Advanced studies on RPCs

Doctorate Thesis in Physics

by

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Introduction - Plan of the thesis

The purpose of the present work is to investigate the properties of the RPC detectors with particular reference to the high rate operation that is more and more required by the experiments at present and future hadron colliders.

This purpose brings in a natural way to investigate on RPC detector physics and to develop a more complete working model including the avalanche saturation phenomenon that was not accounted for in previous simulations.

After a short presentation of the ATLAS experiment, with particular emphasis on the muon physics (chapter 1), RPCs are presented in their historical development.

The behaviour of RPCs high rate is studied in chapter 3, where a working model based on global parameters as applied voltage, working current, incident particle flux and counting rate, and electrode plate resistivity. The results of this analysis are the basis of the Logistic Saturated Avalanche Model that is developed in chapter 4. This model explains the previous experimental results, and correctly predicts measurable physical quantities as the total charge to prompt charge ratio. This permits to implement an accurate detector simulation and can be the base for a deeper comprehension of the discharge process in a uniform field.

The last chapter is dedicated to the systematic study of the detector ageing problems that are analyzed both on fully assembled detectors and on some of the individual components.

One of the principal contributions to the measured detector performance loss is evidenced and a possible solution is tested, with encouraging results.
Chapter 1

The ATLAS experiment at LHC and the RPC muon trigger

1.1 The LHC project

The simplest and most feasible way to reach energy values which can permit to continue the search for the fundamental constituents of matter and for their interactions, is the construction of a p-p collider. The Large Hadron Collider is the project, to be constructed at CERN, of the highest energy proton-proton collider ever realized. The project consists in two rings of 27 Km of circumference, in which particles bunches, composed by $\sim 10^{11}$ protons, circulate and are accelerated to an energy of 7 TeV. Every 25 ns, a bunch-crossing provides p-p collisions with a total energy in the center of the mass of 14 TeV. At the beginning, the luminosity will be of $10^{33} cm^{-2}s^{-1}$ and, at the standard working conditions, will reach $10^{34} cm^{-2}s^{-1}$. These luminosity values are higher than those of the previous hadrons machines like $\sqrt{s} \sim 6 \times 10^{30} cm^{-2}s^{-1}$ and the Tevatron L $\sim 2.5 \times 10^{31}$.

The intersection between the beams will be in four points, where four experiments will be installed: ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid), which are general purpose detectors, LHC-b, which is the only asymmetric apparatus, explicitly dedicated to the b-physics, and ALICE (A Large Ion Collider Experiment) which is dedicated to quark-gluon plasma studies through heavy ions collisions.

The principal fields of investigations in LHC will be: the first period at low luminosity will be dedicated to obtain high statistic precision measurements about the heavy quarks "bottom" and "top", with particular attention to the study of the CP violation through the neutral $B_0 - \overline{B_0}$ decays; the high luminosity period will be dedicated to the search for the Higgs boson on a wide range of mass. It will, also, be dedicated to investigate new phenomena not previewed from standard
model (in particular, the extension to energies up to $\sim 1$ TeV and to supersymmetric theory.

The total cross-section for non-diffractive events is calculated to be $\sim 70$ mbarn. The high rate and luminosity results in high occupancy and events pile-up in the detectors which should therefore provide high radiation hardness, fine granularity, fast response and small dead-time.

1.2 Higgs physics at LHC

The Electro-weak Standard Model, conceived by Glashow, Weinberg and Salam, has received important experimental confirmation, such as the discovery of neutral currents interactions and the discovery of vector bosons $W^\pm$ and $Z^0$. This model introduces a lagrangian density able to conserve the invariance compared to gauge transformations and renormalizability. This is possible adopting a local gauge group extended with respect to $SU(2)$, utilized for the weak interaction, with the introduction of $U(1)$ group relative to the conservation of the weak hypercharge. The invariance of the lagrangian density under local gauge transformations $SU(2) \times U(1)$ has as a consequence the unification of weak and electromagnetic forces. On the other side, in order to preserve the renormalizability and the gauge invariance, we have to renounce to introduce explicitly in the lagrangian density the mass terms of fermions and $W^\pm$ and $Z^0$ gauge bosons fields [2]. Certainly, this assumption are not realistic, except in the case of the photon and the neutrino.

