Development of Gas Systems for Gaseous Detector Operation at HL-LHC

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Introduction

Who am I?

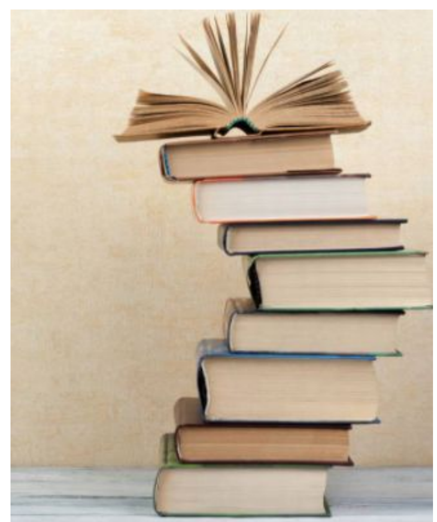
- From Italy > Brianza/Lecco
- Master in Applied Physics @Milano Bicocca
- PhD based @CERN, close to the end :D
- In my (very little) free time I mostly read books and cook pizza with Gianluca

My PhD:

Development of Gas Systems

for Gaseous Detector Operation at HL-LHC

- Work with Detector Technologies Gas Team
- Operation of LHC Gas Systems
- R&D on strategies for reducing GHG emission



OUTLOOK

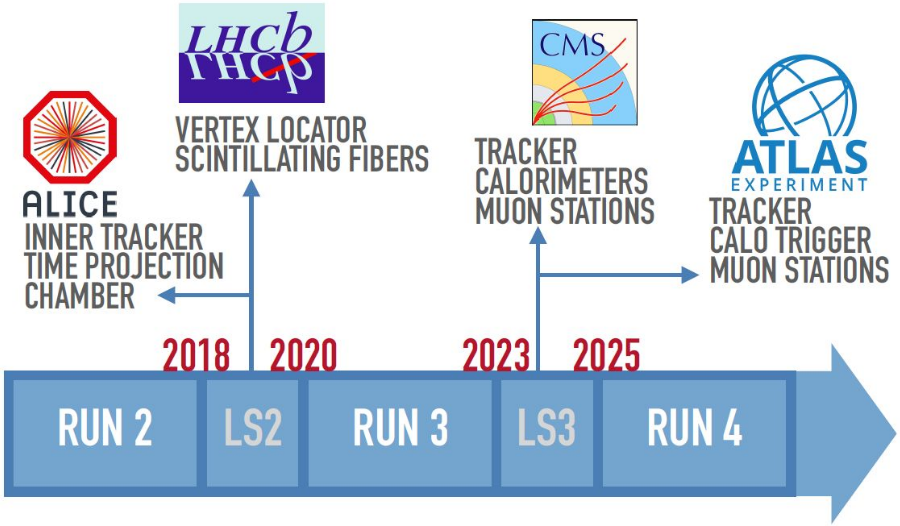
- ➔ LHC Upgrades : HL-LHC
- ➔ LHC Gaseous Detectors & Gas Systems
- ➔ Gas Systems requirements
  - ◆ Greenhouse gas emission
  - ◆ Strategies
- ➔ Gas Recirculation for Triple-GEM detectors
  - ◆ Triple-GEMs at the LHC
  - ◆ Triple-GEMs in high-rate radiation environment
- ➔ Gas Recuperation : CF4
  - ◆ LHCb RICH2
  - ◆ CMS CSC
- ➔ Gas Recuperation : R134a
- ➔ Conclusion

LHC Upgrades : HL-LHC

The Large Hadron Collider will reach in 2025 its High-Luminosity phase,
to enlarge experimental data samples and push forward its Physics Program

- Improved performance of LHC will come from Accelerator upgrades,
  but the future high particle rate imposes consolidation and upgrades for LHC Experiments too

- All detectors systems will be affected: Tracker, Calorimeters, Muon Systems
- Upgrades will take place in LS2 for ALICE and LHCb,
  while major improvements will be faced
  by ATLAS and CMS mainly during LS3



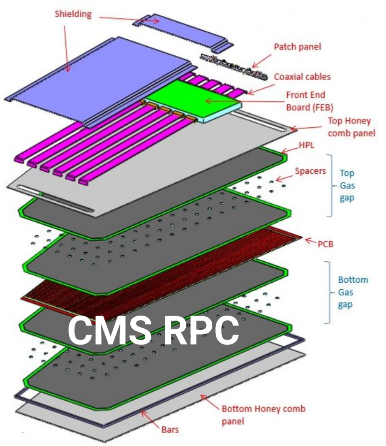
LHC Gaseous Detectors & Gas Systems

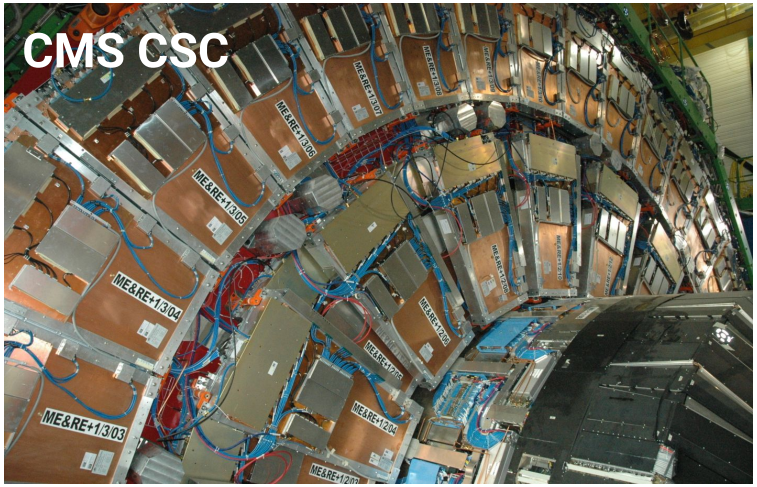
Muons escape Electromagnetic Calorimeter: detected with dedicated systems

- Muon systems are composed of various layers of **Gaseous Detectors**: Multi-Wire Chamber, Cathode Strip Chambers, Resistive Plate Chambers, Triple-GEMs, Micromegas…

- Muon detectors are capable of identifying, tracking and measuring Muons momentum

- To operate large volumes of gaseous detectors, complex gas systems are necessary





Gas Systems requirements

Gas Mixture is the primary element influencing Gaseous Detector performance:
its quality and stability are fundamental for good and safe long-term operation

- Some of the gases used in LHC Experiments have
  a high Global Warming Potential and their emission favours Greenhouse effect

- The use of Greenhouse gases is discouraged by European Union,
  their cost will start increase and some will be phased out by 2030

CERN is taking steps to lower GHG consumption

to reduce their emission in the environment

and to limit the cost of Gas Systems

Strategies

CERN EP-DT Gas Team works to put in place measures
to fulfill the requirement of reduced GHG usage

Strategies to reduce GHG usage

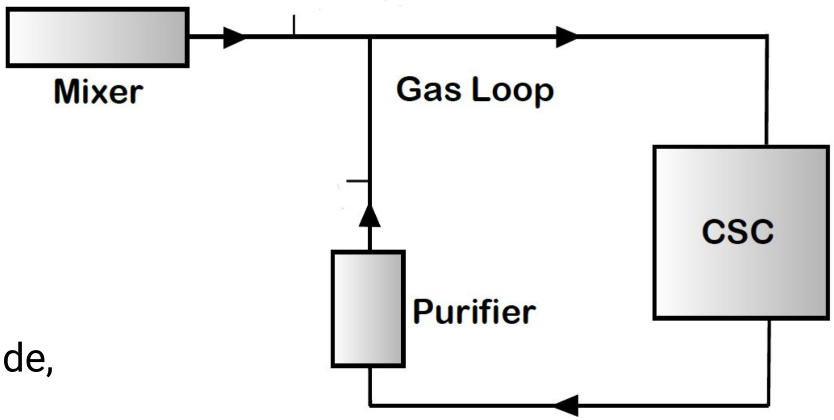
- Gas Recirculation
  - Gas Recirculation for Triple-GEMs
- Gas Recuperation
  - CF_4 Recuperation CMS CSC
  - CF_4 Recuperation LHCb RICH2
  - R134a Recuperation RPC gas mixture
- Alternative Gases
- Gas Disposal

Gas Recirculating Systems

- Systems operated in open loop, exhaust gas is let out in the atmosphere
- Gas extracted from the system is re-injected after purification
- 100% recirculation not always feasible, i.e. due to gas system leaks
- Usually 90% recirculation, 10% fresh mixture injected

Pros:
> Reduced operational costs
> Lower Greenhouse Gas emissions

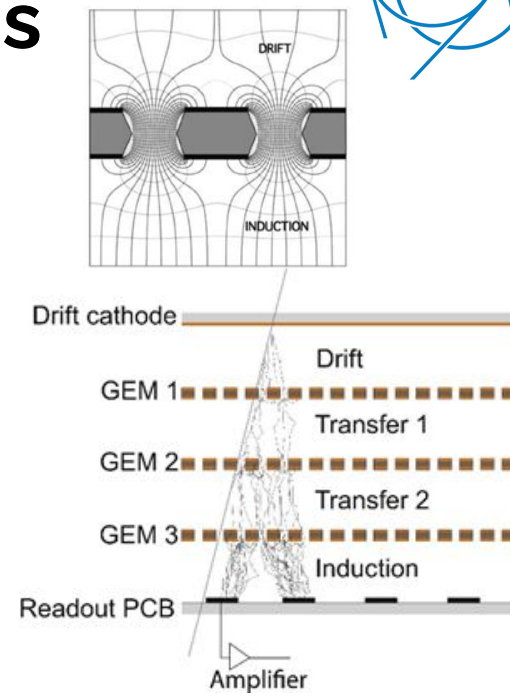
Cons:
> Increased complexity of the system
> Compromised gas mixture quality
> Accumulation of impurities as N_2, O_2, H_2O, Fluoride, from detectors volume or gas system



Gas mixture quality and stability are primary elements influencing detectors performance, it is fundamental for good and safe long-term operation

Gas Recirculation for Triple-GEMs
Triple-GEMs @ LHC

- Gas Electron Multiplier detector, latest generation of MPGD
  good performance as Muon tracking devices
- GEM electrode = 5 um Kapton + Cu coating, 70um holes
  each hole acts locally as a proportional amplifier
- Gas mixture: Ar/CO_2 (70/30) or $Ar/CO_2/CF_4$ (45/15/40)
  CF_4 added to enhance time resolution

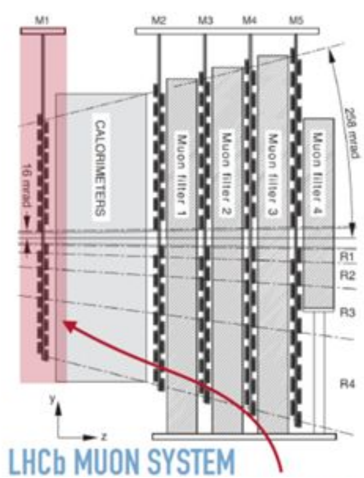


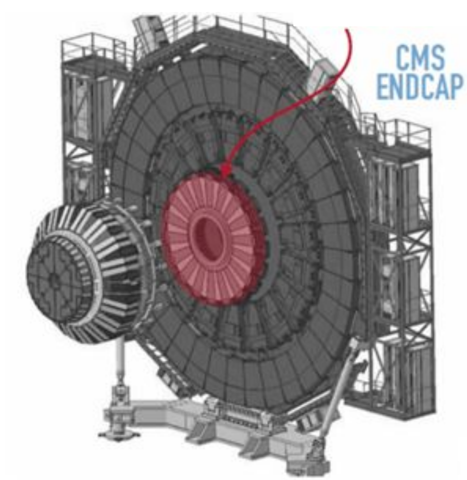
Triple-GEMs

- Three foils with consecutive injection of multiplied electrons
- Three amplification stages, lower voltage to single foils

