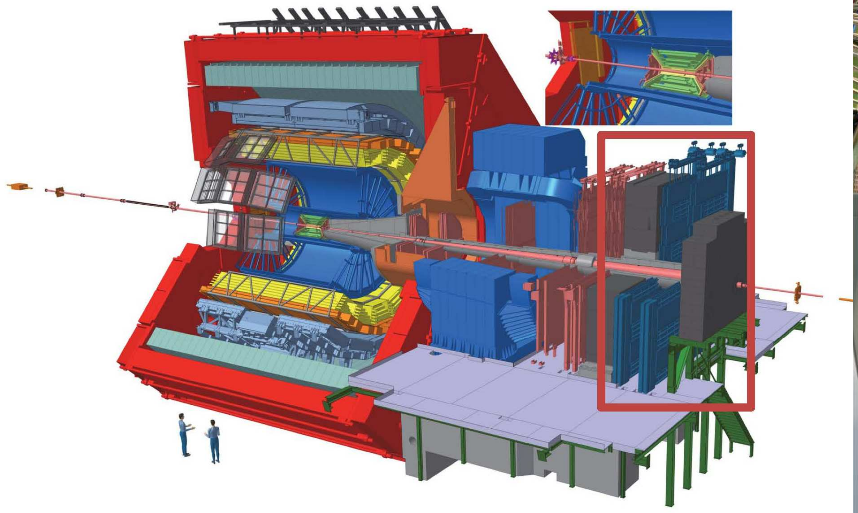
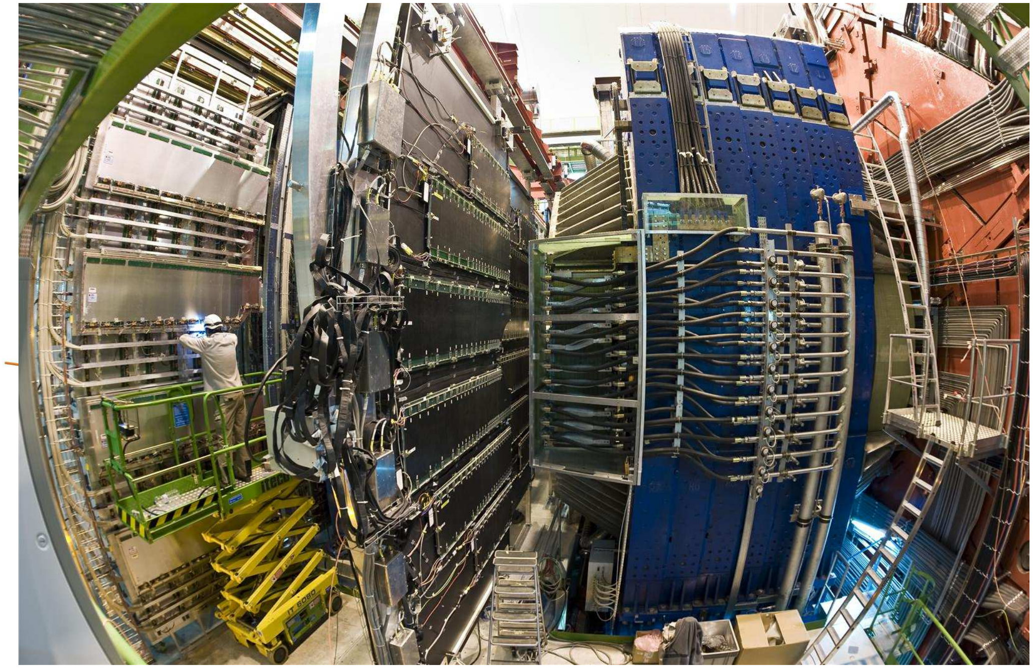
RPCs of ALICE Muon Trigger: a saga of more than 20 years





- ***The ALICE Muon Trigger at LHC***
  - 4 detection planes of 36 m^2 each
  - 72 Resistive Plate Chamber (**RPC**) detector, single-gap
  - 21k readout channels
  - Muon Identification
  - Trigger of the muon spectrometer based on muons with transverse momentum selection

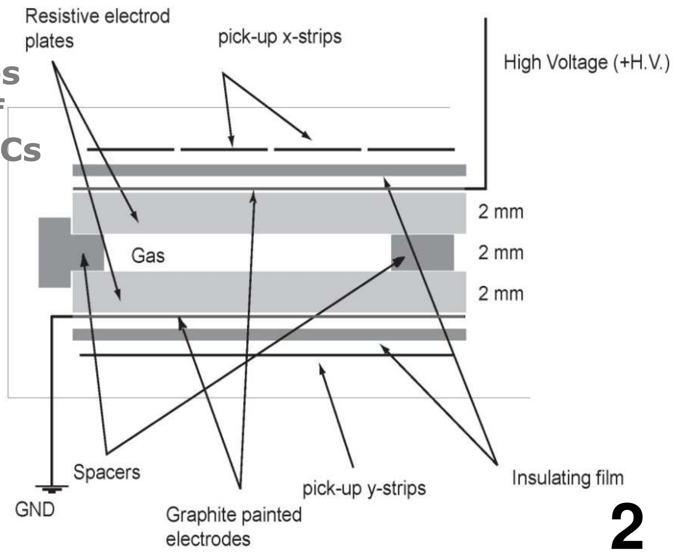
- ***Physics***
  - Quark Gluon plasma study in heavy ion (Pb-Pb) collisions at LHC
  - Via **dimuon** production from quarkonia (J/ψ, Υ) decay
  - Via single muon production from heavy flavor (D and B mesons) decay

Choice of Resistive Plate Chambers (RPC) single-gap

- Robust, *large detection area at moderate cost*
- *Integrated charge up to few hundreds of mC/cm²*
- *Operating modes*
  - Streamer => few hundred pC/hit => up to 10 Hz/cm² *("commonly")*
    - ✓ Historical mode
    - ✓ L3, Babar, ALICE-R&D
    - ✓ FE wo amplification, threshold~100mV/50Ω
  - Maxi-avalanche => ~100 pC/hit => up to 100 Hz/cm²
    - ✓ ALICE-present
    - ✓ FE wo amplification with low discrimination threshold (~10 mV/50 Ω)
  - Saturated multi-avalanche => ~30 pC/hit => few hundred Hz/cm²
    - ✓ ATLAS, CMS, ALICE-upgrade
    - ✓ FE with amplification
- *Spatial resolution of few millimeters*
- *Time resolution of 1 to few ns*

⇒ ***Well suited for ALICE Muon Trigger***

Bakelite Electrodes in case of ALICE RPCs



Initial publications (1999-2004)