A spontaneous symmetry breaking mechanism has, therefore, been introduced which generates dynamically the particles’ masses due to the interaction terms between these and a scalar field with mass ($H$) appropriately introduced. The Phenomena by which the gauge bosons and the fermions acquire a mass without spoiling the gauge invariance of the lagrangian density is called Higgs’ mechanism, and the scalar particle with mass $H$ introduced is called Higgs boson.

The search for Higgs boson is one of LHC’s principal goals, since its eventual discovery would permit to verify completely the standard model. The disposable energy in the center of mass permits the search of $H$ in a value interval which includes values previewed from the supersimmetric extensions of standard model (in particular of the minimal model MSSM). It is also possible to investigate on the existence of new particles with a mass in the order of $1 \ TeV$, such as $Z'$. The theory does not give a prediction on the mass of the Higgs boson, so the detectors of LHC’s experiments must be able to observe eventual decays of that particle in the widest energy interval, beginning from the one explored till now. In particular, it is expected that the interval which will be explored in LHC will be the $90 \ \text{GeV} \leq m_H \leq 800 \ \text{GeV}$ interval. Nevertheless, the data collected in the experiments
at LEP and at Tevatron indirectly suggest a preference for values of Higgs’ mass $< 300 \text{ GeV}$. In effect, using the relation for top mass $m_t$ in function of $m_H$ [6]:

$$m_t \sim 180 \pm 7 + 13 \ln \left( \frac{m_H}{300 \text{ GeV}/c^2} \right)$$

and the value for top mass measured at CDF and D0, $m_t = 180 \pm 12 \text{ GeV}$, we have $m_H \sim 300 \text{ GeV}/c^2$.

The most convenient channels for the observation of Higgs boson are, depending on $m_H$ values, the following ($l = e \circ \mu$) [1]:

- $H \to b\bar{b}$ da WH, ZH e $t\bar{t}H$ per $80 < m_H < 100 \text{ GeV}/c^2$;
- $H \to \gamma\gamma$ per $90 < m_H < 150 \text{ GeV}/c^2$;
- $H \to ZZ^* \to 4l^\pm$ per $130 \text{ GeV}/c^2 < m_H < 2m_Z$;
- $H \to ZZ \to 4l^\pm$, $2l^\pm 2\nu$ per $2m_Z < m_H < 600 \text{ GeV}/c^2$
- $H \to WW$, ZZ $l^\pm$ 2 jet, $2l^\pm$ 2 jet, per $m_H$ fino a 1 TeV.

The cross-sections for the great majority of these processes are small on a great part of the interval of the mass values which are intended to be explored at LHC, for example $\sigma \times BR$ for the channel $H \to ZZ^* \to 4l^\pm$, for $m_H < 2m_Z$ isin the order of $f \text{ barn}$ [4].

Let’s consider, for example, the case of $2m_Z < m_H < 600 \text{ GeV}/c^2$ and the specific channel $H \to ZZ \to 4l^\pm$. In this case, the most important contributions to the background come from the production of couples $t\bar{t}$, of $Zb\bar{b}$ and ZZ couples produced in QCD processes; we have also to consider the Z couples coming from the superposition of different events. without operating any cutting for background’s reduction and for a detector with an infinite resolution, the dominant background is the one due to the $t\bar{t}$ processes, which give a signal to noise ratio of $\sim 1$, in correspondence of the resonance peak. The background due to ZZ couples is not reducible, while the one due to other contributions can be reduced in the following ways:

- requiring that the leptons couples come from the decay of two Z, i.e. operating a cut on the invariant mass of the two couples of leptons $M_{ll} = m_Z \pm \delta m_Z$;
- requiring the leptons to be isolated, in order to exclude those coming from the semileptonic decays of quarks.
The $\chi^2$ calculation permits to resolve any eventual ambiguity in the lepton coupling, choosing for each combination the one with the minimum $\chi^2$. In this way, the background due to $t\bar{t}$ couples and the one due to $Z\bar{b}b$ are remarkably reduced. Nevertheless, in the region close to $200 \text{ GeV}/c^2$ per $m_H$, the limited resolution in the momentum renders the rejection criteria less effective, bringing the signal to noise ratio to a value $\simeq 1$; for this reason, in addition to improve the cut on the invariant mass of the $\mu$ couples, it is important to obtain a resolution $\Delta p/p$ better than 10%.