@LHC

- LHCb Muon System Run1/Run2,
- CMS Endcap Run3/Run4
- Useful in high-rate radiation regions
  suitable for HL-LHC environment

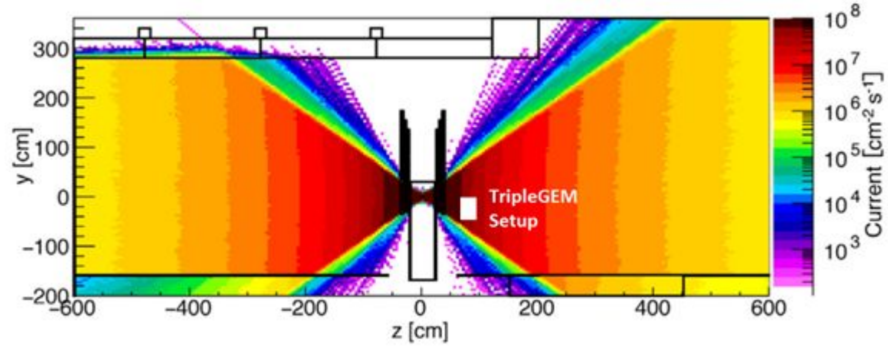




Gas Recirculation for Triple-GEMs
Gamma Irradiation Facility (GIF++)

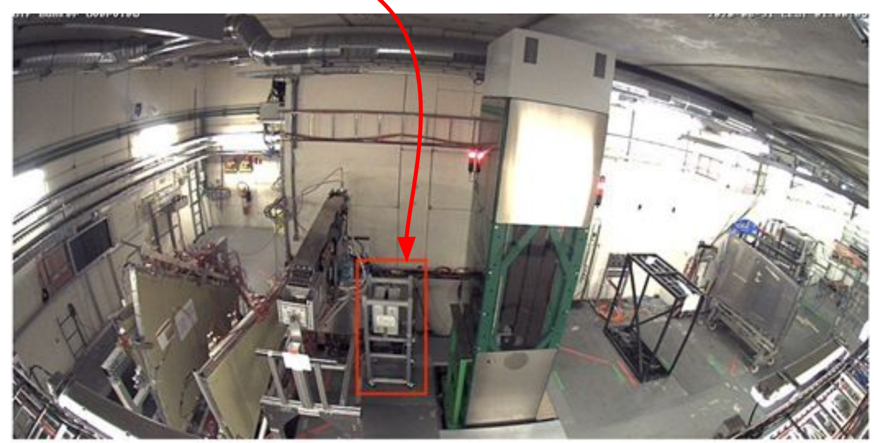
Dedicated test zone for large-area muon chambers, performance characterization and aging tests

- Irradiation provided by ^{137}Cs source, 662 keV photons, activity 14 TBq
- Variable source intensity thanks to integrated absorption filter system
- Dose rate suitable to mimic high-rate radiation of HL-LHC Phase (1G/h at 1m)

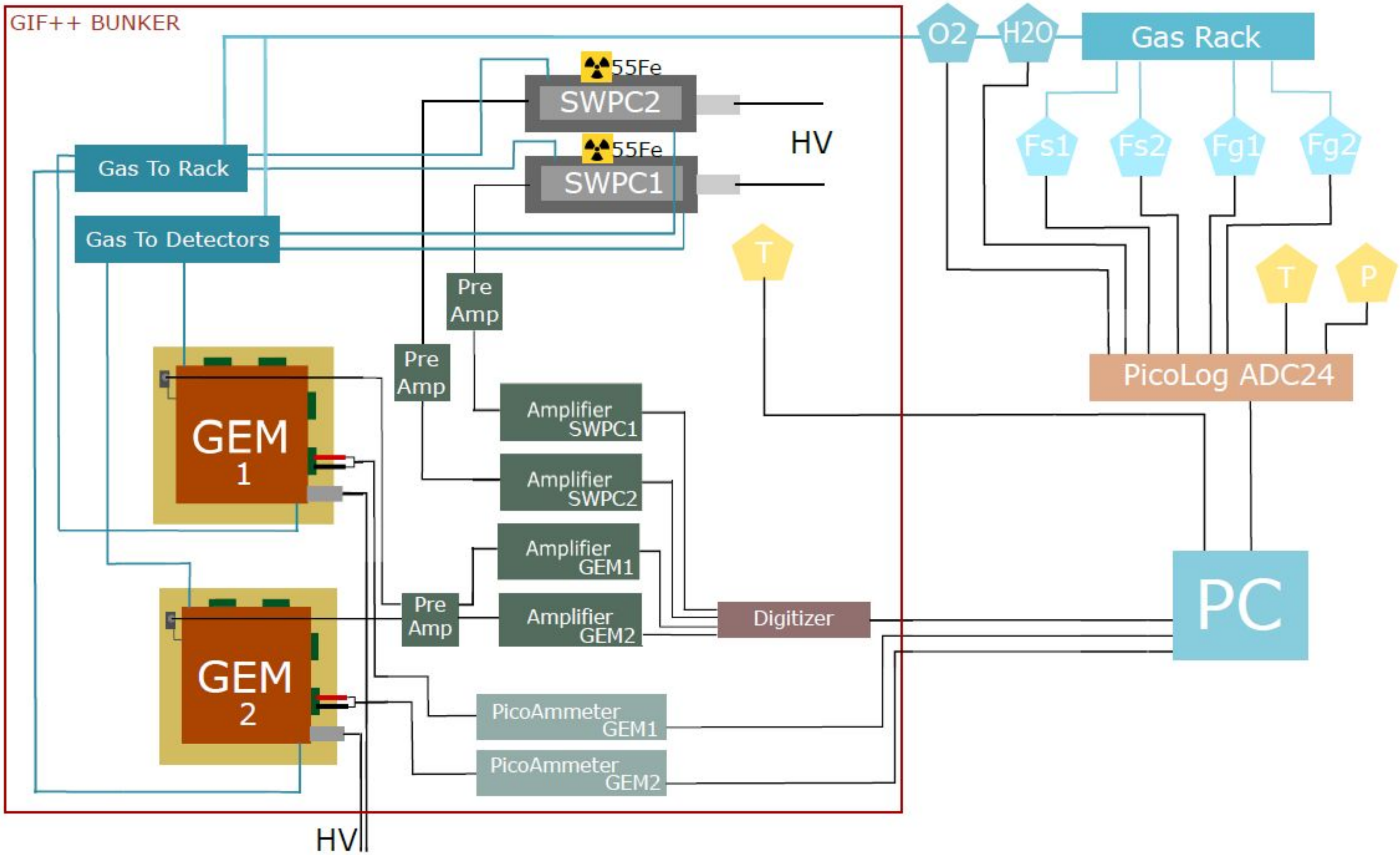


Triple-GEM Gas R&D Setup

- Two 10x10 cm2 detectors (gaps 3-1-2-1 mm)
- Ar/CO_2 70/30 or Ar/CO_2/CF_4 45/15/40
- Irradiated with ^{137}Cs and ^{55}Fe + Muon Beam
- *Closed Loop Gas System*:
  > Small replica of LHC Gas Systems
  > Purifier Module for H_2O and O_2 removal
  > Monitoring of gas quality with SWPC
- *Data Acquisition:*
  > Detector Current and Signal
  > Environmental and gas Parameters



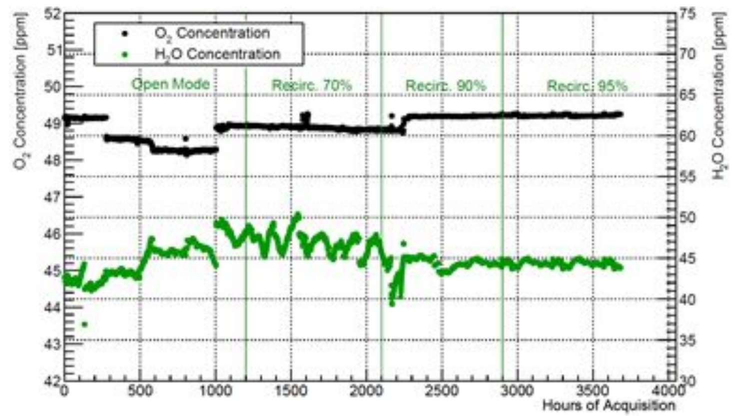
Gas Recirculation for Triple-GEMs
Gamma Irradiation Facility (GIF++)



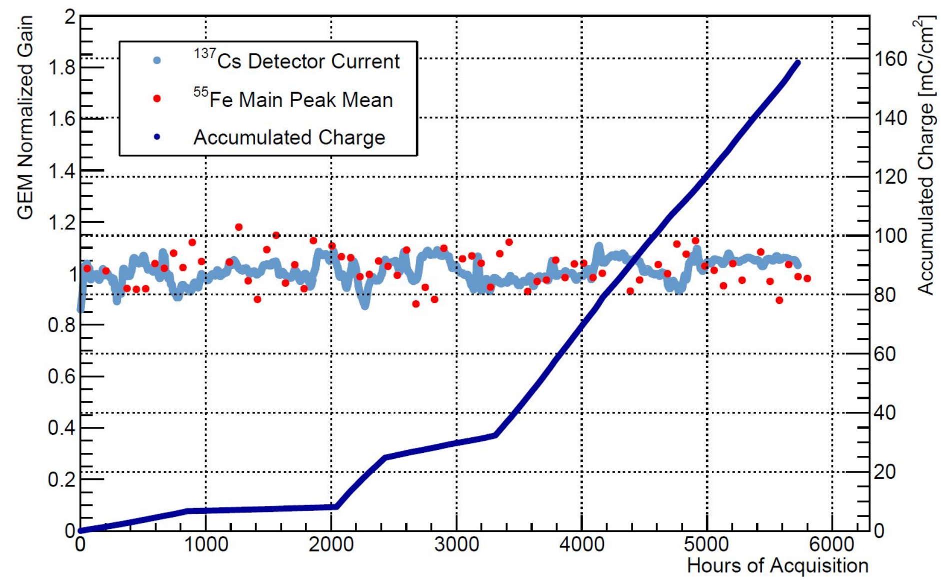
Gas Recirculation for Triple-GEMs Long Term Irradiation

Long-term performance stability test

- Continuous irradiation at rate 50 x 10^6 Hz/cm^2 (about 6000 hours), HL-LHC rate equivalent
- Ar/CO_2 and $Ar/CO_2/CF_4$ gas mixture
  Gas recirculating fractions 50%, 70%, 90%, 95%
- Monitoring detector current at working point