- **ALICE technical design report of the dimuon forward spectrometer.**
  By ALICE Collaboration. CERN-LHCC-99-22, Aug 1999. 333pp.
- **A low-resistivity RPC for the ALICE dimuon arm.**
  Nucl.Instrum.Meth.A451:462-473,2000.
- **Influence of temperature and humidity on bakelite resistivity.**
  5th Workshop on Resistive Plate Chambers and Related Detectors (RPC 99), Bari, Italy, 28-29 Oct 1999.
  Nucl.Instrum.Meth.A456:140-142,2000.
- **The ALICE dimuon trigger: Overview and electronics prototypes*.***
  5th Workshop on Resistive Plate Chambers and Related Detectors (RPC 99), Bari, Italy, 28-29 Oct 1999.
  Nucl.Instrum.Meth.A456:126-131,2000.
- **Study of the resistive plate chambers for the ALICE dimuon arm.**
  5th Workshop on Resistive Plate Chambers and Related Detectors (RPC 99), Bari, Italy, 28-29 Oct 1999.
  Nucl.Instrum.Meth.A456:73-76,2000.
- **A dual threshold technique to improve the time resolution of resistive plate chambers in streamer mode.**
  Nucl.Instrum.Meth.A457:117-125,2001.
- **Spatial resolution of RPC in streamer mode.**
  Nucl.Instrum.Meth.A490:51-57,2002.
- **A new front-end for better performances of RPC in streamer mode.**
  6th Workshop on Resistive Plate Chambers and Related Detectors (RPC 2001), Coimbra, Portugal, 26-27 Nov 2001.
  Nucl.Instrum.Meth.A508:185-188,2003.
- **Ageing tests on the low-resistivity RPC for the ALICE dimuon arm.**
  6th Workshop on Resistive Plate Chambers and Related Detectors (RPC 2001), Coimbra, Portugal, 26-27 Nov 2001.
  Nucl.Instrum.Meth.A508:106-109,2003.
- **Aging tests and chemical analysis of Resistive Plate Chambers for the trigger of the ALICE dimuon arm.**
  7th Workshop on Resistive Plate Chambers and Related Detectors (RPC2003), Clermont-Ferrand, France, 20-22 Oct 2003.
  Nucl.Instrum.Meth.A533:112-115,2004.

Linseed oil treatment …

- ***Linseed oil must be applied on the bakelite surfaces facing the gas gap***
  - Smoothing of the bakelite inner surfaces => strong reduction of dark noise/current
  - The original idea of using linseed oil for RPCs would have come to R. Cardarelli (ATLAS) while he was observing a painter varnishing his canvas with linseed oil (!)
  - The polymerization of linseed oil at open air is quasi-spontaneous
  - Very complex mixture=> risks (aging, radiations, reproducibility, etc.)
- ***The RPCs are put in vertical position and filled with boiled linseed oil through the gas in/out, diluted with pentane or heptane***
- ***This mixture is slowly taken away, and finally the emptied gas volume is flowed with clean dry air in order to speed up the polymerization process. This process results in the deposition of a thin and solid layer of linseed oil***
- ***In case of strongly diluted mixture (30/70 oil/n-pentane)=> thin layer of linseed oil of ~3 µm. Can be repeated 2-3 times such as increasing the linseed oil layer thickness => influence RPC aging (not short term perf.)***
- ***The Babar case, summer 1999*** (summary of NIMA 515 (2003) 322-327)
  - Low linseed oil dilution 70/30 oil/n-pentane, 3 layers
  - Partial polymerization only
  - High temperature in the area of RPC operation
  - Very soon after start of RPC operation : fast “dark current” increase and drop of efficiency
  - Few RPCs opened : linseed oil “bridges” between the two bakelite electrodes (!)
  - « RPC crisis » at CERN, just before the start of the RPC productions for LHC exp. => explanations requested to experts by the CERN director …

Choice of the operating mode of the ALICE RPCs

From NIM A451:462-473,2000

* In the most RPC irradiated area. Obtained from detailed simulations (cross-checked by means of test experiments) considering the expected LHC run-1 and run-2 luminosity in ion-ion collisions

The hit rates expected in ALICE are of the order of 50 Hz/cm^2 *at most* * and this rather low value made us investigate the possibility of working in streamer mode. Therefore, we have revisited this mode of operation to enhance its rate capability.

- **The first step was the study of the gas mixture**
- **The second step was the use of electrodes made of low-resistivity bakelite**

Comment n1 in favor of the streamer mode in ALICE: the streamer mode (large signals) is less sensitive to external noise which was basically unknown at the time of the R&Ds. And the shielding of the readout system of ALICE RPCs, based on ***segmented strips***, cannot be as efficient as in ATLAS/CMS.

Comment n2: the beam gas rate in p-p was unknown at the time of the R&Ds. For this reason, it was not excluded to operate the RPCs in maxi-avalanche mode in p-p (depending on noise level of course) and in streamer mode (*lower cluster size*) in ion-ion.

Comment n3: the choice of the streamer mode for ALICE was risky since we were a small group for carrying out the R&Ds. However this choice has resulted in a quite original scientific production.

Choice of the gas mixture

- ***R&D with cosmics for a gas mixture optimized for streamer mode at high rate***
  - Tables from NIM A451:462-473,2000

- ***"Historical" gas mixtures***
  - ***L3 initial =>*** (58:38:4) argon (Ar), isobutane (i-C4H10) and freon (CF3Br)
  - ***Babar initial =>*** (48:4:48) argon, isobutane and forane (C2H2F4)
- ***Idea (~1996) in our group of adding SF6 for lowering the streamer charge***
  - SF6 used in power transformers for its properties of insulation and quenching of electric arcs
  - Re-used by our colleagues of ATLAS/CMS, with the goal of delaying the streamer formation vs. avalanche signal, in saturated avalanche mode
  - Very efficient, even at small percentage in the gas mixture

- ***The mixture n3 in the table below was chosen initially for ALICE***

Table 1
Composition of the gas mixtures

Mixture no.	Mixture composition
1	$Ar/i\text{-}C_4H_{10}/C_2H_2F_4 = 70/20/10$
2	$Ar/i\text{-}C_4H_{10}/C_2H_2F_4 = 10/7/83$
3	$Ar/i\text{-}C_4H_{10}/C_2H_2F_4/SF_6 = 49/7/40/4$
4	$Ar/i\text{-}C_4H_{10} = 80/20 + 4\%\ SF_6$

At strip level (i.e. ~x10 higher in the gas)

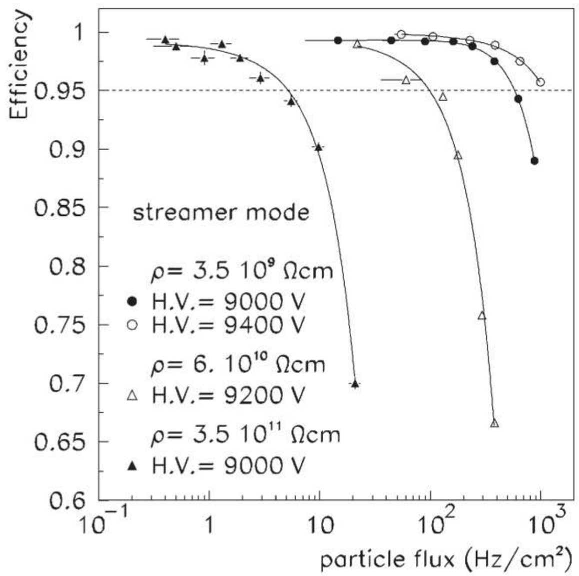
Table 2
Summary of the results for the gas mixtures

