High-rate and fine space resolution RPCs operated with eco-gases

Lorenzo Massa
INFN & Università di Roma Tor Vergata
on behalf of Task 13.2.3 collaboration
CERN, Gangneung Wonju, Ghent, INFN-BA, INFN-BO, INFN-LNF, INFN-TO, INFN-TOV, MPI Munich, USTC

3rd AIDA-2020 annual meeting
Bologna, 24-27 April 2018
Motivations, tasks and strategy

• Almost 10000 RPCs have been installed for the experiments at LHC
  - An established standard: Gas, Material, Internal structure.

• A new challenge: a new generation of RPCs for HL-LHC and beyond, with the overall simplicity of the old standard

• Targets:
  - Rate capability $\rightarrow$ tens of kHz/cm$^2$
  - 6x packing factor for installing in narrow spaces
  - Space-time resolution up to $\rightarrow$ 0.2 ns x 100 mm
  - Ability to run with inexpensive and eco-compatible gases

• Parallel studies by ATLAS and CMS groups, both on new RPCs and new eco-compatible gases
Research of a new gas mixture

The European Community has prohibited the production and use of gas mixtures with Global Warming Power > 150 (GWP(CO2) = 1).

C2H2F4 is the main component of the present RPC gas mixture:
- GWP(C2H2F4) = 1430, GWP(SF6) = 23900, GWP(iC2H10) = 3.3
- C2H2F4 and SF6 Crucial to ensure a stable working point in avalanche

To test molecules similar to C2H2F4 but with lower GWP
- HFO=1234ze (1,3,3,3-Tetrafluoropropene) has been identified as a possible choice
- No aging test has been performed yet on HFO!

CO2-HF0 plus SF6 series  GWP=700
R&D ongoing in collaboration with RPC ATLAS group:

- HFO based gas mixture showed promising results on standard single-gap RPC: streamer probability < 2% at > 90% of efficiency, with an High Voltage working point < 12 kV.

- HFO-based mixtures (50% of HFO, 45.2% of CO₂, iso 4.5, 0.3 SF₆) tested on iRPC (mounting ATLAS FE): efficiency is consistent with standard gas mixture, with a shift in the working point of 1.3 kV.
Starting from HFO and CO₂ binary mixtures

We could not get Novec™ 5110 fluid, very promising eco-compatible substitute of SF₆, so we decide to try some interesting molecules which are available at environmental temperature and pressure in liquid state:

1) Ethylmethylketone (MEK)
2) Methyl Tert-Butyl Ether
3) Dimethyl Sulfide

- Difficult to handle with these molecules, because of high vapor pressure, leading to vapor condensation
- The HV working point is lowered, but the average total prompt charge increases for equivalent efficiency
R&D for the new ATLAS RPCs

Main challenges: higher rate capability, better aging, smaller dimensions, reliability and efficiency, eco gas compatibility

New Gas Gap
- Thinner gas gap (2 mm → 1 mm)
- Thinner electrodes (1.8 mm → 1.2 mm)
  - Lower detector weight
  - Thinner supports allowed
  - More efficient signal collection
  - Almost halve the applied HV
  - Improved charge distribution
  - Double time resolution

New FE
- SiGe BiCMOS instead of Si
- Higher rate capability
- Radiation hardness
- Better space-time resolution
- Inexpensive high performance low power FE
- All in one ASIC with amplifier, discriminator, TDC and serializer
New ATLAS Readout strips

- Cross-talk simulation studies
  - **Best Result:** with ground wire and adapted impedances
- Panels of fiberglass, with 25 mm copper strips along with their respective ground wires
- Both the strips and the ground wire are adapted from the front-end and back-end side with an impedance
- FE soldered directly on the panel

Readout strips, 25mm width, with 27.4Ohm to GND on the readout end, and 24.3Ohm on the other end

Ground wire, 1mm width, and 1mm gap between the wire and strip. The match resistor of both end is 100Ohm

Blank for FE Board

Ground

Power Line for FE Board
New ATLAS Front End board

8-channels Front-End Board composed by a new Amplifier, a full-custom ASIC Discriminator and an LVDS transmitter.