Purifier module: O_2, H_2O=50 ppm
oscillations reduced to less than 5%



Safe and stable operation with:
> Ar/CO_2 and $Ar/CO_2/CF_4$ gas mixtures
> Gas recirculating fraction up to 95%
> Different background irradiation rates
> Accumulated charge higher than 100 mC/cm

Weekly performance monitoring (^{55}Fe)
coherent with detector current from ^{137}Cs

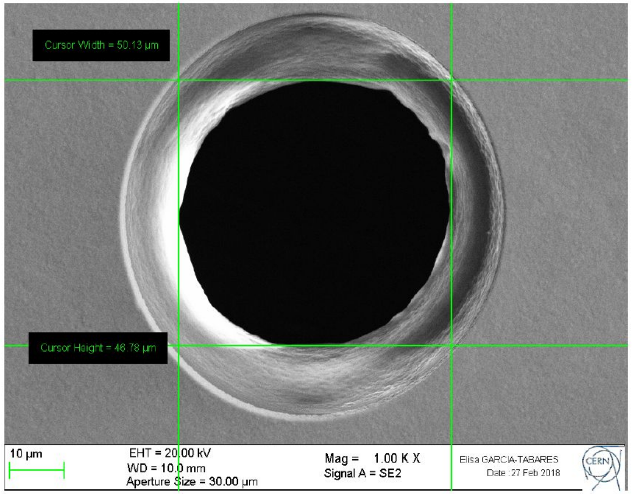
SWPC monitoring systems showed stable
gas mixture composition (fresh, recirculated)

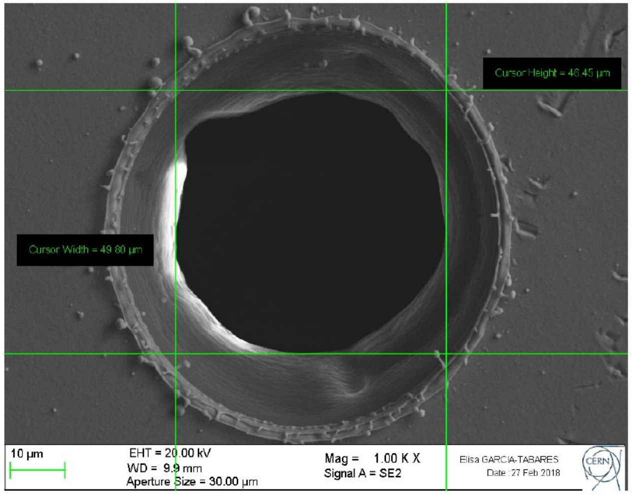
Gas Recirculation for Triple-GEMs
GEM holes radiation damage

GEM holes analysed with Scanning Electron Microscopy after irradiation with Ar/CO_2 mixture
> gives as output eye-like images of the hole morphology
> analysis realized by the CERN EN-MME-MM department

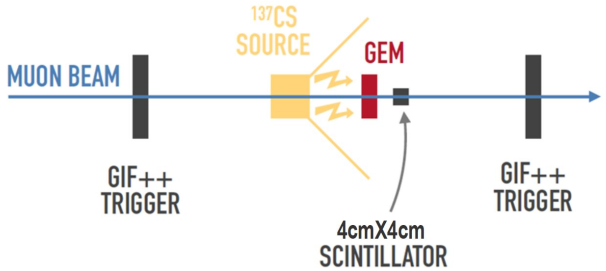
- Only a fraction of the holes are damages, most of them are ok
- Holes diameter remains the same, but outline strongly irregular
- Drops around the hole perimeter > possibly Copper?

No evidence of reduction of amplification gain



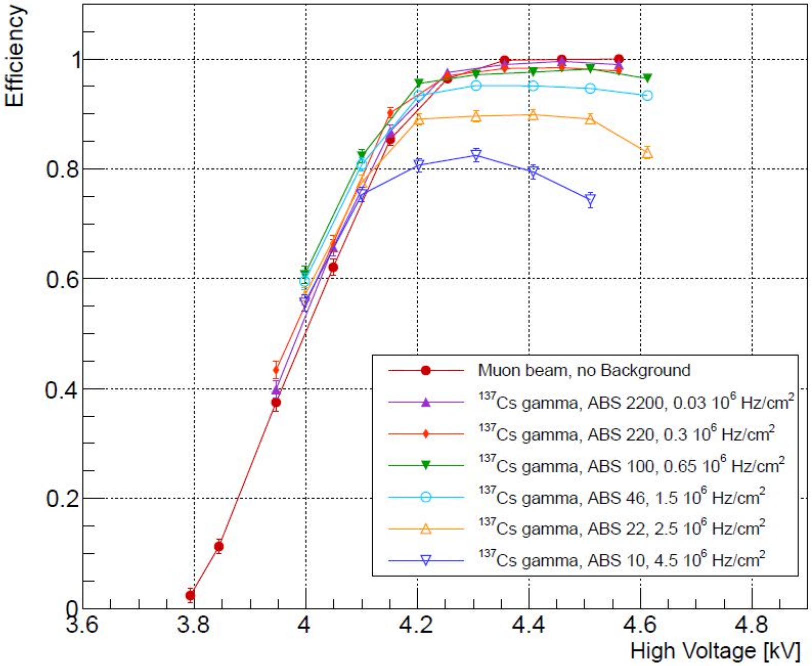


Gas Recirculation for Triple-GEMs Muon Detection Efficiency



Muon detection efficiency studied:

- Muon beam from SPS
  in coincidence with scintillators
- ^{137}Cs source irradiation as background
- HV scans repeated at different
  gas mixture and irradiation conditions

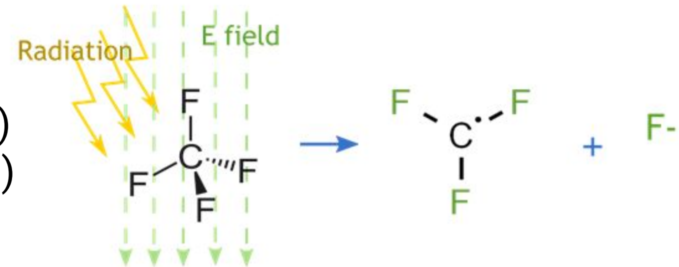


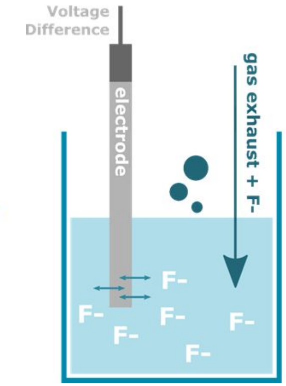
Triple-GEM performance:

- Reach 100% efficiency without background
- Equivalent inopen mode and gas recirculation
- Efficiency remains optimal (>90%)
  for background rate up to 10^5 Hz/cm^2
- Amplification gain at working point voltage
  (gain around 10^4 without background)
  remains constant regardless the irradiation rate

Gas Recirculation for Triple-GEMs Fluoride Impurities @GIF++

CF_4 breaks up in the electron avalanche
Highly reactive products: F-, CF_3+, CF_2+, …
> Polymerized deposits (HF acid, if H_2O present)
> Material etching (GEM foils, readout electrode)

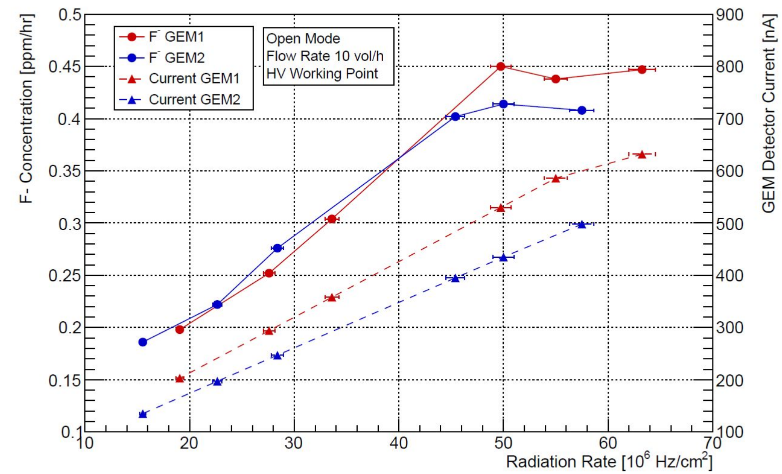




Ion Selective Electrode station (ISE),
Voltage is proportional to F- concentration

Factors affecting impurities production

- Gas mixture composition (CF_4 concentration)
  > does not affect much
- Charge density = Electric field and irradiation rate
  > both contributing to linearly increase production
  > irradiation rate should be further investigated
- High gas flow rates can avoid impurities creation



LHC gas systems with standard purifier module are safe for operation in gas recirculation with CF_4
>The O_2/H_2O purifier also traps fluoride impurities

Same test on LHCb GEM gas system, Run 2
> confirmed purifier action
> dependence of F- on Luminosity/Rate

Gas Recuperation Systems

- Not always feasible to have systems with 100% gas recirculation, up to 10% of gas mixture can be re-injected in the system
- 10% of mixture exhaust to air + emission due to systems maintenance
- Exhaust gas mixture can be recuperated

Aim of gas recuperation:

separate most valuable component of the gas mixture

to reuse it in the gas system in place of fresh gas

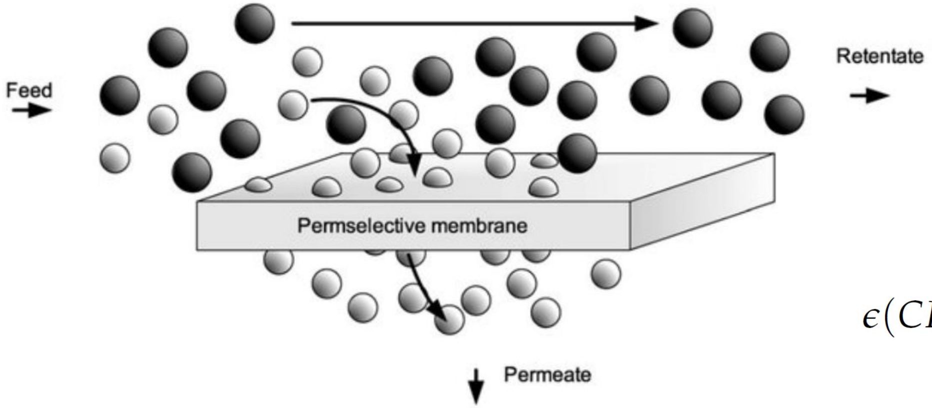
CF4 Recuperation for LHCb RICH2

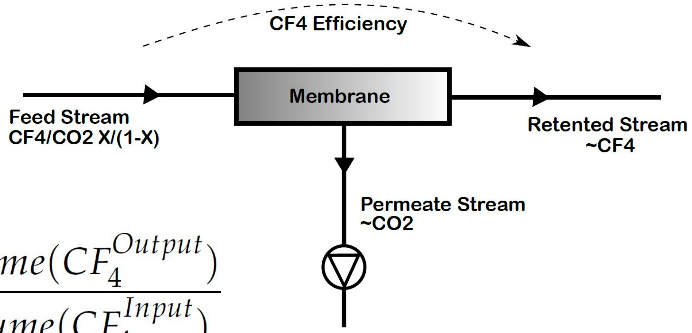
CF4 Recuperation for CMS CSC

R134a Recuperation for RPCs gas systems

Gas Recuperation Systems - CF4 Separation Membranes

- CF_4 is well separated by selective membrane technology
- UBE Industries hollow fiber membranes, arranged in straws bundle
- By design, CO_2 permeates through membrane walls
  and it is removed from the retented output (~100% CF_4)
- Balance to have optimal performance:
  > high purity of separated CF_4 in retented stream
  > lowest possible loss of CF_4 in permeate stream