Mixture no.	H.V. (V)	Neigh. eff (%)	Charge (pC)	Ampl. (mV)
1	6700	46	330 ± 160	390 ± 170
2	10 000	15	106 ± 43	183 ± 53
3	9500	11	48 ± 25	113 ± 44
4	7300	13	70 ± 40	144 ± 51

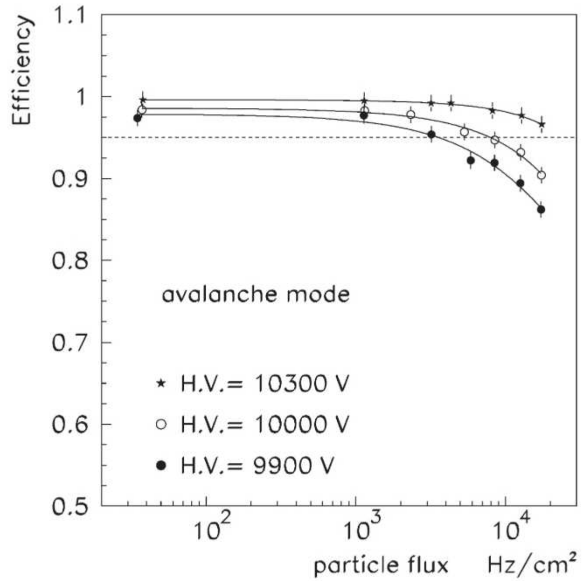
« Low » resistivity RPC

From NIM A451:462-473,2000

- ***RPC 50x50 cm^2, phenolic bakelite 3.5 10^9 Ω.cm (10^{10}-10^{12} Ω.cm for "common" bakelite)***
- ***CERN/SPS/H6 pion beam of 120 GeV/c (beam spot of few cm^2 on the RPC)***
- ***Gas mixture***
  - ***(49:7:40:4) Ar/i-C4H10/C2H2F4/SF6 in streamer***
  - ***(3:95:2) i-C4H10/C2H2F4/SF6 in avalanche***
- ***Comparison of the limitation of the detection efficiency vs. (local) particle flux***
  - Streamer vs. avalanche
  - vs. RPC resistivity

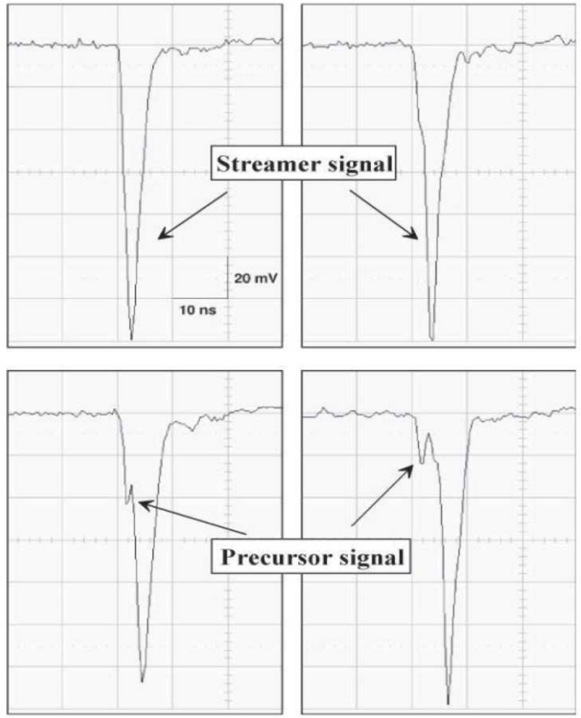


This limitation is due to the large charge released in the streamer, that causes a local reduction of the voltage between the electrodes. Since RPC are made of high-resistivity material (typically 10^{10}-10^{12} Ω.cm), tens or hundreds of milliseconds are necessary to restore *(locally)* the operating voltage. Therefore, during this time, the detector is blind in the area where the streamer developed.

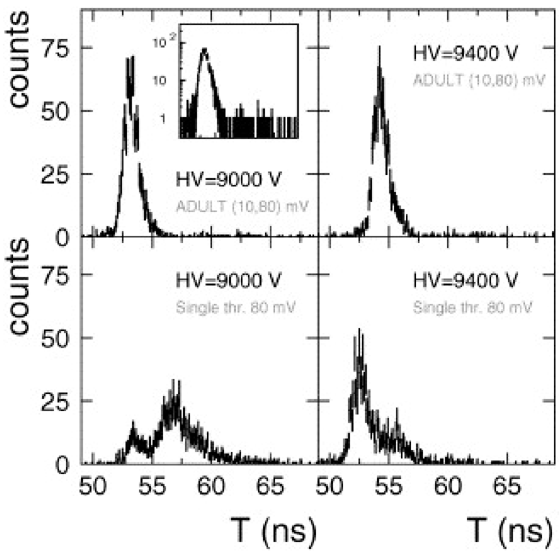


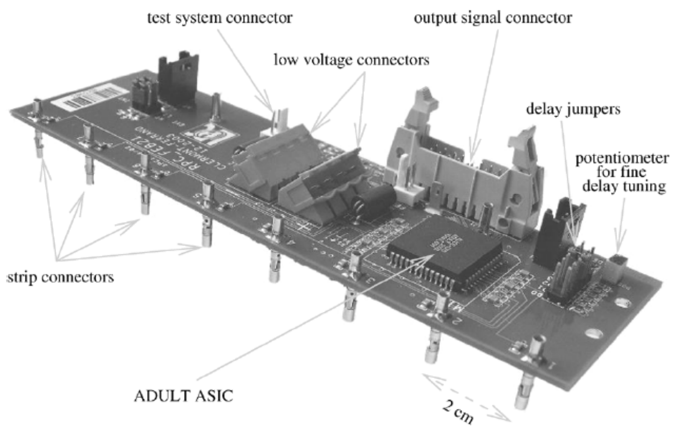
Optimisation of the time resolution in streamer mode: ADULT

- ***RPC signals with two components***
  - Avalanche (or « pre-cursor »)
  - Followed by streamer (or not !)
  - Avalanche ~synchronous with particle crossing the RPC
  - Streamer => up to few ns after the avalanche
- ***FE electronics ADULT for the streamer mode***
  - ADULT : A DUaL Threshold discriminator
  - Time reference on the low threshold (pre-cursor)
  - Signal validation on the high threshold (streamer)
- ***Time resolution in streamer mode with ADULT***
  - ***Similar to avalanche mode (~1 ns)***