### Amplifier

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>Si BJT</td>
</tr>
<tr>
<td>Voltage Supply</td>
<td>3-5 V</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>2-4 mV/fC</td>
</tr>
<tr>
<td>Noise</td>
<td>1700 e⁻ RMS</td>
</tr>
<tr>
<td>Input impedance</td>
<td>100-50 Ohm</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10-100 MHz</td>
</tr>
<tr>
<td>Power consumption</td>
<td>10 mW/ch</td>
</tr>
<tr>
<td>Rise time input</td>
<td>300-600 ps</td>
</tr>
<tr>
<td>Radiation hardness</td>
<td>10 kGy, 10¹³ n/cm⁻²</td>
</tr>
</tbody>
</table>

### Discriminator

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>SiGe BiCMOS</td>
</tr>
<tr>
<td>Voltage Supply</td>
<td>3-3 V</td>
</tr>
<tr>
<td>Threshold</td>
<td>3-200 mV</td>
</tr>
<tr>
<td>Input impedance</td>
<td>100 Ohm</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>500 MHz</td>
</tr>
<tr>
<td>Power consumption</td>
<td>10 mW/ch</td>
</tr>
<tr>
<td>Rise time input</td>
<td>300 ps</td>
</tr>
<tr>
<td>Radiation hardness</td>
<td>10 kGy, 10¹³ n/cm⁻²</td>
</tr>
<tr>
<td>Minimum duration</td>
<td>0.5 ps</td>
</tr>
<tr>
<td>Double pulse separation</td>
<td>1 ns</td>
</tr>
</tbody>
</table>
High rate test on a multiplet

- Intermediate size RPC made by 2 mono-gaps 50x100 cm² with full X-Y readout with the new amplifier
- Gas gap 1 mm, electrodes 1.2 mm
- Beam tests in 2016-2017 at CERN GIF++
- Muon beam, plus photons from a $^{137}$Cs source
- Trigger from 2 scintillators 12x12 cm²
Electrical noise

- Electrical noise measured in terms of standard deviation of the baseline distribution.
- Analysis is done using only pure beam data.
- Standard deviation almost stable between 3.8 V and 3.9 V
Efficiency at high rate

- Use 1 chamber as monitor and calculate the efficiency of the other chamber.
- An efficient hit must be correlated in time (20 ns) and space (± 1 strip) with the monitor hit on both X-Y views.

Different values of absorption factor on a radioactive $^{137}$Cs source, simulating the photon background of HL-LHC

Working point: 5400 V (95% efficiency)

~98% efficiency in plateau region
- Hit position determined through the «center of gravity» method, using the amplitude of the signals in the strips as input
- Spatial resolution obtained dividing by a factor $\sqrt{2}$ the standard deviation of the hit position difference between the two RPC detectors
- **Spatial resolution of 1 mm** on both X-Y planes, read homogeneously by two sets of orthogonal strips
The cluster size measured on the doublet was higher than expected (5)
- delayed hits from the gap and strip plane couplings
- cluster size 1-2 can be found removing these delayed hits
- Reason: not optimized values of the graphite resistivity

A new mono-gap 50x100 cm$^2$ with different graphite resistivity (620 kΩ/□ instead of 120 kΩ/■) added in 2017 to the doublet, making a triplet
- Cluster size in the new mono-gap is 3.
- 620 kΩ/□ is the new reference value for graphite resistivity
Test with new FE

- Large size RPC made by 3 mono-gaps of size $180 \times 120$ cm$^2$
- Full X-Y readout with new FE
- Gas gap 1 mm, electrodes 1.2 mm
- Beam test in October 2017 at CERN North Area (H8)
- Muon beam
- Trigger from 2 scintillators $10 \times 10$ cm$^2$

![Graph](image)
Applying time-walk corrections

Time resolution obtained dividing by a factor $\sqrt{2}$ the standard deviation of the difference between the time measurements of two different gaps.

Best result ever with a 1 mm RPC!
CMS Improved RPC

Detector Design and specifications

<table>
<thead>
<tr>
<th></th>
<th>New RPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Pressure Laminate thickness</td>
<td>1.4 mm</td>
</tr>
<tr>
<td>Num. of Gas Gap</td>
<td>2</td>
</tr>
<tr>
<td>Gas Gap width</td>
<td>1.4 mm</td>
</tr>
<tr>
<td>Resistivity ($\Omega \text{cm}$)</td>
<td>$0.9 - 3 \times 10^{10}$</td>
</tr>
<tr>
<td>Charge threshold</td>
<td>50 fC</td>
</tr>
<tr>
<td>$\eta$ segmentation</td>
<td>2D readout</td>
</tr>
</tbody>
</table>

**New readout schema:**
one PCB with radial strips inserted between the two gaps. Coaxial cables connects the strips to the FEB. Both ends strips will be readout.
1 cm pitch strip
CMS Detector Validation (small and large scale)