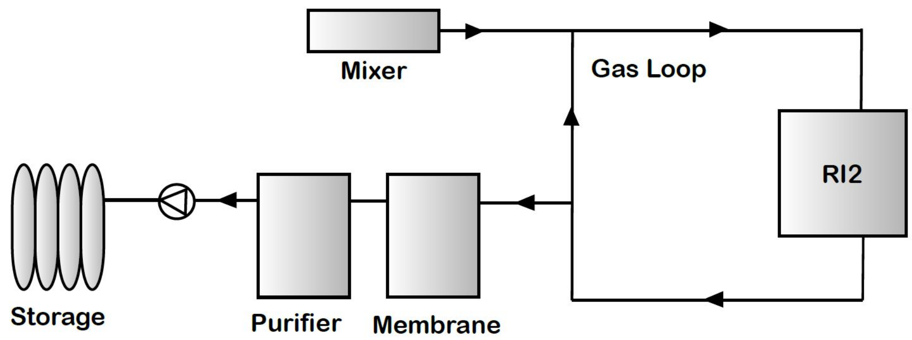


$$\epsilon(CF_4) = \frac{volume(CF_4^{Output})}{volume(CF_4^{Input})}$$

Gas Recuperation Systems - CF_4
LHCb RICH2

RICH2 gas mixture: CF_4/CO_2 92/8

- LS2, filled with 100% CO_2 for maintenance
- Output of the system: mainly CF_4, 100 M^3

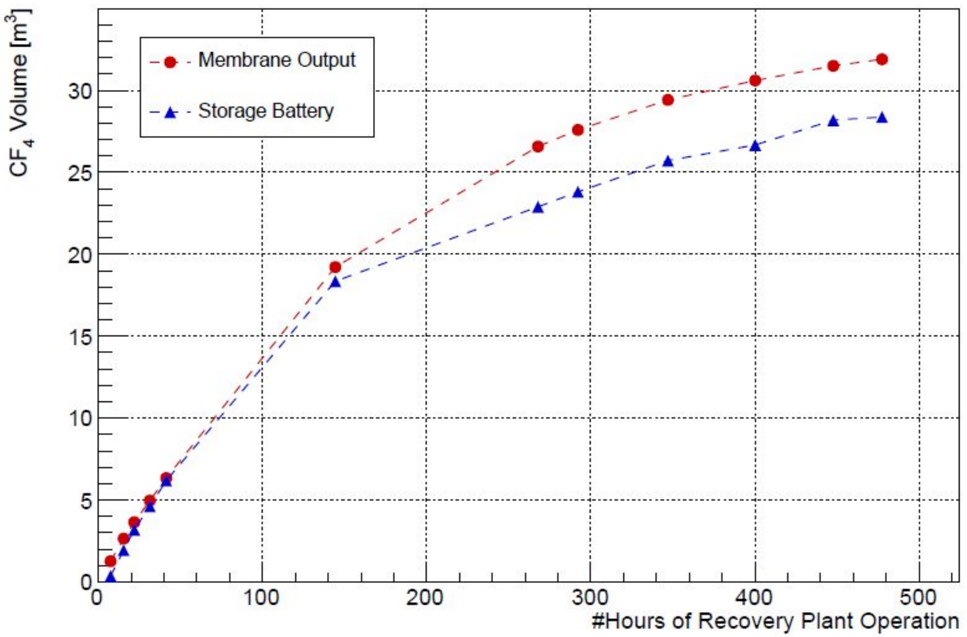


Recuperation plant with membrane

- Average efficiency 60%

  > variable with input CF_4 concentration
- about 30 M^3 of recuperated CF_4

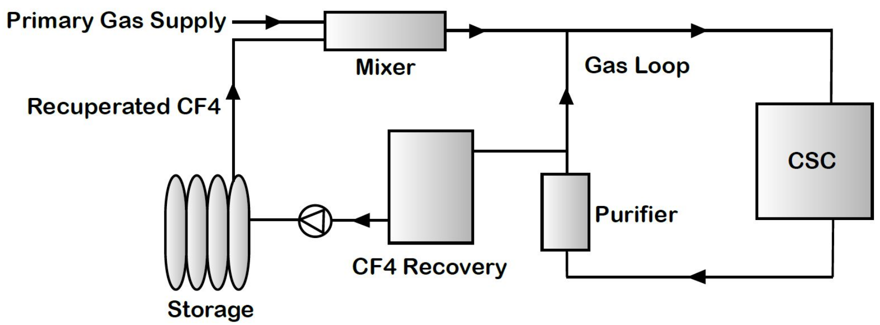
  impurities < 1% (air)



Onoging system improvements

+ re-injection of recuperated gas before Run3

Gas Recuperation Systems - CF_4 CMS CSC

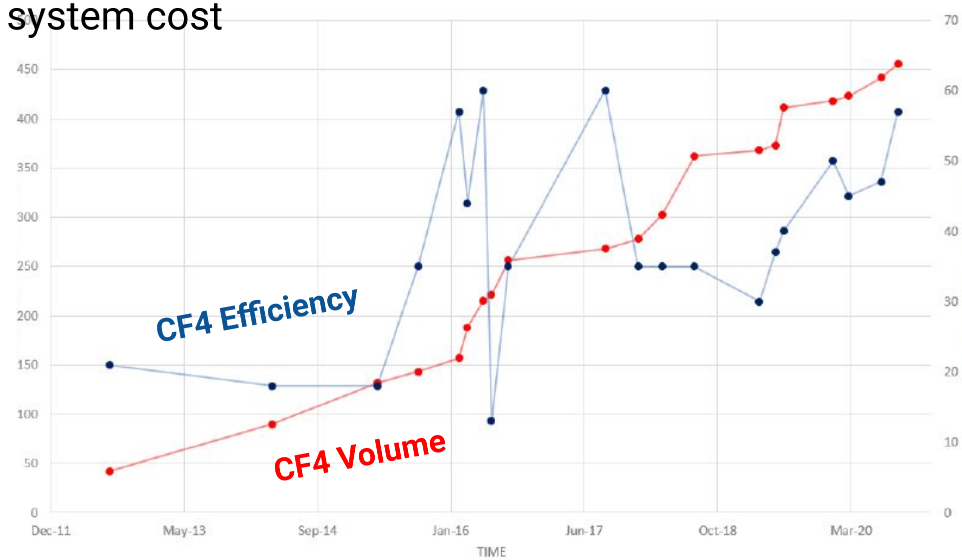


CSC gas mixture: $Ar/CO_2/CF_4$ 40/50/10

CF_4 Recuperation plant operational since 2012

- Variable efficiency, improvements last years
- About 450 M^3 of CF_4 recuperated in total
- 44% reduction on GHG emissions + gas system cost
- Direct injection into the CSC mixer

  > monitoring with GC + SWPC



Single Wire Chambers monitoring

- operational since 2015
- monitoring of gas quality of

  mixer output and recirculated gas

Gas Recuperation Systems - R134a RPC Gas Mixture

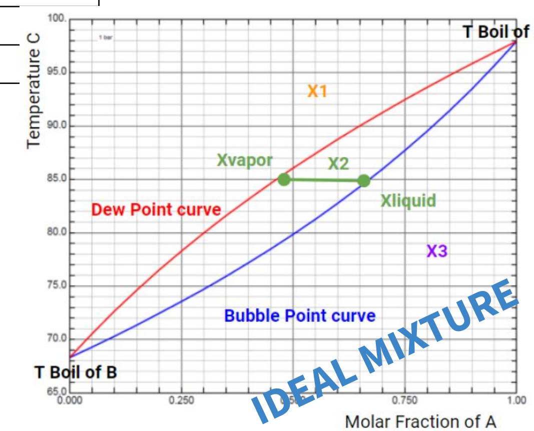
Component	Concentration
iC_4H_{10}	4.5 %
R134a	95.7 %
SF_6	0.3 %
N_2	0.05 %

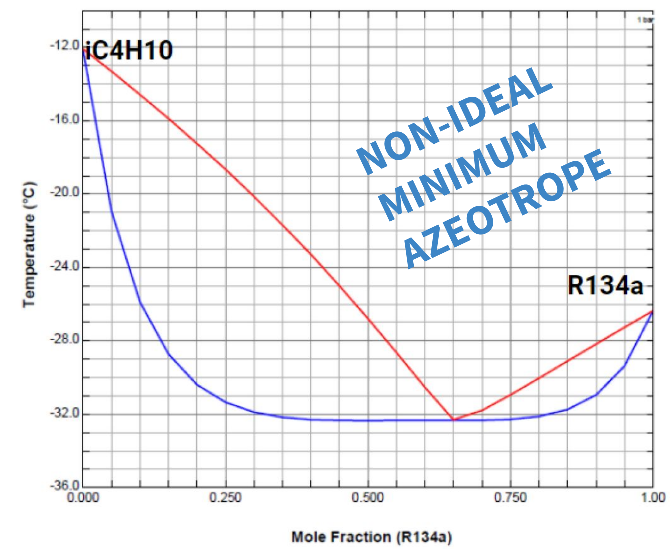
RPC gas mixture: R134a/iC_4H_{10}/SF_6 + N_2

R134a ~80% GHG emissions LHC Experiments
> currently mostly due to detectors leaks
> when leaks fixed, exhaust available for recuperation

Separated through thermodynamic phase transitions

- **Phase1**: removal of N_2/SF_6 by simple distillation from gas mix +20°C, decrease to -36°C
  N_2/SF_6 removed in vapor phase, rest is liquid
- **Phase2**: separation of pure R134a from iC_4H_{10}
  >binary mixture with minimum azeotropic point!
  intramolecular force of same-species is much higher than the reciprocal attraction
  > separation by quasi-static increase of temperature