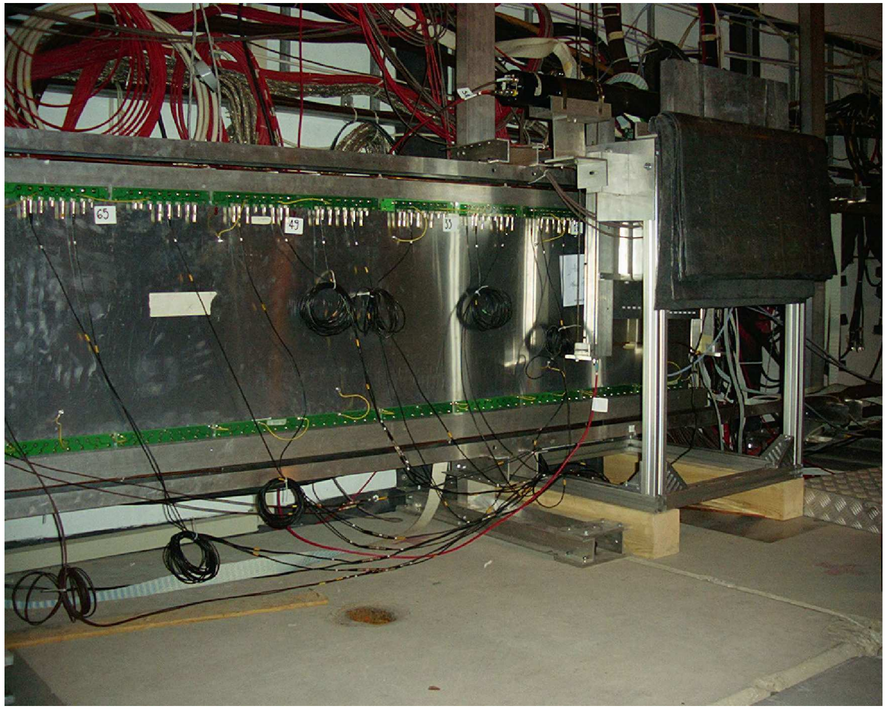
RPC signals
(gas mixture with SF6)
(from NIM A457 (2001) 117-125)





The ageing test era

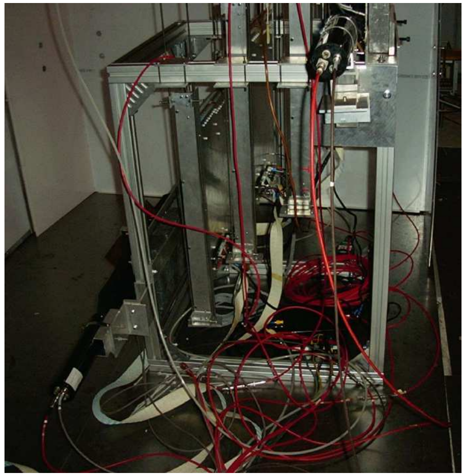
- *Ageing tests at the CERN/GIF (Gamma Irradiation Facility, Cesium source) from 2001-2003 with small (50x50 cm²) size RPCs*
- *Permanent monitoring of efficiency, current (dark current), rate (dark rate) with GIF on (off)*
- *Very first size-1 (270x65 cm²) RPC tests in 2002*



Aging tests @ 50-150 Hz/cm²
(hit rate from Compton effect mostly)

Time unit = LHCperiod
- **~ 1 month Pb-Pb** ***in most exposed RPC area***
- ***~1 GIF_day at 50 Hz/cm²***
- ***~ 2.2 mC/cm² (in streamer mode)***

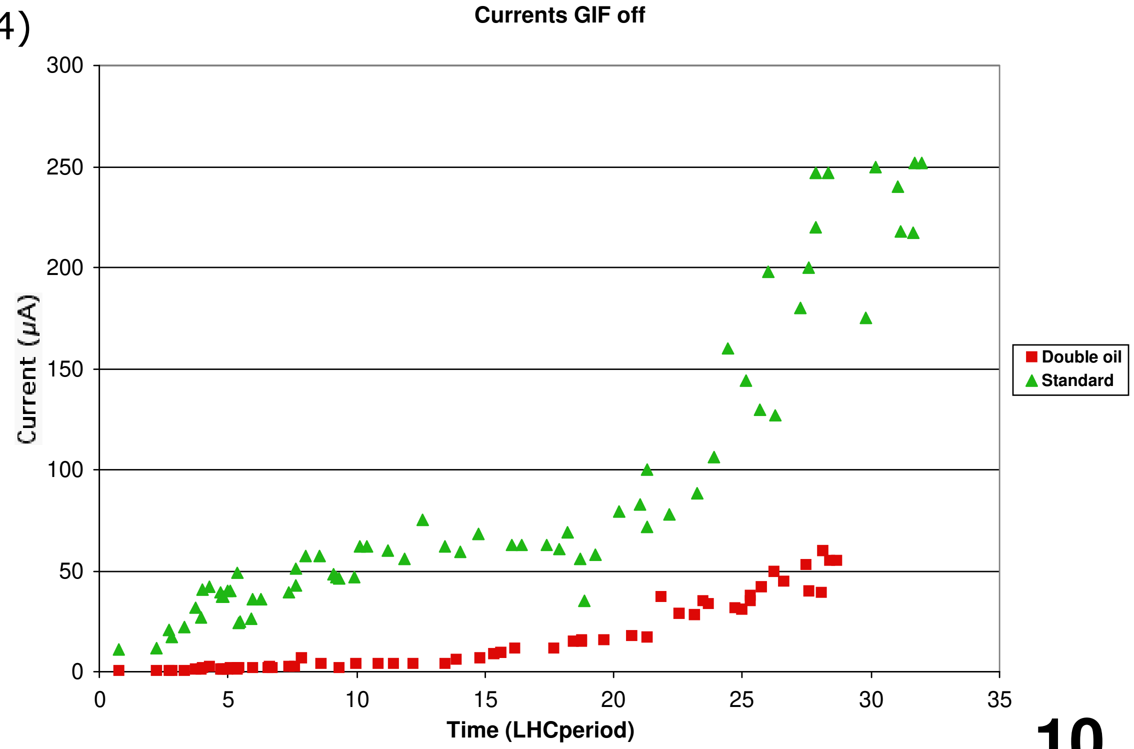
25 LHCperiod
- ***~ Run1+2 HI program in ALICE***
- ***~100 Mhits/cm² (~50 mC/cm² in streamer mode)***