On the other hand, at the upper limit of the mass interval considered, the Higgs peak is large and the resolution has a minor importance. The measure for these values of the mass is limited by the statistics and the intrinsic width of the signal.

### 1.3 The ATLAS detector

The ATLAS detector (shown in figure 1.1) is intended to exploit completely the investigation possibilities offered by LHC. At both luminosity conditions the complex intends to recognize a great variety of final-states signatures from decay processes channels: muons, electrons and photons, hadronic jets and missing energy, on the larger acceptance coverage in $\eta$\(^1\). The basic design consists in [3]:

- an efficient central tracking system (with 30% resolution at $p_T = 500 \text{ GeV}/c$ for momentum measurements and secondary vertex identification (section 1.3.1)

- An electromagnetic calorimetry with 10%/$\sqrt{E}$ $\oplus$ 0.7% resolution for the identification of electrons and photons together with an hermetic hadron calorimetry for the measurement of jets energy and missing $E_T$ (section 1.3.2)

- A stand-alone, precision tracking system for measure of muon momentum with a resolution of 10% at $p_T = 1 \text{ TeV}$ and angular acceptance up to $|\eta| = 31$ (section 1.3.3).

The magnet system, consists of two independent subsystems: a superconducting solenoid around the inner detector cavity, with a field of 2 $T$ and three large superconducting air-code toroids outside the calorimettes. This configuration allows to avoid particular constraint on calorimetry and inner detectors, leaving full choice for technological solutions, and to realize a high resolution, large acceptance and robust stand alone muon spectrometer.

\(^1\)The pseudorapidity $\eta = -\ln \tan(\theta/2)$ is the limit of the rapidity $y = 1/2 \ln \frac{E+P}{E-P}$ for $E \gg P$ (m $\ll$ E). It is used to substitute the $\theta$ angle in polarity coordinates system.
1.3.1 The Inner detector

The inner detector occupies the inner cylindrical cavity defined by the electromagnetic calorimeter cryostats. It combines high resolution detectors in the inner part with lower resolution but higher pattern recognition detectors in the outer part: The inner detector, dedicated to momentum resolution and interaction vertex identification, is subjected to a solenoidal field of 2 T intensity. Due to the high track density expected, it should possess high granularity and high resolution. Different technologies are used.

High spatial resolution detectors are provided at inner radius: Semiconductor Tracking detectors (SCTs) with silicon microstrips and pixels. At outer radii straw tube tracker (TRT) realizes pattern recognition with an almost continuous track-following, minimizing the amount of material and the cost. For inner detectors the spatial resolution on the $r,\phi$ plane is $\sim 10 - 15 \, \mu m$, for the TRT it is about $\sim 170 \, \mu m$.

In the barrel high-precision detectors layers are arranged in concentric cylinders around the beam axis and TRT straws are parallel to the beam direction. In forward directions tracking elements are on planes perpendicular to the beam, with strips and straws along radial directions. The layout provides full tracking
coverage over $|\eta| < 2.5$ for vertex and impact parameter measurements for heavy flavor and $\tau$ tagging. The secondary vertex measurements, necessary for the b-physics, is guaranteed by an additional layer of SCT pixels. This is mounted very close to the beam pipe, and its lifetime is limited to the initial low luminosity period because of radiation damage. The vertex resolution in $\mu m$ is parametrized as $\sigma_{r,\phi} = 11 \oplus \frac{60}{p_T \sqrt{\ln \theta}}$ and $\sigma_z = 70 \oplus \frac{100}{p_T \sqrt{\ln \theta}}$. Figure 1.2 shows the pattern recognition capability of the system.

1.3.2 The Hadronic and Electromagnetic calorimeters

ATLAS calorimeter is designed to reconstruct the energy of electrons, photons and jets, and to measure the transverse missing energy. It consists in an electromagnetic calorimeter and an hadronic one. ATLAS Electromagnetic calorimeter must provide identification and reconstruction for electrons and photons in a wide energy spectra such as $100 \text{ MeV} \leq E \leq 1.5 \text{ TeV}$ covering $|\eta| \leq 1.4$ on barrel region and $1.4 \leq |\eta| \leq 3.2$ on end-caps. It utilizes on ionization chambers which use liquid Argon as the active medium, and lead absorbers. It is realized based on an ‘accordion’ geometry. The energy resolution should be better than $(10\%/\sqrt{E}) \oplus 1\%$ (for $E$ reported in GeV). The calorimetry segmentation is vari-
able in different $\eta$ region, but in a great part of the rapidity interval it is fixed at $\Delta\eta \times \Delta \phi \approx 0.025 \times 0.025$.