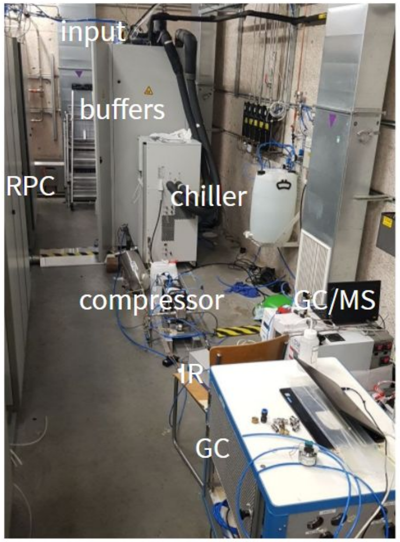




Gas Recuperation Systems - R134a Plant Prototype @CMS

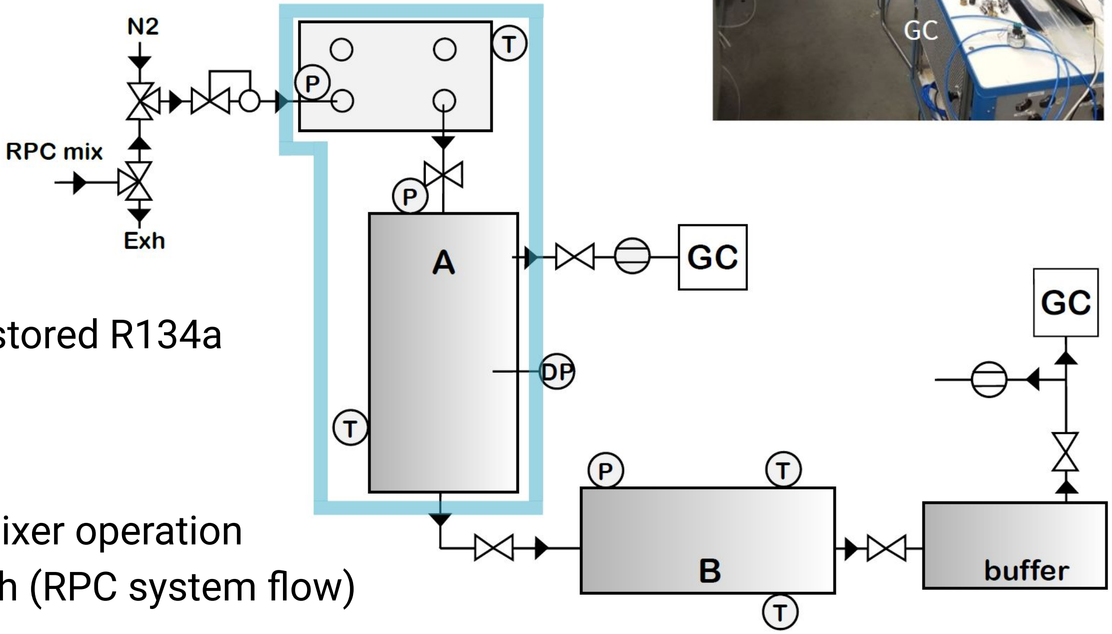
Prototype of separation plant tested from 2018 (first in ATLAS, then CMS)

- Many technical challenges in realizing the separation
- GC analysis fundamental to tune plant parameters (ex Temperature)



Plant Characterization

- 100-400 l/h input flow
- 100-250 l/h output flow
- Optimization of volume B temperature stability to favor better R134a/iC_4H_{10} separation
- Recuperation efficiency 80-90%
- High purity of recuperated and stored R134a



Next Steps

- Include recuperated R134a in mixer operation
- Test for input flow up to 1000 l/h (RPC system flow)

Conclusion

Gas Recirculation for Triple-GEMs

Long term irradiation

- Stable operation with recirculating fraction up to 95% and 100 mC/cm^2 of accumulated charge
- Purifier module: same gas quality after recirculation (O_2, H_2O)

Muon Detection Efficiency

- Efficiency remains >90% for background rate up to 10^5 Hz/cm^2

Fluoride Impurities Production

- Operation parameters have an effect on production rate (HV, γ rate, flow)
- Purifier traps F-, no accumulation

LHC Gas Recuperation

CF4 for LHCb RICH2

- Average efficiency 60%
- 30 M^3 recuperated in 2019

CF4 for CMS CSC

- Average efficiency 50%
- 450 M^3 recuperated since 2012
- CF_4 re-injected into system by mixer

R134a for RPC gas systems

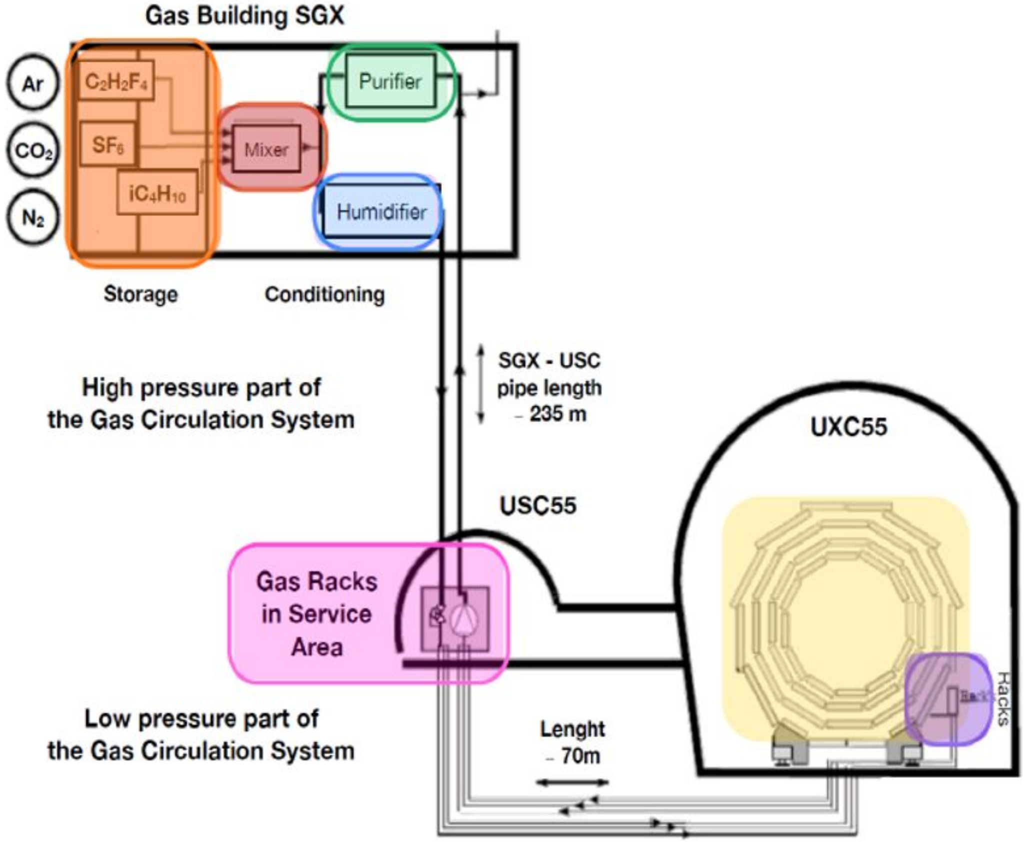
- Prototype operational since 2018
- High separation efficiency (80-90%)
- Good quality R134a recuperated
- Further tests needed to be ready for usage on experiments

Thank you for your attention

Backup

Gas Recirculation in LHC Gas System

- Supply
- Mixer
- Humidifier
- Purifier
- Pump
- Distribution
- Detector



Experimental Setup: Triple-GEM 10x10cm2 prototype

10x10 cm2 Triple-GEMs from CERN PBC Workshop

- 3 gem foils, 50µm Kapton
  (two-side 5µm Copper-clad) + 1 drift foil
- 70µm diameter holes (140µm pitch)
- Gap spacing 3-1-2-1 mm

Cleaning

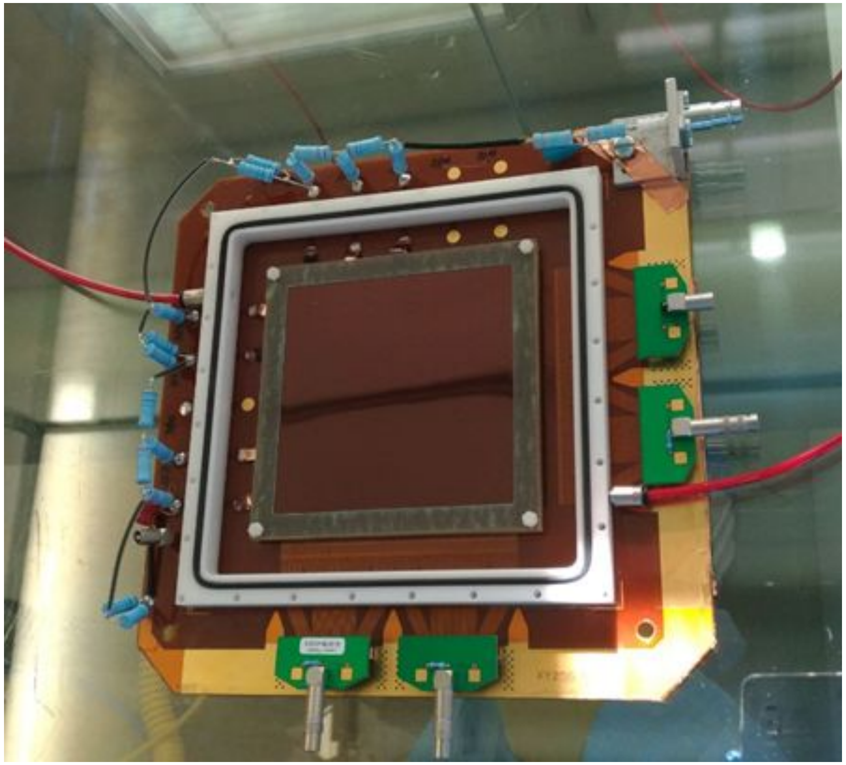
- Foils and readout board cleaned in several steps
- Baths with $KMnO_4$, H_2SO_4, Chromic acid and final rinse with deionized water

Assembly procedure

- Foils spaced with fiberglass spacers
  (EM-470 FR4 base material from EMC)
- Foils stack inside epoxy gas box frame

High Voltage Supply

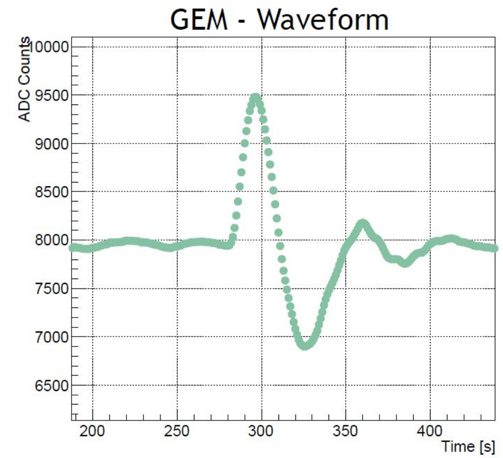
- single High Voltage line
- custom-made ceramic voltage divider
  (300 V-400 V per foil)