Double oil vs. single oil layer

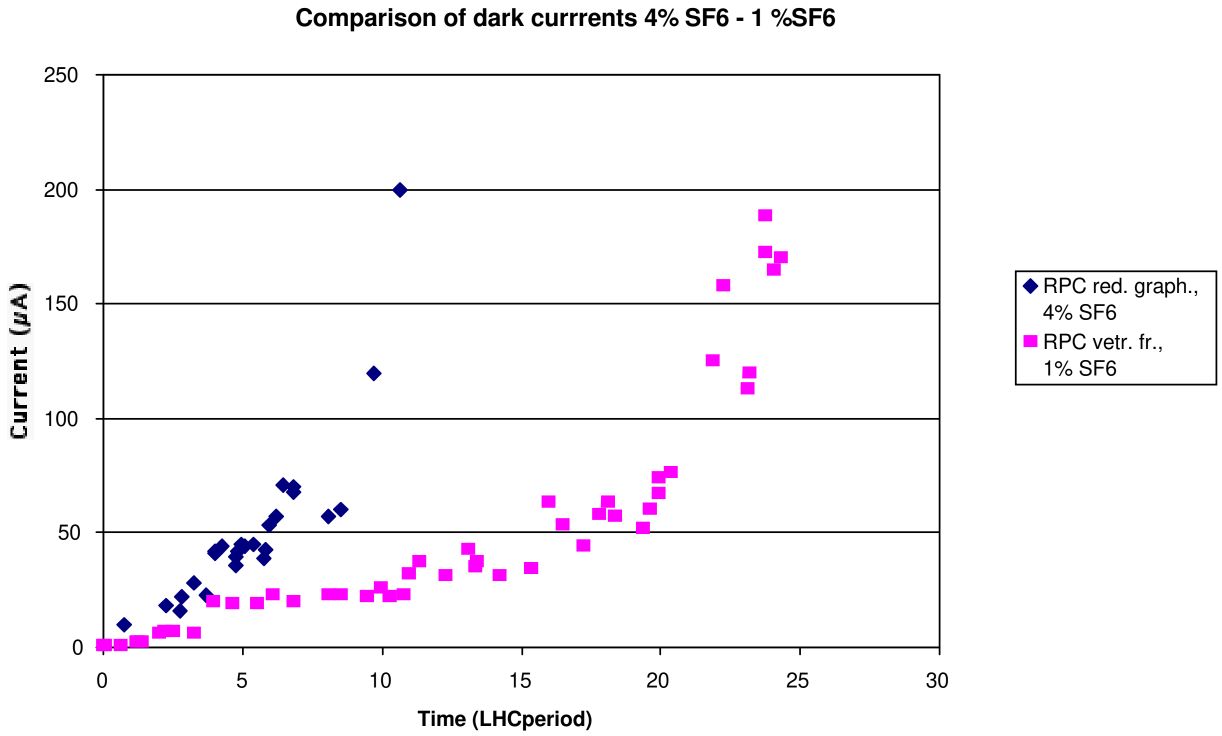
- ***After ~30 LHCperiods, RPCs with 2 linseed oil layers show lower dark current (GIF off) as compared to RPCs with one single layer***
  (same trend measured with GIF source ON)
  - One damaged RPC with single oil layer was opened
  - Electrode surfaces were quite deteriorated and chemical analysis shows that they are contaminated by Fluorine *(**HF acids**, tens of µg per liter of gas as measured by exhaust gases analyzed with gas chromatography and potentiometry* in samples taken when the chambers operate under GIF irradiation*)*. According to this idea, the double oil coating holds out better against deterioration.
    (from NIM A533:112-115,2004)

- ***Tests with a 3rd oil layer have not shown very significant improvements***



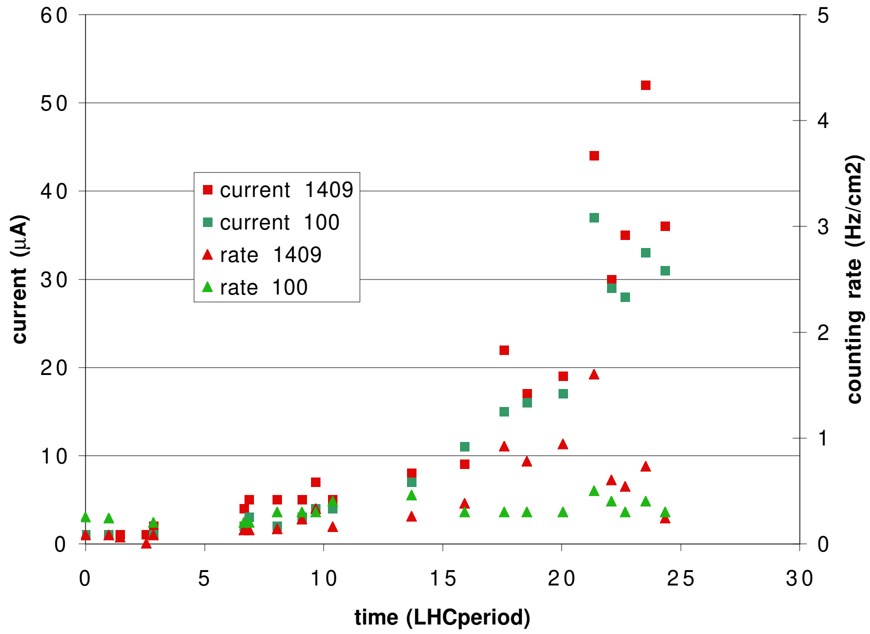
Gas mixture with 1% vs. 4% SF6

- ***Gas mixtures***
  - ***(49:7:40:4) vs. (50.5:7.2:41.3:1) Ar/i-C4H10/C2H2F4/SF6***
- ***Dark current increases more slowly in the RPC flowed with less SF6***
- ***Moreover, the operating voltage is shifted to lower value from ~1 kV***
  (tentative explanation) leading to smaller probability to produce polluting molecules in the interaction of electrons produced in the streamer with gas molecules (from NIM A533:112-115,2004)



Dry vs. wet gas mixture

- ***Wet mixture to keep bakelite resistivity constant***
  - A lab test with wet/dry gas mixture demonstrated that flowing RPCs with dry mixture causes an increase in the bakelite resistivity, i.e. reduces rate capability
  - Confirmed by climatic chamber measurements (showing also strong temperature dependence)
    see e.g. NIM A456:140-142,2000
    and ieeexplore.ieee.org/document/1462249
  - Also RPC mechanical stability is better under wet gas mixture flow



- ***The gas is fluxed through a bubbler filled with water at 10°C; in this way about 1% of water vapor (RH~50%) is added to the gas mixture***
- ***RPC-1409 flowed with dry while RPC-100 flowed with wet gas mixture***
  - Both RPCs with 2 linseed oil layers
- ***No significant difference in dark rate/current after ~25 LHCperiods***