The Hadronic calorimeter is designed to identify hadronic jets, to measure the missing transverse energy and also to improve the ability to identify particles in the electromagnetic calorimeter. In the barrel region it is constituted by scintillators planes, read-out by wavelength shifter fibers for a segmentation $\Delta\eta \times \Delta \phi \sim 0.1 \times 0.1$, alternated with iron absorbers. The resolution that can be reached by this configuration is $(50\%/\sqrt{E}) \oplus 3\%$. In the end-caps, where a higher radiation resistance is required, the active medium is liquid Argon and the estimated resolution will be $(100\%/\sqrt{E}) \oplus 10\%$.

An important parameter for reducing the charge particle punch-trough background in the muon spectrometer is the hadronic thickness of absorber medium in interaction length $\lambda$, that is fixed at 11 in the barrel and 14 in the end-caps regions.

### 1.3.3 The Muon Spectrometer

An essential characteristic of the ATLAS detector concept, also reflected in the "ATLAS" acronym, is the magnetic field configuration generated by three air-code toroidal apparatus, one for the barrel and two for the endcaps (see fig. 1.3). Each is constituted by 8 superconducting rectangular coils placed around the beam, taken as a symmetry axis. The barrel toroid extends for 26 m length, with internal and external diameters respectively of 9.5 m and 19.5 m. The two endcap toroids, 5 m long, have inner bore of 1.65 m and an outer diameter of 10.7 m. The barrel and the endcap coils are alternated in the transition region along the $\phi$ coordinate, so that their superposition is granted.

The principal advantage of an air-coil apparatus is in the limitation of the multiple Coulomb scattering of the charged particles in the spectrometer, so improving the muon momentum measurement resolution. Furthermore the toroidal structure permits to extend the field on a remarkable region, enhancing the bending power for the charged tracks.$^2$ This permits a relatively low value of the magnetic field ($\sim 0.6 \, T$) that reduces many technological problems.

The spectrometer, represented in fig. 1.4, is therefore designed to take advantage from the magnet system bending power, thanks to high resolution detectors and hermetic coverage of the solid angle, so that a wide range of muon transverse momentum $5 \, GeV \leq p_T \leq 1 \, TeV$ can be measured with good resolution independently of the rest of ATLAS detector [7].

For fulfillment of the scheduled physics programme, the performance required for the muon detectors are summarized as follows:

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$^2$The magnetic field bending power is defined as the path integral of the magnetic field component $B_\phi$ orthogonal to the beam axis
A momentum and mass resolution at the level of 1% are essential for reconstruction and charge identification.

A track non-bending projection measurement with a r.m.s. of 5-10 mm is desired for safe reconstruction and momentum determination.

Different transverse momentum trigger thresholds for high-$p_T \geq 20$ GeV and low-$p_T \geq 6$ GeV are required for Higgs-mass states and CP violation with beauty physics respectively.

A trigger coverage of $|\eta| \leq 2.4$ is considered sufficient.

For the first level trigger system the time resolution scale is fixed by the 25 ns LHC bunch-crossing interval.

The background conditions at the LHC must be carefully studied and simulated. Basic detectors parameters such as coverage, rate capability, granularity, ageing properties and radiation hardness, are affected by the high particle flux. The expected signal in the spectrometer can be classified in low energy background, that is described in section 1.4 and primary collision products.

These are correlated in time to the primary interaction, and reach the muon spectrometer through the calorimeters. This background is composed by semileptonic decays of light $\pi,K$ and heavy c,b,t flavours in $\rightarrow \mu X$, by gauge boson decays $W,Z,\gamma^* \rightarrow \mu X$, and by shower muons and hadronic punch-through.
Figure 1.4: The transverse view of the ATLAS muon spectrometer.
At small $p_T \leq 10$ GeV muons from flight decays of $\pi$ and $K$ dominate the background. At $p_T \geq 10$ GeV the largest contribute is given by charm and beauty decays. At larger $p_T \geq 30$, appears the $t$ and $Z$ decays contribution.