- **Small** (66x36 cm²) iRPC prototypes tested in February 2017 at KODEL with cosmic muons and γ source up to ≈2kHz/cm²: at maximum background efficiency dropped 3%

- **Large** (166x92 cm²) iRPC prototypes tested in June 2017 at GIF++ with muons beam: confirmed efficiency ≈ 94% for maximum background

Intrinsic noise ≈ 0.2 Hz/cm²
Conclusions

- Combined ATLAS and CMS R&D on eco-gas is still on going
  - An aging test on HFO-mixtures is needed
- New standards for RPCs in adronic colliders
- ATLAS RPC: 3 monogaps 1 mm thick
  - ~98% efficiency in plateau region with HL-LHC photon background (600 Hz/cm²)
  - Working point: 5400 V
  - Minimum cell in the phase-space: 1 mm³ x 0.35 ns
  - Tests performed with small (50x100 cm²) and large (180x120 cm²) size prototypes
- CMS RPC: 2 monogaps 1.4 mm thick
  - 94% efficiency with maximum photon background
  - Tests performed with small (36x66 cm²) and large (92x166 cm²) size prototypes
TDC prototype

- TDC prototype in SiGe BiCMOS technology, with a time resolution of 100 ps.
- Perfect resolution to enhance the characteristics of the new thin RPCs
- Time Over Threshold measurements

TDC intrinsic jitter (ultimate precision limit)

\[ \sigma_{vco} = \frac{\sigma}{\sqrt{2}} = 10.77 \text{ ps} \]
Starting from HFO and CO2 binary mixtures

... we could not get NovecTM 5110 fluid, very promising eco-compatible substitute of SF6, so we decide to try some interesting molecules which are available at environmental temperature and pressure in liquid state:
1) Ethylmethylketone or MEK
2) Methyl tert-Butyl ether or MTBE
3) Dimethyl Sulfide
1) Ethylmethylketone or MEK

- Preferred IUPAC name: Butan-2-one
- Other names:
  - Ethyl methyl ketone
  - Methyl ethyl ketone (deprecated)
  - MEK
  - 2-Butanone
  - Methylpropanone
  - Ethylmethylketone
  - Methylacetone

**Butanone**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical formula</td>
<td>C₄H₈O</td>
</tr>
<tr>
<td>Molar mass</td>
<td>72.11 g·mol⁻¹</td>
</tr>
<tr>
<td>Appearance</td>
<td>Colorless liquid</td>
</tr>
<tr>
<td>Odor</td>
<td>mint or acetone-like</td>
</tr>
<tr>
<td>Density</td>
<td>0.8050 g/mL</td>
</tr>
<tr>
<td>Melting point</td>
<td>−86 °C (−123 °F; 187 K)</td>
</tr>
<tr>
<td>Boiling point</td>
<td>79.64 °C (175.35 °F; 352.79 K)</td>
</tr>
<tr>
<td>Solubility in water</td>
<td>27.5 g/100 mL</td>
</tr>
<tr>
<td>Vapor pressure</td>
<td>78 mmHg (20°C)</td>
</tr>
<tr>
<td>Acidity (pKₐ)</td>
<td>14.7</td>
</tr>
<tr>
<td>Magnetic susceptibility (χ)</td>
<td>-45.58·10⁻⁶ cm³/mol</td>
</tr>
<tr>
<td>Refractive index (n_D)</td>
<td>1.37880</td>
</tr>
<tr>
<td>Viscosity</td>
<td>0.43 cP</td>
</tr>
</tbody>
</table>
2) Methyl tert-Butyl ether or MTBE

**Methyl tert-butyl ether**

![Methyl tert-butyl ether](image)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical formula</td>
<td>C₆H₁₂O</td>
</tr>
<tr>
<td>Molar mass</td>
<td>88.15 g mol⁻¹</td>
</tr>
<tr>
<td>Density</td>
<td>0.7404 g cm⁻³</td>
</tr>
<tr>
<td>Melting point</td>
<td>−109 °C (−164 °F; 164 K)</td>
</tr>
<tr>
<td>Boiling point</td>
<td>55.2 °C (131.4 °F; 328.3 K)</td>
</tr>
<tr>
<td>Solubility in water</td>
<td>42 g/L (20 °C)[1]</td>
</tr>
<tr>
<td>Viscosity</td>
<td>0.36 cP at 25 °C</td>
</tr>
</tbody>
</table>

**Names**

- IUPAC name: 2-Methoxy-2-methylpropane
- Other names: Methyl tertiary-butyl ether; Methyl tert-butyl ether; MTBE; tert-Butyl methyl ether; tBME; tert-BuOMe