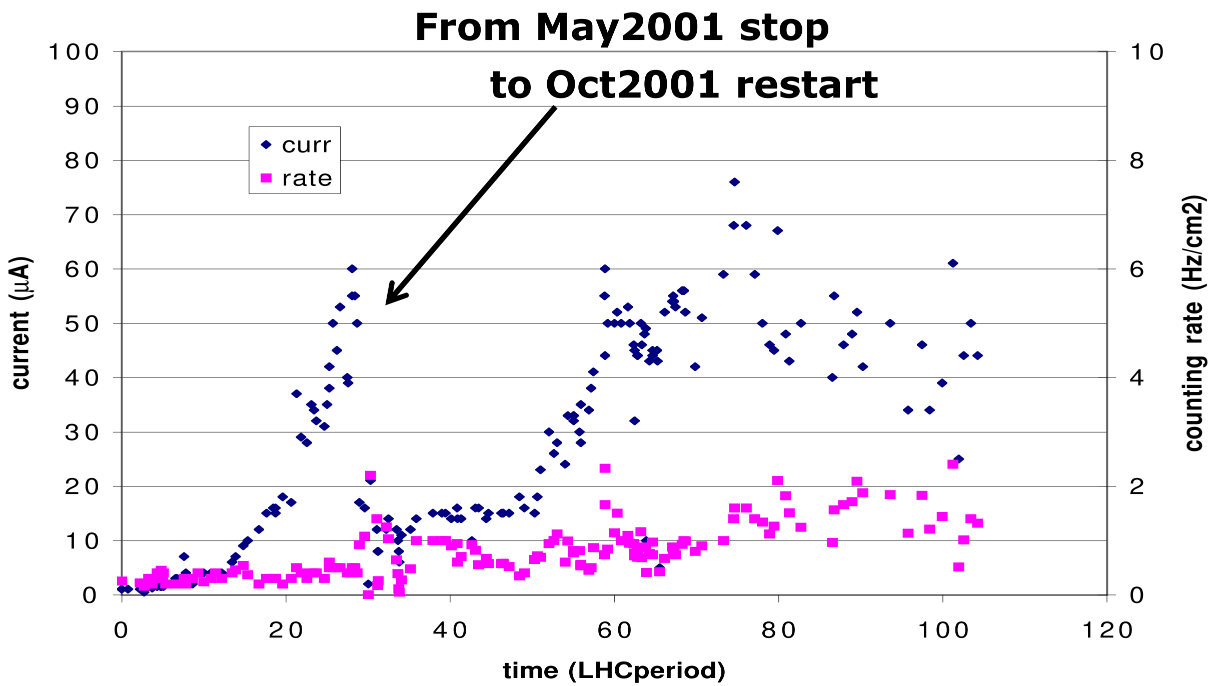
Conclusion on ageing test in streamer mode

- ***~100LHCperiods (~200 mC/cm²) accumulated with RPC-1409 with 2 layers of linseed oil (flowed with dry gas mixture with 1% SF6)***
- ***Good efficiency up to the end of the test periods but quite high dark current/rate***
- ***For RPCs with 2 layers of linseed oil flowed with wet gas mixture, the test stopped after ~50 mC/cm²***

Not discussed here

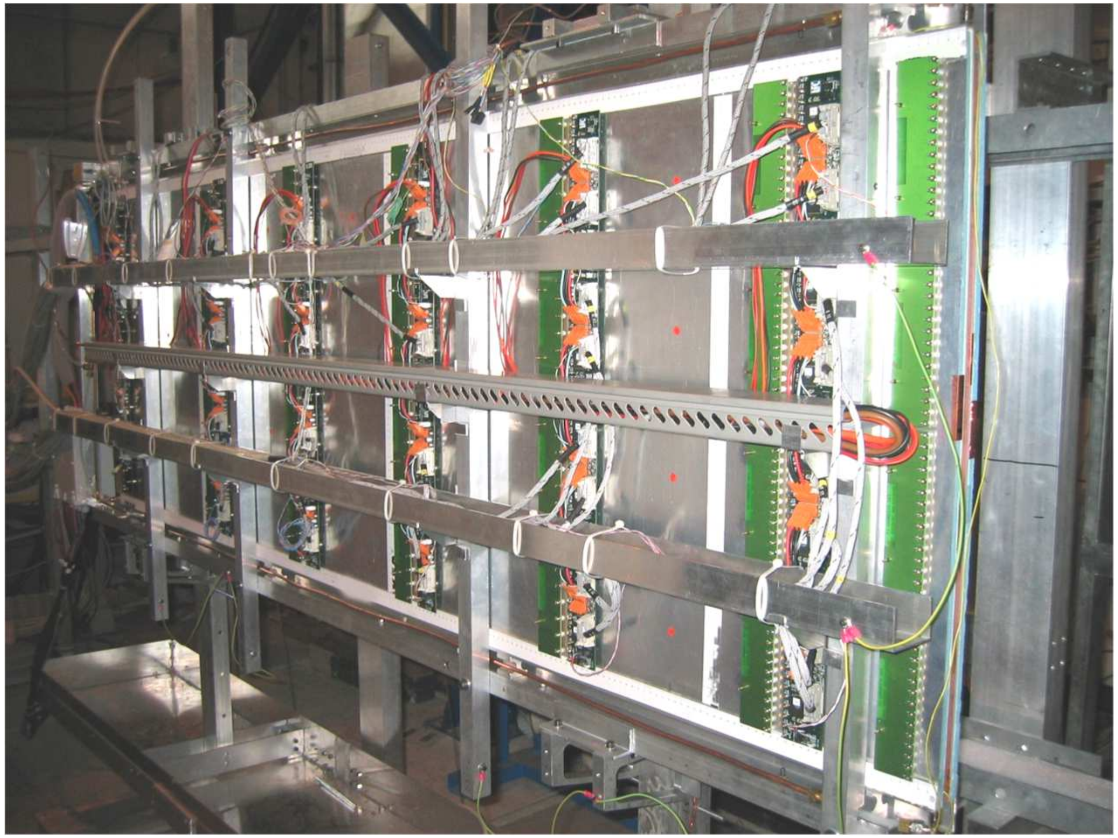
- ***Gas flow***
- ***Gas pipe material***
- ***Spacer material***
- ***Gas in/out material***
- ***Mechanical frame***
- ***T/P effects***
- ***etc***

=>All "details" are of importance for long duration tests !



Size-1 RPC tests in streamer and avalanche mode (2002-2003)

