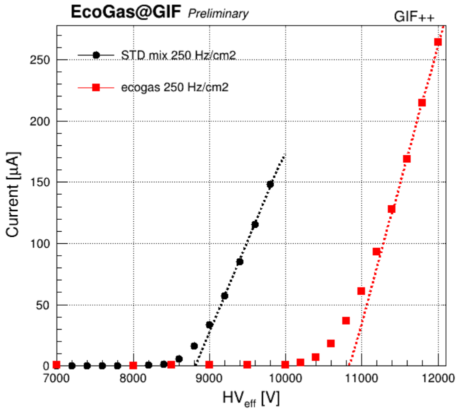
Background rate vs R

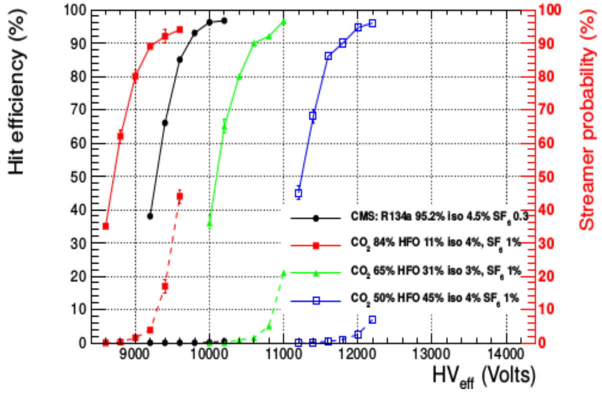


Average background rate of ≈ 600 Hz/cm^2 indicates the requirement of a minimum rate capability of **≈ 2 kHz/cm^2** for the iRPCs when considering a safety factor of 3

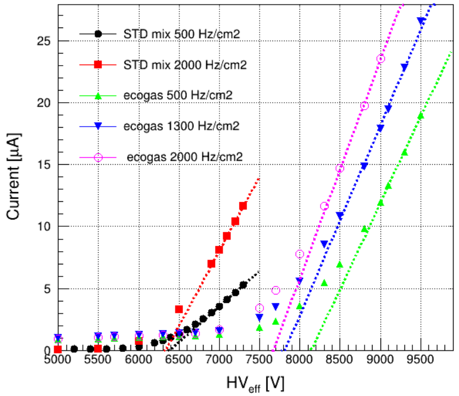
Search for RPC ecogas

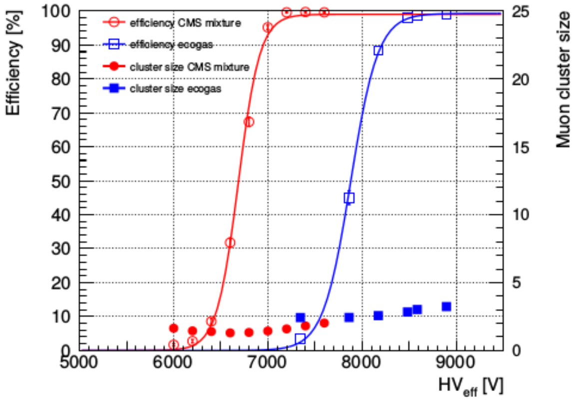
- 2mm gap: 2 kV of HV shifts @ 250 Hz/cm2 between the eco-gas and CMS mixture was measured in agreement with TDR results done with cosmic muons





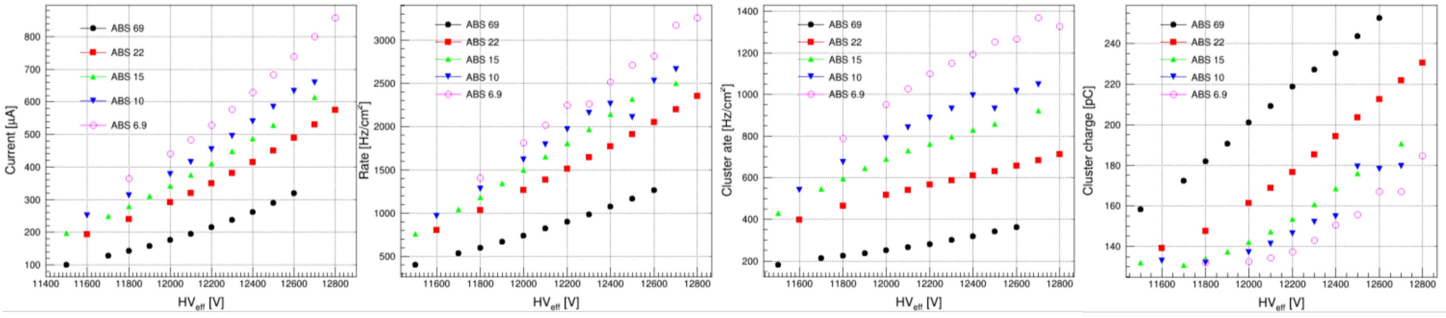
- 1.4 mm gap: ~ 1.5 kV of HV shift between the eco-gas and CMS mixture was measured in agreement with TDR results done with cosmic muons (similar gas mix: 50% HFO, 4.5% isobutane, 0.3% SF6, 45.2% CO2)