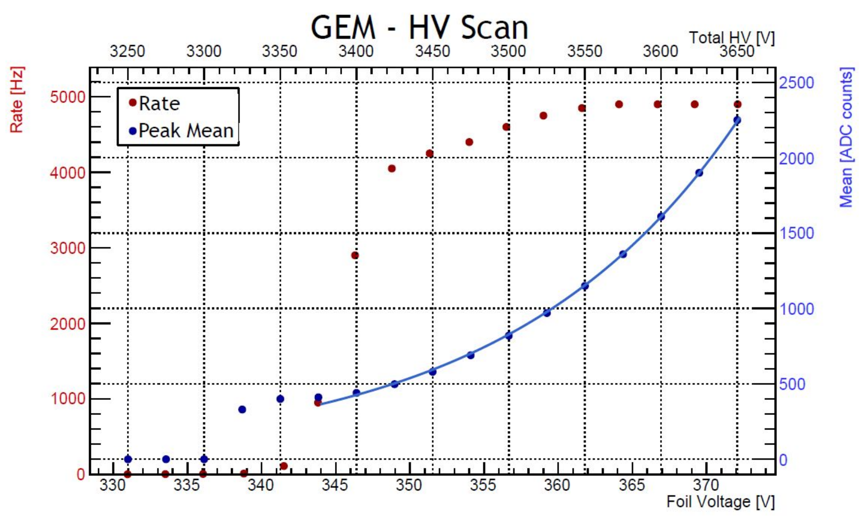


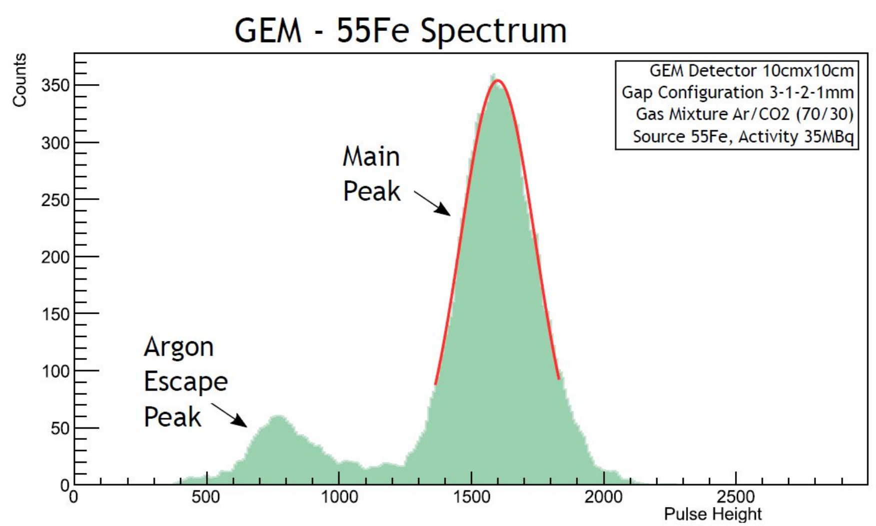
Experimental Setup: Triple-GEM 10x10cm2 prototype

Measured signal is used to obtain pulse height spectrum

- Detector current and peak mean position are proportional to the effective amplification gain
- Efficiency is tested with HV scans (Gain and Rate)
- Performance is monitored with gain prolonged acquisition



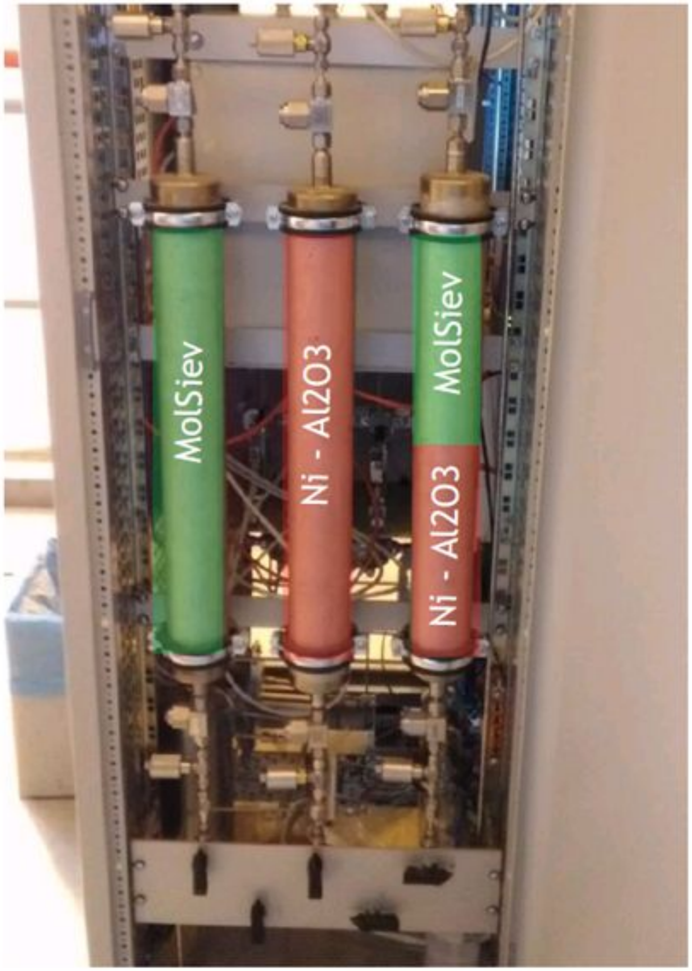




Experimental Setup: Purifier Module

2 + 1 cartridges (1 liter)

- Molecular Sieve 5Å (MS5A), used for H_2O removal (130 g(H_2O)/kg)
- Catalyst $NiAl_2O_3$, effcient in removing both H_2O and O_2 (15/50 g(H_2O/O_2)/kg)
- Mix of the two materials, allows to operate system when regeneration is needed for the other two



Standard LHC Purifier module, reproduced with smaller columns (LHC column 25 liters)

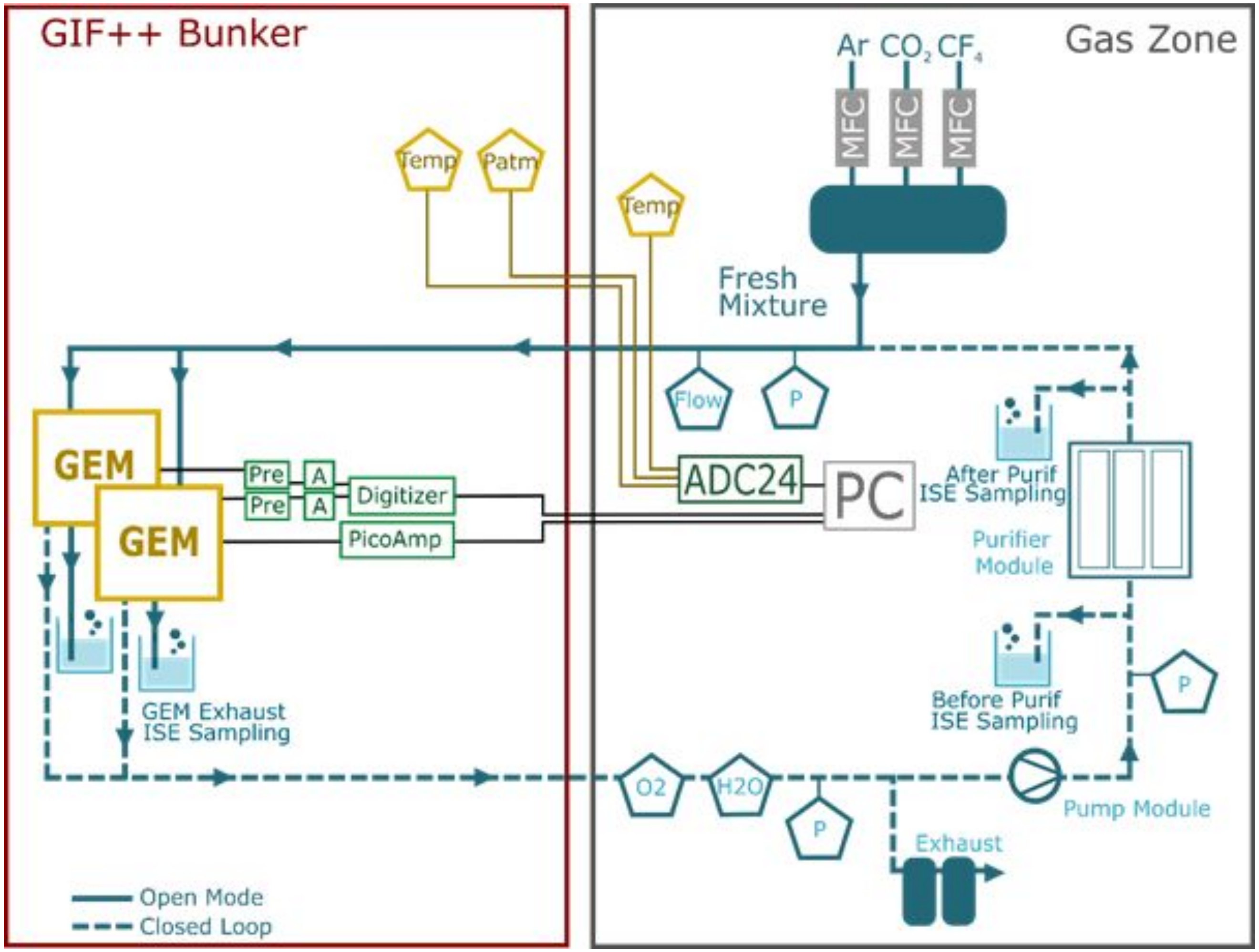
Fluoride Ion measurement: Estimation of chamber F- concentration

$$C_{GEM}^{F^-} = \frac{mg_{GEM}^{F^-}}{V_{GEM}} = \frac{mg_{exh}^{F^-}}{V_{exh}} = \frac{mg_{s}^{F^-}}{V_{exh}} = \frac{C_s^{F^-} \times V_s}{V_{exh}}$$

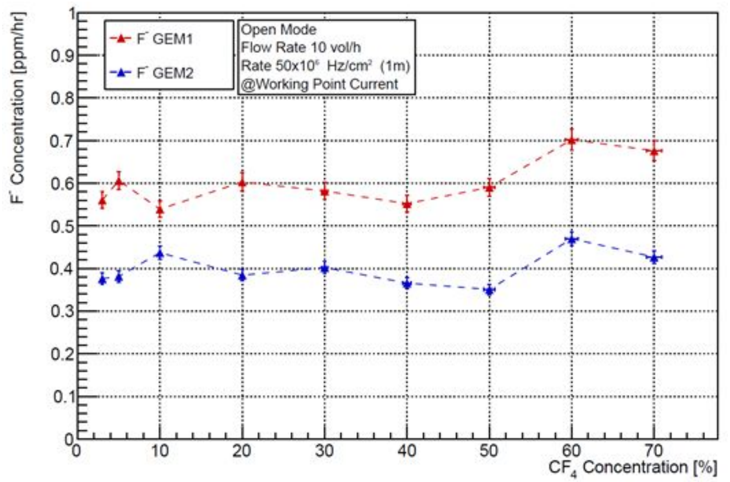
- $C^{F-}GEM$ = concentration in ppm in the Triple-GEM chamber
- mg = quantity of Fluoride ion in milligrams
- V = volume in liters
- exh = gas extracted from the sampling point
- s = sample solution
- Gas at chamber exhaust has the same F- concentration as gas in chamber volume
- Equivalence between the F- volume rate in the exhaust flow and F- volume deposited in the sample solution