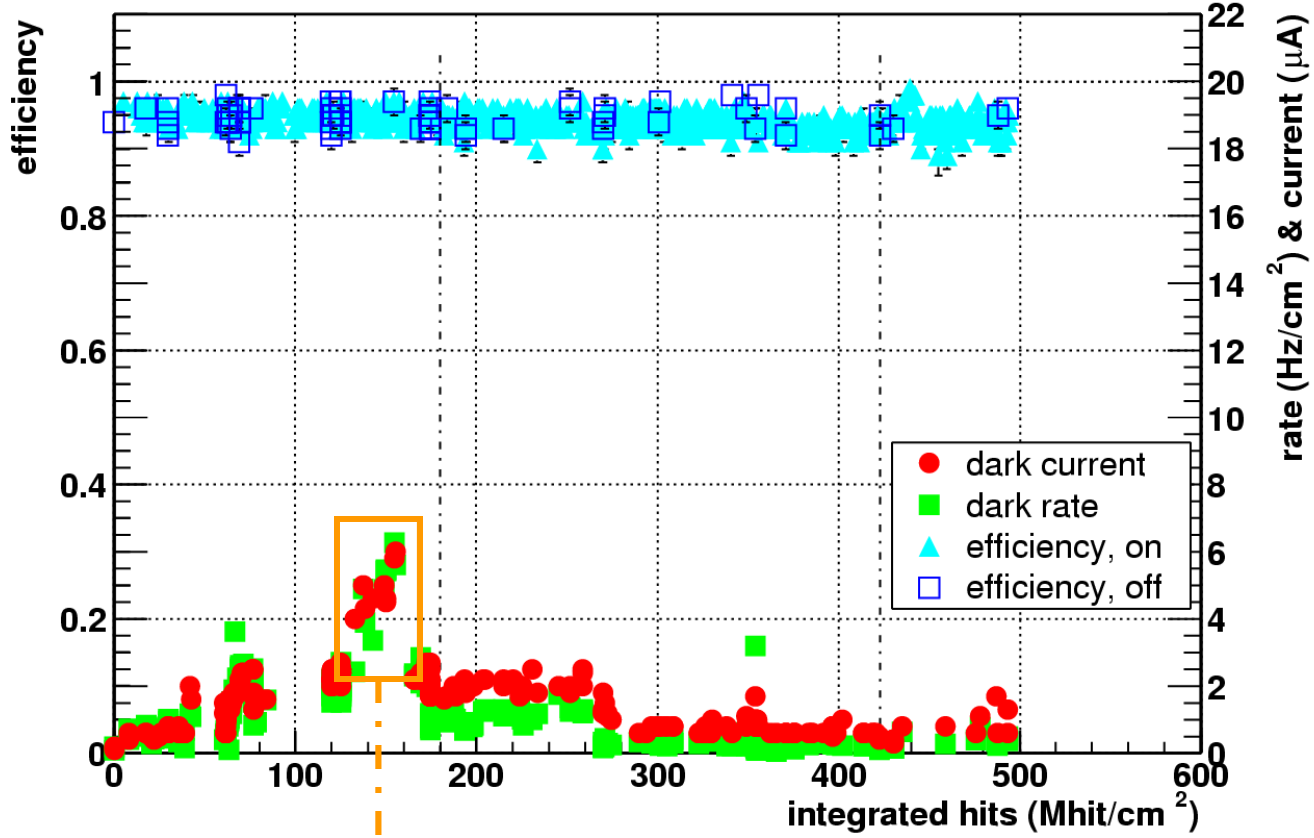
- ***First partial test of efficiency and rate capability (April 2002-GIF only)***
  - Chamber behaves "normally" up to ~70 Hz/cm2
- ***Complete test of efficiency and rate capability extended to the whole surface of the chamber in Aug.2002 (GIF+SPS-beam)***
  - We do not observe unexpected problems, apart from rate capability disuniformity in a reduced region of the chamber at high rate (~160 Hz/cm2)
- ***Size-1 RPC with ADULT FEE in Sept. 2003 (GIF+SPS-beam, this picture)***



Aging tests in maxi-avalanche mode (2004-2005)

- ***Developed for ALICE <u>p-p</u> program***
  - 100 Mhits/year expected (in most exposed area)
  - Background from beam-gas quite unknown
- ***With same FE electronics as in streamer mode (no amplif.), thresh ~10mV***
- ***With 2 new RPCs of 50x50 cm²***
- ***Gas mixture (RH=50%)***
  - Initial $C_2H_2F_4$(88%) + C_4H_{10}(10%) + SF_6(2%) => some discharges
  - **Replaced by $C_2H_2F_4$(89,7%) + C_4H_{10}(10%) + SF_6(0.3%) => HV -1kV**
- **Results**
  - **500 Mhit/cm² accumulated => 100 mC/cm² (in maxi-avalanche)**
  - Good time resolution (< 1 ns r.m.s.)
  - Worse cluster size quality as comp. to streamer mode (esp. with 1cm wide strips) but acceptable for p-p
  - Dark current <1 μA, dark single rate <0.1 Hz/cm² (after irradiation)
  - Current drawn under irrad. ~1/3 current drawn in streamer mode
  - Very encouraging aging indications from exhaust gas analysis, drastic diminution of HF content as compared to streamer mode

Aging tests in maxi-avalanche mode (2004-2005)



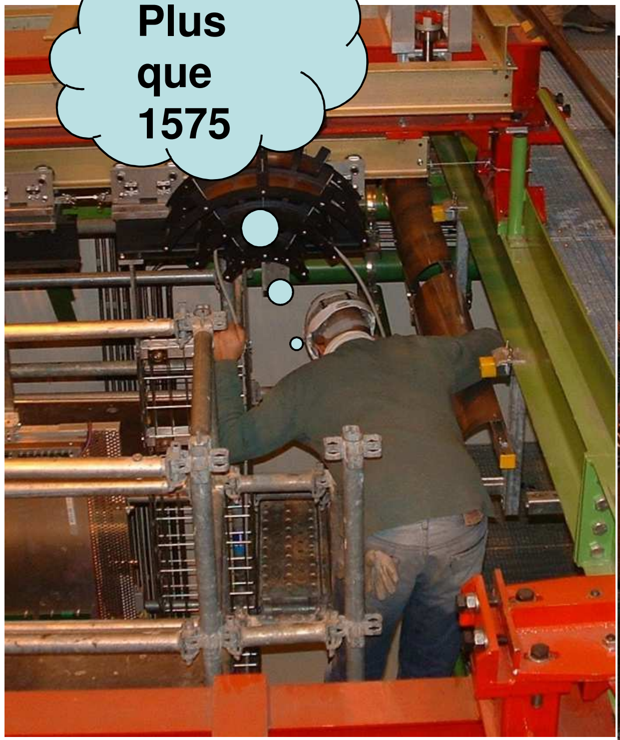
problem with the refrigerator used to add water in the gas mixture due to power cut

Pascal Dupieux, IN2P3/CNRS, DetGaz2018, 8/10/2018

Production phase (2002-2006)

Start of installation (March 2006)