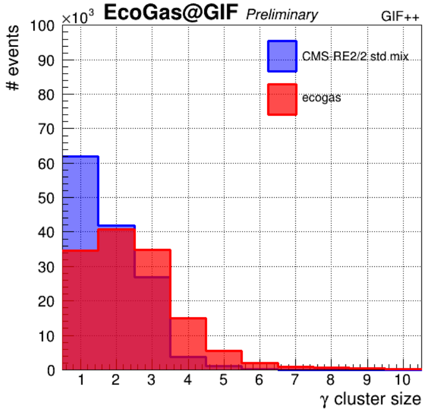




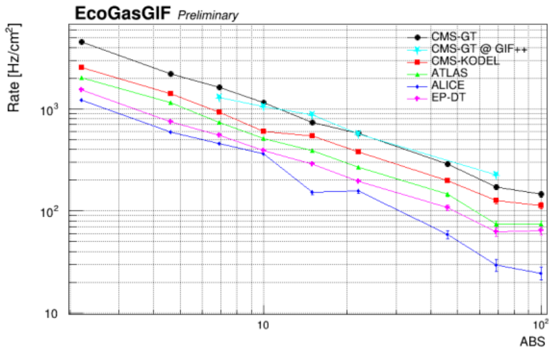
Search for RPC ecogas

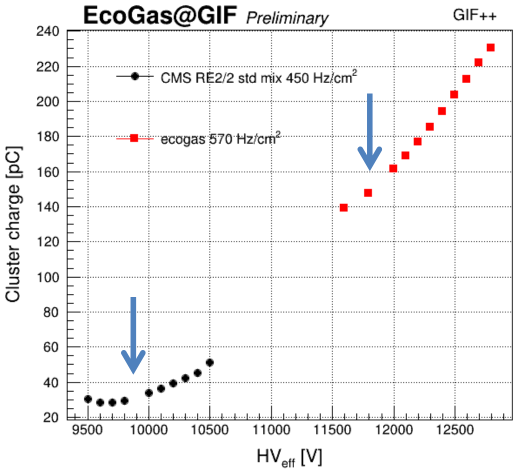
current | rate | cluster rate | charge





Good agreement between simulated rate and rate measured @ GIF++

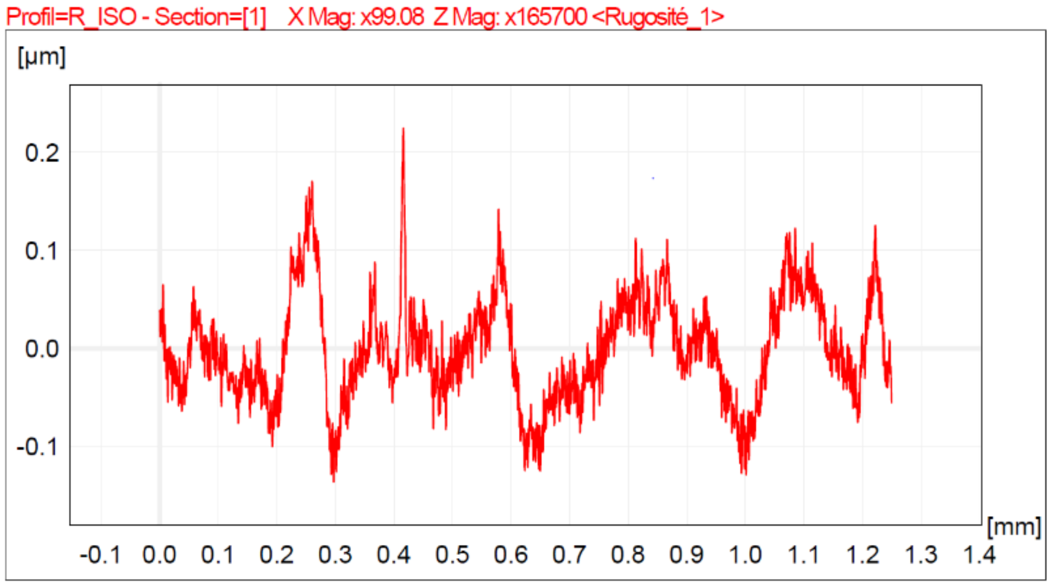


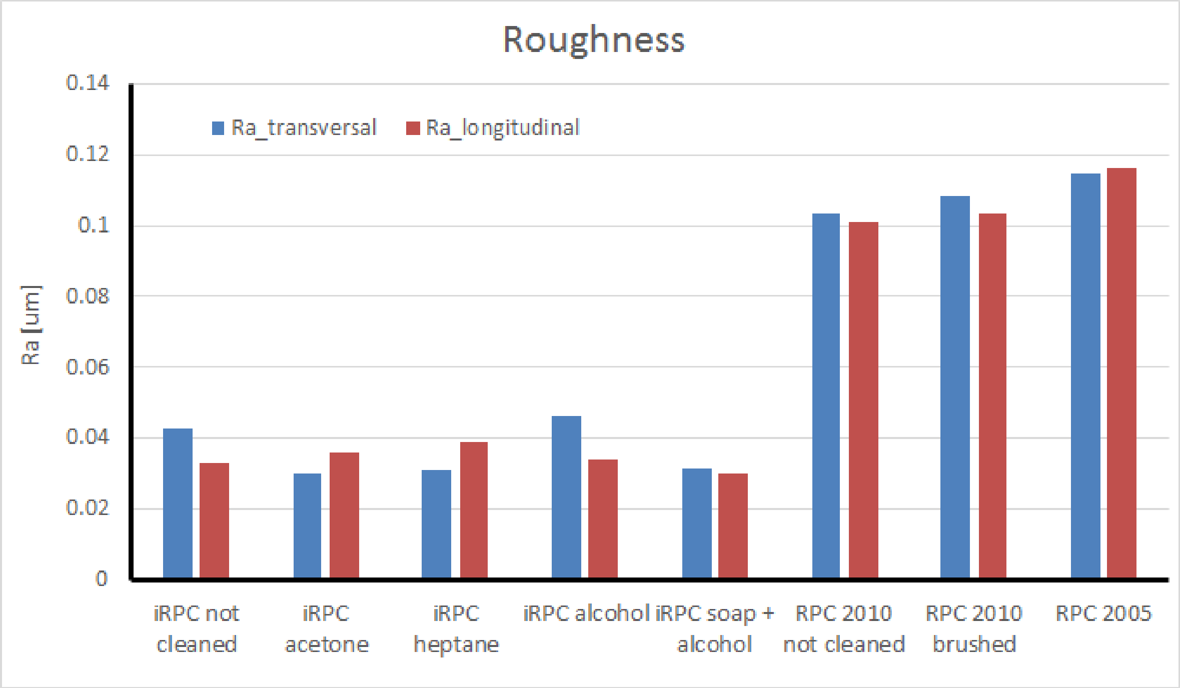


- **Average charge ~ 5 time higher:** ≈ 25-30 pC for STD mix and ≈ 150 pC for ecogas
- **Average Cluster size at WP:** 2.6 strips for eco-gas and 1.9 strips for CMS

Inner-gap surface analysis

SURFACE ROUGHNESS





PhD courses I year

Course	Credits	Status
LHC phenomenology	2 CFU	✓
Gas detectors	2 CFU	✓
Interpolation methods and techniques for experimental data analysis	2 CFU	✓
LabVIEW introductory course	2 CFU	✓
Programming with Python	2 CFU	✓
European research model and promotion of research results	2 CFU	✓
How to prepare a technical speech in English	2 CFU	✓
C++	2 CFU	✓