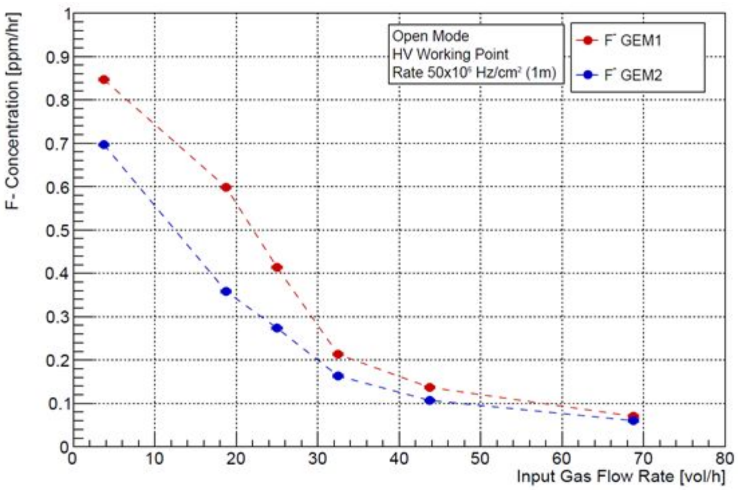
>> 1 ppm in sample solution = 0.04 ppm in chamber volume

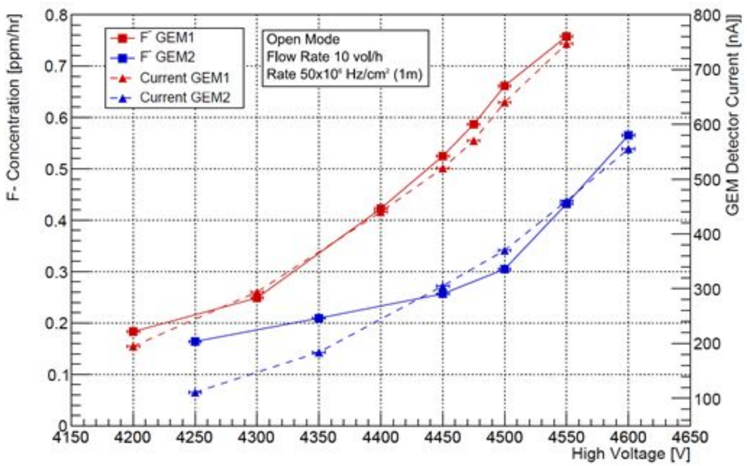
Gas Recirculation for Triple-GEMs Fluoride Impurities @GIF++

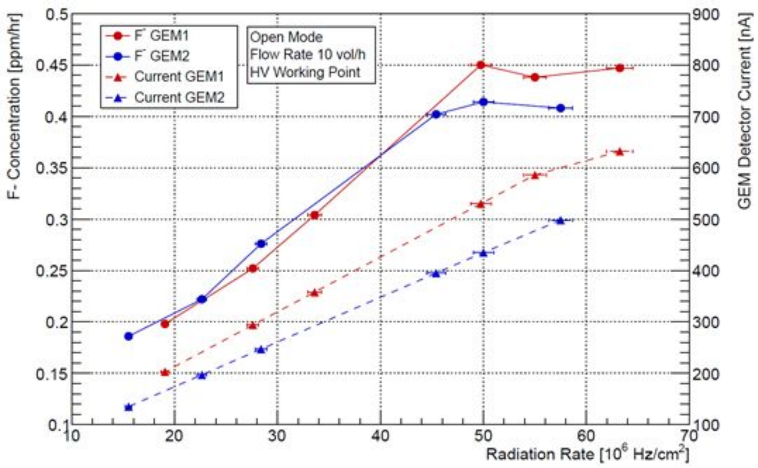


Gas Recirculation for Triple-GEMs Fluoride Impurities @GIF++





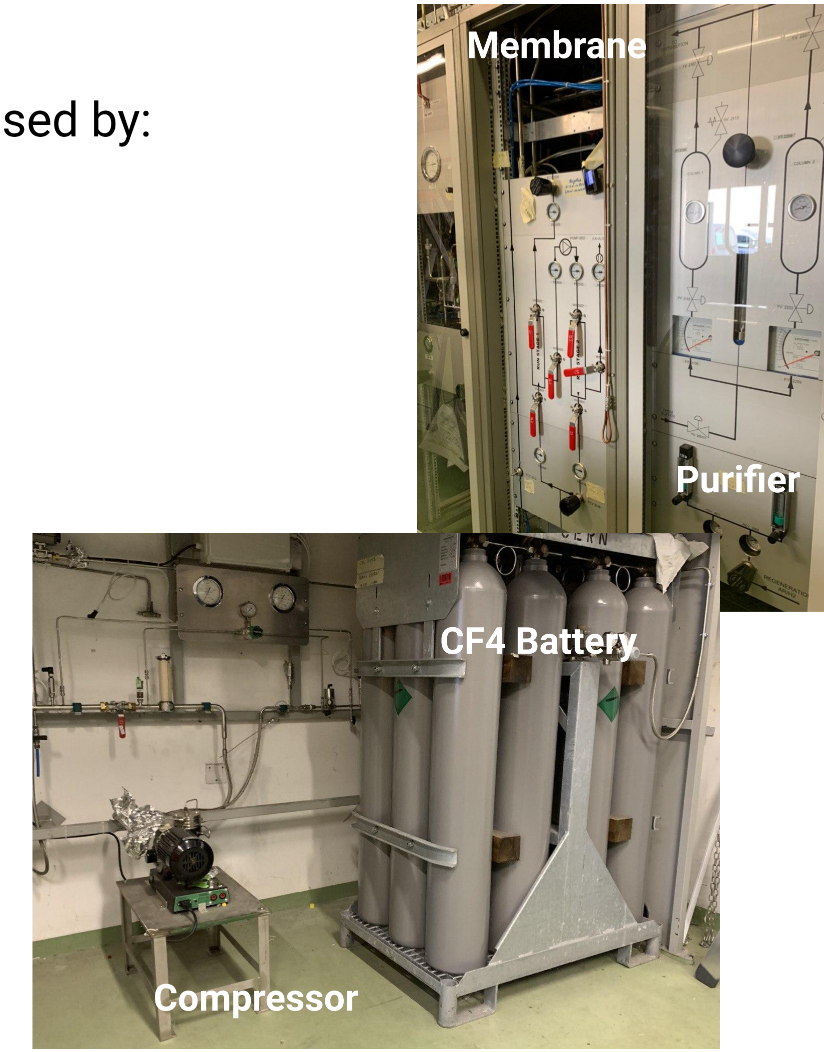




Gas Recuperation Systems - CF4 LHCb RICH2

RICH2 CF4 recuperation System is composed by:

- **Membrane Module:**
  contains membranes
  that separates CF_4 from CO_2
- **Purifier Module:**
  normally in the Loop,
  moved after the Membrane module
  to increase purification of
  CF_4 from residual CO_2
- **Recovery Module:**
  allows CF_4 storage



Gas Recuperation Systems - CF_4 LHCb RICH2

Membrane module configuration:

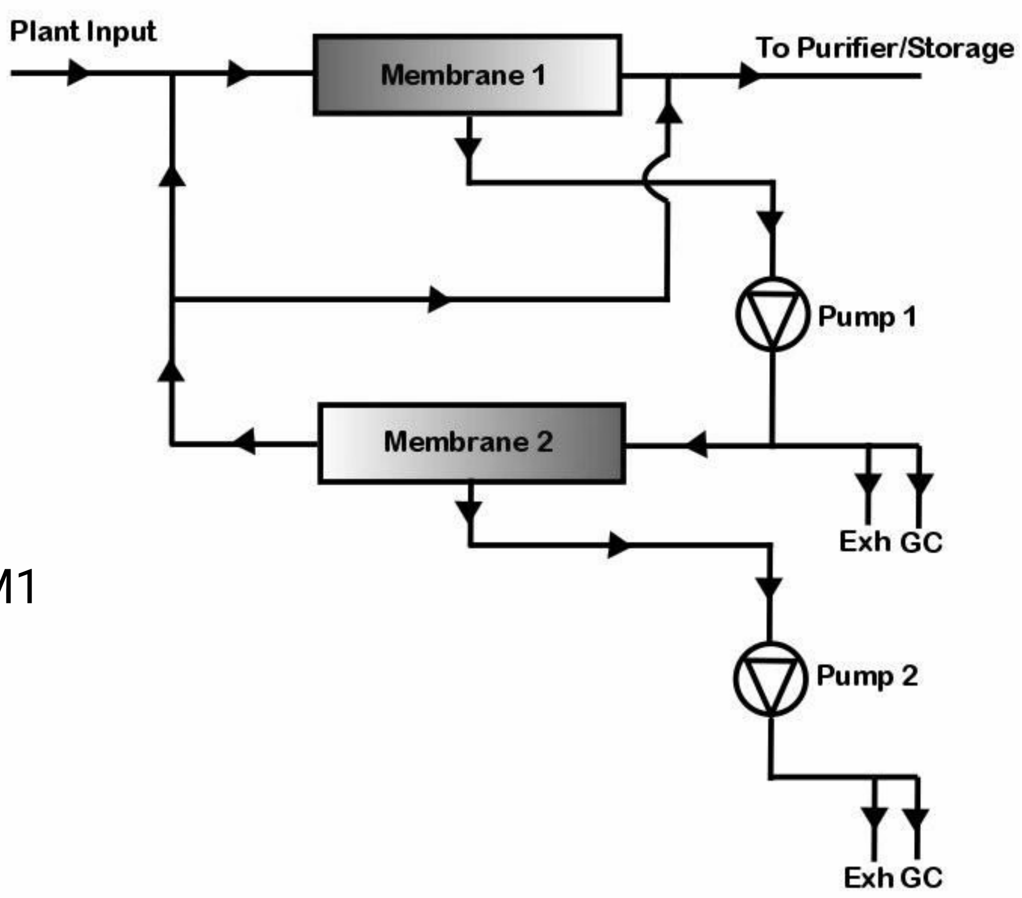
- **Single membrane**
- **Double membrane series**