![Figure 1.5: Inclusive muon cross-section integrated over $|\eta| \leq 2.7$ versus transverse momentum at production.](image)

The simulated inclusive cross-section for prompt muons produced in the decays of heavy-flavor hadrons ($c, b, t \rightarrow \mu X$) and gauge bosons ($W, Z, \gamma \rightarrow \mu X$), together with the contributions from muons generated in the hadronic cascades and from hadron punch-through are shown in figure 1.5.

**Tracking and fast response trigger**

Different technologies are employed in the muon spectrometer. Chambers for tracking and chambers for trigger are coupled together to form the ‘stations’ of the spectrometer. The barrel stations are arranged in three cylinders concentric with the beam axis, at radii of about 5, 7.5, and 10 m. They cover the pseudorapidity range $|\eta| \leq 1$. The end-cap stations, vertically installed, cover the range $1 \leq |\eta| \leq 2.7$ and consist of four disks at distances of 7, 10, 14, and 21-23 m from the interaction point, concentric with the beam axis. This system provides almost complete coverage on $\eta$ except for an opening at $\eta = 0$ necessary for cables and services of the inner detectors.

The precision measurement of the muon tracks is made along the bending direction of the magnetic field (the $r$-$z$ projection). The $z$ axial coordinate is measured in the barrel and the radial $r$ coordinate in the transition and end-cap regions. Monitored Drift Chambers (MDTs) are mounted over most of the $\eta$ range, on the
three barrel stations and three of the end-cap stations. They provide for a single-wire resolution $\sim 80\mu$m, when operated at high gas pressure (3 bar) and for a mechanical accuracy of $\sim 30\mu$m. A fourth end-cap station, nearest to the interaction point, for $|\eta| \geq 2$, is made of Cathode Strip Chambers (CSCs), used to provide the finer granularity required to cope with the rate and background conditions in this particular region. Optical alignment systems were designed on purpose to guarantee the mechanical accuracy strictly required for precision chambers.

The trigger system covers the pseudorapidity range $|\eta| \leq 2.4$. The basic requirement for the system is the bunch crossing identification, that implies a detector time resolution much better than 25 ns. A granularity of order of 1 cm is required for trigger well-defined $p_T$ cut-off in moderate magnetic fields. The system employs two different types of detectors, both characterized by fast response and high time resolution. Resistive Plate Chambers (RPCs) are used in the barrel ($\sigma_t \leq 1.5\text{ns}$) and Thin Gap Chambers (TGCs) in the end-cap regions ($\sigma_t \leq 5\text{ns}$). Both the trigger chambers provide the ‘second’ coordinate measurement of track, orthogonal to the precision measurement and parallel to the magnetic field lines. The trigger chambers cover a total area of 3650 m$^2$ in the barrel and of 2900 m$^2$ in the end-cap region (both with more than $\sim 4 \times 10^5$ channels).

### 1.3.4 Trigger and DAQ

The ATLAS Trigger and Data-Acquisition (DAQ) is organized on three levels of data elaboration [9]. The bunch-crossing rate of 40 MHz must be reduced to $\sim 100$ Hz for permanently storage of selected events. The level-1 (LVL1) examines data coming from from the calorimeter and the $\mu$ spectrometer and has to identify collisions which have in their final state possible products of the searched interactions. The level-1 (LVL1) triggers can’t exceed the rate of 75 kHz because of the front-end system limit, and have to uniquely identify the reference bunch-crossing. This level trigger bases its selection on simple basic criteria, using reduced granularity information from the muon trigger and calorimeters. During the latency time, needed to form and distribute decisions, data from all detectors are kept on ‘pipeline’ memories. The LVL1 latency, from the proton-proton collision until the trigger decision is available to the front-end electronics, must be less then 2.5 $\mu$s. The system is a purpose-built hardware processor, constituted of synchronous pipelined processors running at 40 MHz. The driving signals come from the LHC machine, to obtain an absolute bunch-crossing identification. The LVL1 trigger produces ‘region-of-interest’ (RoI) information to be used by the level-2 trigger (LVL2). Selected events are readout from front-end electronics into ReadOut Buffers (ROBs) and kept until LVL2 produces its decision.

The LVL2 uses RoIs information, as $\eta$ and $\phi$ position, $p_T$ range and energy sums of candidate objects, to selectively access data. By this way only a few
percent of the full event data are moved on dedicated data paths. The LVL2 trigger latency depends on a particular event but is $\sim 1-10$ ms.