**Hazards**

- NFPA 704
- Flash point: −33.0 °C (−27.4 °F; 240.2 K)
3) Dimethyl Sulfide

![Dimethyl Sulfide](image)

**Names**

- Preferred IUPAC name: Dimethyl sulfide
- Other names: (Methylsulfanyl)methane, Dimethyl sulfide

**Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical formula</td>
<td>C₂H₆S</td>
</tr>
<tr>
<td>Molar mass</td>
<td>62.13 g·mol⁻¹</td>
</tr>
<tr>
<td>Appearance</td>
<td>Colourless liquid</td>
</tr>
<tr>
<td>Odor</td>
<td>Cabbage, sulfurous</td>
</tr>
<tr>
<td>Density</td>
<td>0.846 g cm⁻³</td>
</tr>
<tr>
<td>Melting point</td>
<td>−98 °C; −145 °F; 175 K</td>
</tr>
<tr>
<td>Boiling point</td>
<td>35 to 41 °C; 95 to 106 °F; 308 to 314 K</td>
</tr>
<tr>
<td>log P</td>
<td>0.977</td>
</tr>
<tr>
<td>Vapor pressure</td>
<td>53.7 kPa (at 20 °C)</td>
</tr>
<tr>
<td>Magnetic susceptibility ((\chi))</td>
<td>-44.9·10⁻⁶ cm³/mol</td>
</tr>
<tr>
<td>Refractive index ((n_D))</td>
<td>1.435</td>
</tr>
</tbody>
</table>

**Thermochemistry**

- Std enthalpy of formation (\(\Delta H_{f}^{\ominus}\)):
  - 66.9–63.9 kJ mol⁻¹
- Std enthalpy of combustion (\(\Delta H_{c}^{\ominus}\)):
  - 2.1818–2.1812 MJ mol⁻¹

**Hazards**

- Safety data sheet: osha.gov
- GHS pictograms: [image]
- GHS signal word: DANGER
- GHS precautionary statements: P210, P261, P280, P305+351+338
- Flash point: −36 °C (−33 °F; 237 K)
- Autoignition temperature: 206 °C (403 °F; 479 K)
- Explosive limits: 19.7%
Starting from HFO and CO₂ binary mixtures

We could not get Novec™ 5110 fluid, very promising eco-compatible substitute of SF6, so we decide to try some interesting molecules which are available at environmental temperature and pressure in liquid state:

- MEK is able to lower the high voltage working point, the lower the higher is its concentration, and the lower the higher is HFO percentage in the binary mixture. But the average total prompt charge increases for equivalent efficiency.
- MTBE is very difficult to handle with, because of its very high vapor pressure. Because of very high currents in the gas gap, probably due to the vapor condensation, the high voltage could not be increased to achieve higher efficiency. No significant improvement for total charge with respect to lowering the working point.
- Dimethyl Sulfide is impressive with CO₂. In increasing concentration should be better studied. But in excessive concentration it diverges the gap current.

1) Ethylmethylketone (MEK)
2) Methyl Tert-Butyl Ether
3) Dimethyl Sulfide
At high eta region ($1.9 < \eta < 2.4$), the 3\textsuperscript{rd} and 4\textsuperscript{th} CMS muon stations will be equipped with a new generation of RPC capable of handling the challenging conditions expected at the HL-LHC.

- 72 iRPC chambers
- trapezoidal shape chamber
- $20^\circ$ in \( \phi \)
**CMS 3.1 and 4.1 stations requirements**

<table>
<thead>
<tr>
<th></th>
<th>Present system</th>
<th>RE3/1-RE4/1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
<td>$ coverage</td>
</tr>
<tr>
<td>Max expected rate (SF = 3 included)</td>
<td>600 Hz/cm$^2$</td>
<td>2 kHz/cm$^2$</td>
</tr>
<tr>
<td>Max integrated charge (SF = 3 included)</td>
<td>$\sim 0.8$ C/cm$^2$</td>
<td>$\sim 1.0$ C/cm$^2$</td>
</tr>
<tr>
<td>$\phi$ resolution</td>
<td>$\sim 0.3^0$</td>
<td>$\sim 0.2^0$</td>
</tr>
<tr>
<td>$\eta$ resolution</td>
<td>$\sim 20$ cm</td>
<td>$\sim 2$ cm</td>
</tr>
</tbody>
</table>

**Simulated Background expected rates at HL-LHC in 3.1 and 4.1 stations**

![Graph showing simulated background rates at HL-LHC](image-url)