  permeated of M1 as input

  of M2, output of M2 to storage
- **Double membrane loop,**

  permeated of M2 as input

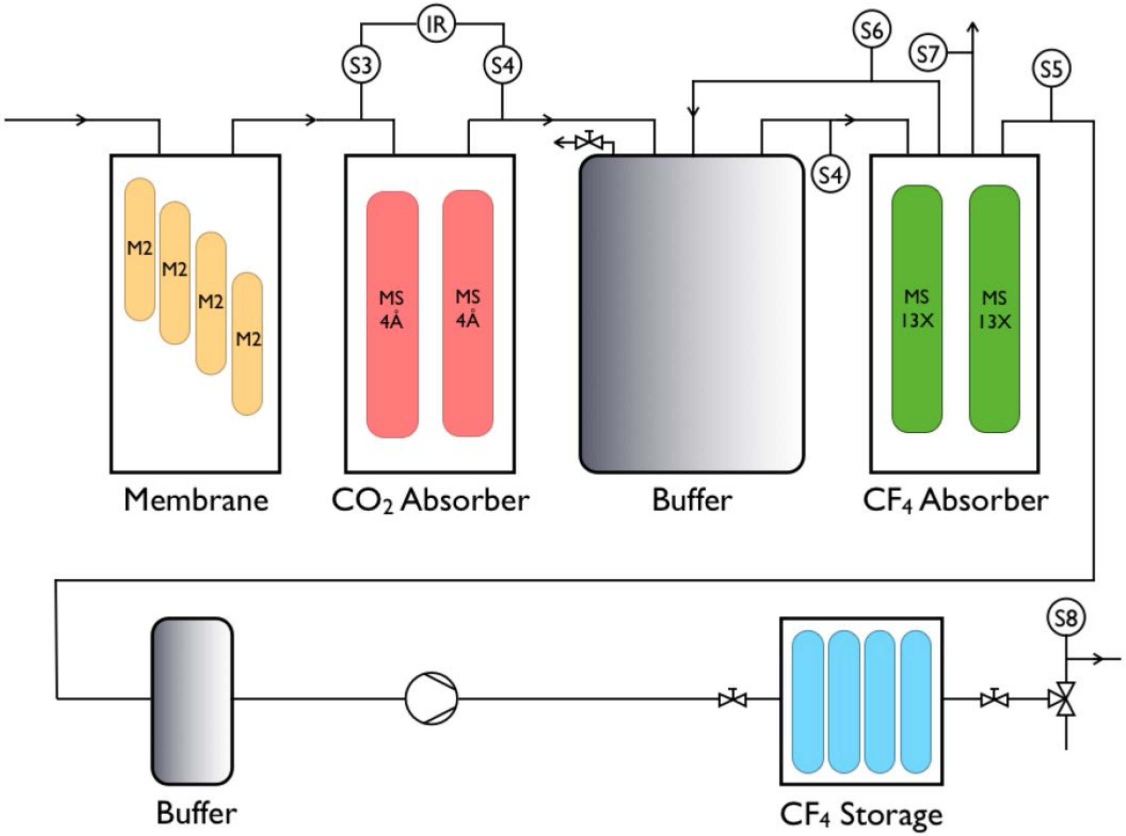
  of M2, output of M2 as input of M1



Gas Recuperation Systems - CF_4 CMS CSC

Separation System Modules:

- Input to plant
- Membrane separation module
- CO_2 adsorption module
- CF_4 adsorption module
- CF_4 compression module
- CF_4 injection module
- Infrared analysis module
- SWC monitoring module



Gas Recuperation Systems - CF_4 CMS CSC

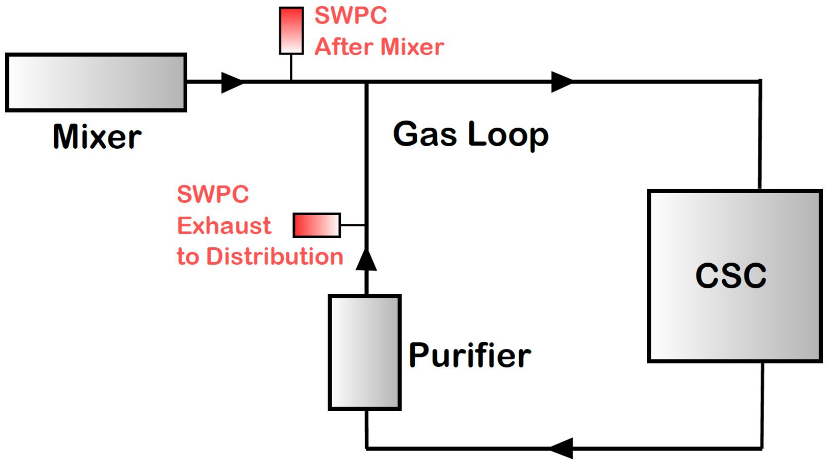
1. System control rack
2. Membrane separation rack
3. CO_2 adsorption rack
4. CF_4 adsorption rack

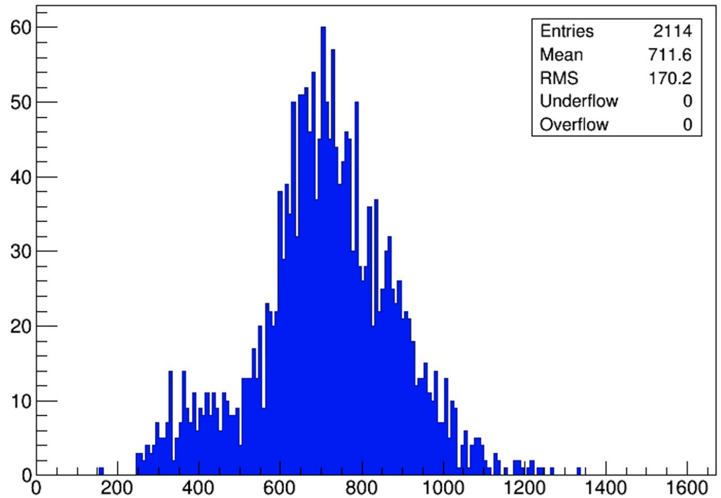
5. CF_4 compressor and storage battery

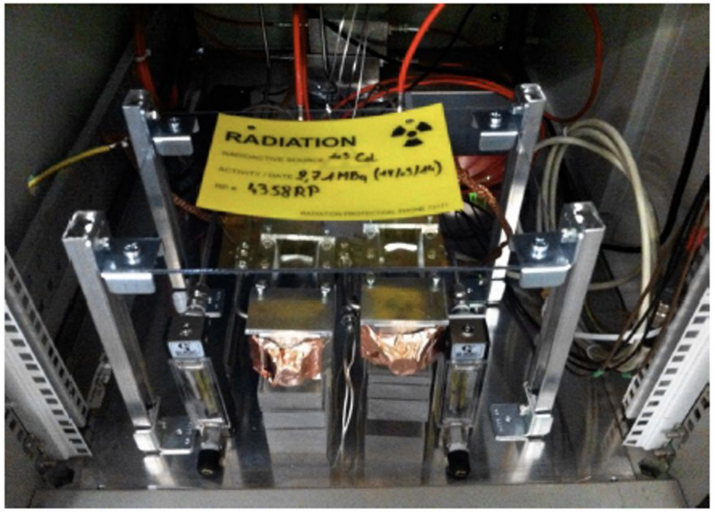
6. CF_4 injection module
7. CF_4-CO_2-Ar analysis module
8. GC analysis module
9. SWC monitoring module

Gas Recuperation Systems - CF_4 CMS CSC, SWPC Monitoring system

- Single Wire Chambers are installed
  - After Mixer
  - Exhaust to Distribution = After Purifier
- Irradiated with ^{55}Fe gamma source
  - Amplification gain monitored > peak position
  - Rate around 400 Hz







Gas Recuperation Systems - R134a Phase Diagram

Ideal binary mixture of components A and B,
with A = less volatile and B = more volatile component (TboilA > TboilB)

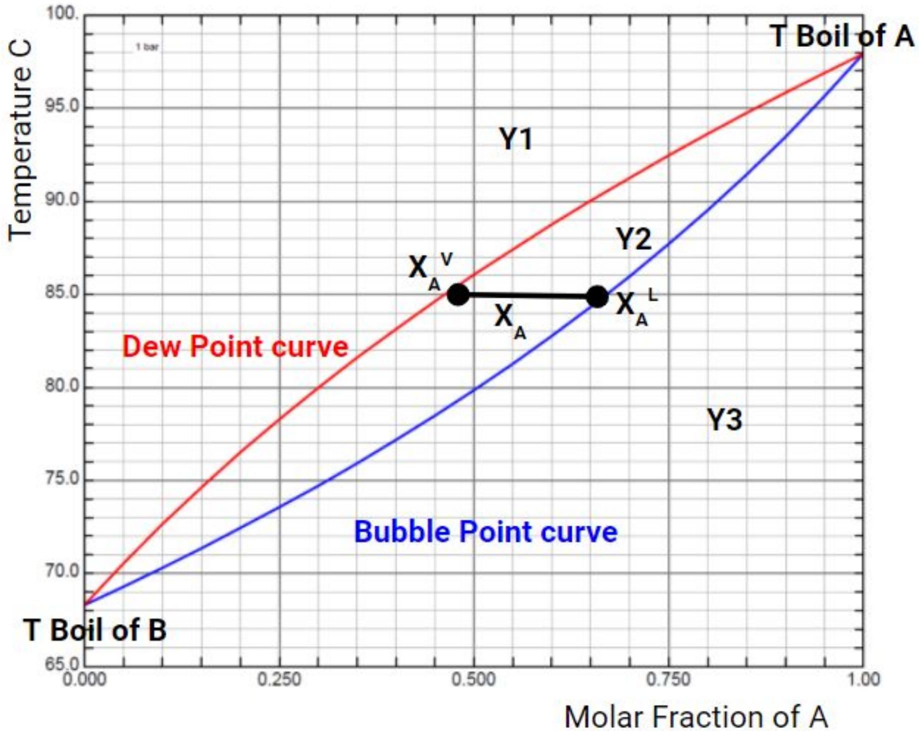
Dew Point curve = vapor phase T(x)

Bubble Point curve = liquid phase T(x)

Y1 = all mixture is liquid
for values below the curves

Y3 = all mixture is vapor
for values above the curves

Y2 = liquid-vapor equilibrium
> part of the mix is vapor with A fraction Xvapor
> part of the mix is liquid with A fraction Xliquid



Gas Recuperation Systems - R134a RPC Gas Mixture

Separation realized with slow and continuous increase in temperature
= quasi-static process, i.e. infinitesimal steps in temperature

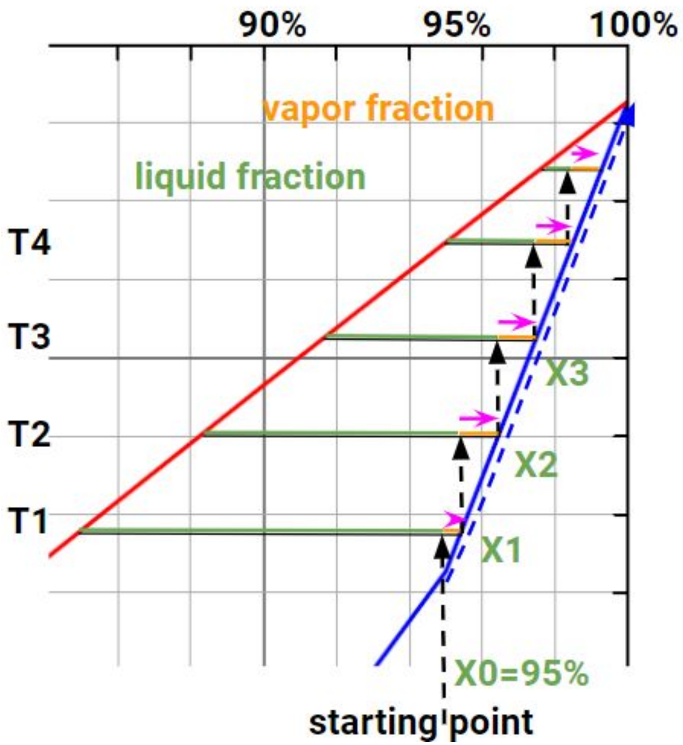
Phase diagram > finite step to see the procedure

Step to T1
vapor phase enriched in Azeo mix
liquid phase enriched in R134a (X1>X0)
exhaust vapor, move to bubble curve

Step to T2
vapor phase enriched in Azeo mix
liquid phase enriched in R134a (X2>X1)
exhaust vapor, move to bubble curve

………. so on until T=T(R134a)

Lever rule favors the liquid fraction



Gas Recuperation Systems - R134a
R134a Recuperation Plant