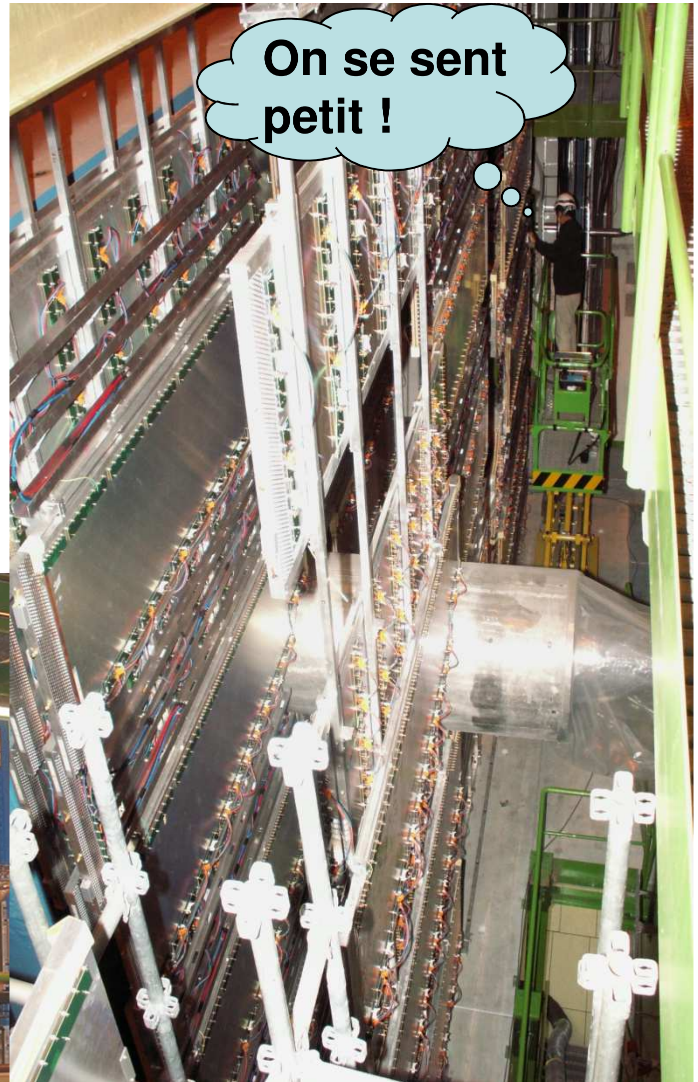
Later in 2006



Plus que 1575

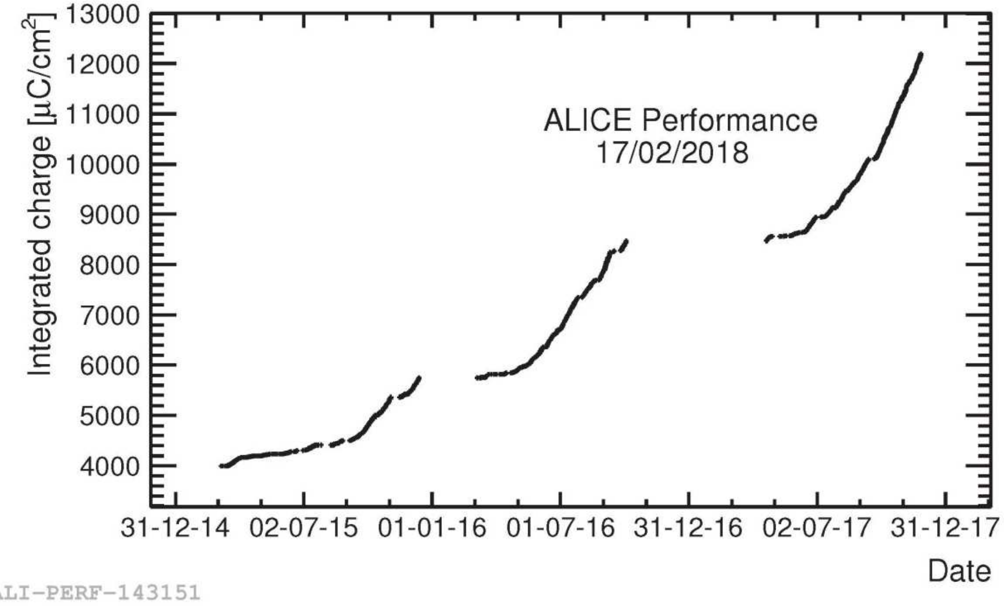
En voilà une petite moitié de faite !!

Later in 2007



Present status (in short…)

- ***Finally, ALICE RPCs have been always operated in maxi-avalanche mode during LHC run1-2, both for p-p and HI program !!***
  - ***with gas mixture*** $C_2H_2F_4$(89,7%) + C_4H_{10}(10%) + SF_6(0.3%)
  - ADULT Threshold 7 mV/50 Ω, charge ~ 100 pC/hit



Accumulated charge (end 2017)

- **Average ~12mC/cm2**
- **Up to ~30mC/cm2 for the most exposed RPCs)**
  => ~300 Mhit/cm²
  => compatible with design value
- **All RPCs still operational after such irradiation, some of them drawing quite high current**

- ***Upgrade program for LHC run3-4 (installation in 2019-2020)***
  - ***FEERIC project (presented in the Nantes session of this workshop)***
  - ***Saturated avalanche mode (i.e. FE with amplification) like ATLAS/CMS, closed loop gas distribution***
  - **Charge ~ 30 pC/hit**
  - ***Gas mixture R&D ongoing in direction of greenhouse, not flammable gases***

SPARES

List of main test beams

- *CERN/SPS/H6 (May 1998):* **low resistivity RPC performance in streamer and avalanche mode with few RPCs 50x50 cm^2**
- **GIF (spring+fall 2001, spring 2002): aging in streamer mode with few RPCs 50x50 cm^2 + first test with size-1 RPC**
- **GIF+SPS muon beam (June 2002): Mini-TRIGGER experiment**
- **GIF+SPS muon beam (Aug. 2002): second test with size-1 RPC in streamer mode**
- **GIF+SPS muon beam (Sept 2003): performance in streamer and maxi-avalanche mode with ADULT FEE with a size-1 RPC**
- **GIF (Feb.-Oct. 2005): aging in avalanche mode with 2 RPCs 50x50 cm^2**

Phenolic Bakelite

From wikipedia

Phenolic sheet

Another market for Bakelite resin was the creation of phenolic sheet materials. Phenolic sheet is a hard, dense material made by applying heat and pressure to layers of paper or glass cloth impregnated with synthetic resin. Paper, cotton fabrics, synthetic fabrics, glass fabrics and unwoven fabrics are all possible materials used in lamination. When heat and pressure are applied, polymerization transforms the layers into thermosetting industrial laminated plastic.

Unit for bakelite plate resistivity

From wikipedia

Sheet resistance is a special case of resistivity for a uniform sheet thickness. Commonly, resistivity (also known as bulk resistance, specific electrical resistance, or volume resistivity) is in units of Ω·m, which is more completely stated in units of Ω·m2/m (Ω·area/length). When divided by the sheet thickness (m), the units are Ω·m·(m/m)/m = Ω. The term "(m/m)" cancels, but represents a special "square" situation yielding an answer in ohms. An alternative, common unit is "ohms per square" (or " Ω / "), which is dimensionally equal to ohm, but is exclusively used for sheet resistance. This is an advantage, because sheet resistance of 1 Ω could be taken out of context and misinterpreted as bulk resistance of 1 Ω, whereas sheet resistance of 1 Ω/ cannot thus be misinterpreted.

The reason for the name "ohms per square" is that a square sheet with sheet resistance 10 Ω / has an actual resistance of 10 Ω, regardless of the size of the square.