After this time data are discarded or transferred by the Event Builder process to a single memory accessed by the Event Filter (EV), which is the third level selection. The selection algorithm uses off-line code and reduces the rate to 100 Hz for final full event size of 1 Mbyte.

1.3.5 The muon trigger LVL1 algorithm

The counting rates induced by the mentioned background (see also section 1.4) in the trigger stations should reach about 10 Hz/cm$^2$ at the nominal luminosity $L=10^{34}$ cm$^{-2}$s$^{-1}$.

![Figure 1.6: Level-1 muon trigger scheme in the barrel and in the end-cap.](image)

The level 1 trigger is based on three trigger stations, as shown in figure 1.6, both for the RPCs system ($|\eta| \leq 1.05$) and for the TGCs ($1.05 \leq |\eta| \leq 2.4$). Two stations, with two detector planes each, are used for low-$p_T$ muon triggers, with threshold range of about 6-10 GeV (the innermost TGC station has three planes). The third station is used for the high-$p_T$ triggers, with threshold range of about 20-35 GeV. Two orthogonal projections are read out for each plane, the bending $\eta$ ($r$-$z$ plane) and non bending one $\phi$ ($r$-$\phi$ plane). The $\eta$ coordinate contributes to the sharpness of the $p_T$ cut applied. The $\phi$ coordinate reduces the background trigger rate and produces the second coordinate measurement for off-line muon
reconstruction. Both coordinate information are combined to generate the RoIs with an area resolution of \( \sim 0.1 \times 0.1 \) in \( \eta-\phi \).

The basic algorithm requires the coincidence of hits in the different chamber layers within a road. The applied \( p_T \) threshold fixes the width of the road as a function of the field integral, of the trigger planes distance, of \( \eta, \phi \), and the energy loss in the calorimeter. Space coincidence in a time gate close to 25 ns are required on both projections: at least three of four layers (on the two inner stations) for the low-\( p_T \) trigger, and for high-\( p_T \) trigger is required in addition one of the two layers on the third station (two of three for the last TGC station).

Muons with transverse momentum larger than a fixed \( p_T \) threshold are selected. The chosen roads should provide about 90\% efficiency at the nominal \( p_T^{\text{thres}} \) for both signs muons. Six programmable thresholds are allowed, half for high-\( p_T \) and half for low-\( p_T \). Dedicated Coincidence-Matrix (CM) boards, implemented in ASICs, perform the trigger logic, using as inputs discriminated and shaped signals from detectors front-end electronics. This chip aligns the timing of input signals, performs the coincidence and majority operations, makes the \( p_T \) cut on three different thresholds defined by roads in the matrix, and contains the level-1 latency pipeline memory and derandomizing buffer. A valid coincidence within a road generates the trigger signal.

Monte-Carlo simulations evaluated the efficiency of the level-1 trigger versus \( p_T \), for the large barrel sectors and for the end-caps, for nominal \( p_T^{\text{thres}} \) thresholds of 6 and 20 GeV (shown in figure 1.7). In figure 1.8 are shown simulated trigger rates versus the luminosity. Rates expected from \( b \) and \( c \) quarks decays and from hadrons decays in flight are compared with background-induced accidental trigger rate. The system ensures an accidental trigger rate below the physics rate.

![Figure 1.7: Simulated efficiency of the trigger system versus the muon transverse momentum at interaction point, a) in the barrel, and b) in the end-cap.](image-url)

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Figure 1.8: Muon and accidental trigger rates as a function of luminosity for low-$p_T$ (top) and high-$p_T$ (bottom) thresholds, in the barrel (left) and in the end-cap (right). Muon rates (solid lines) are compared with low energy particles background (dashed lines) and with background rates increased by a factor 10 for high-$p_T$ and a factor 5 for low-$p_T$ trigger (dash-dotted lines).

1.4 The background in the Atlas detector

Given the expected luminosity level, one of the main problems for the functioning of an experiment at LHC will be the background radiation. In ATLAS the radiation sources are: the production of particles in the interaction vertex, the local loss from the beam and the interactions of the beam with the residual gas in the beam-pipe.

The loss of photons from the beam along the ring are estimated to be in the order of $10^7$ proton s$^{-1}$, which are negligible if compared with the collision frequency for each point, equivalent to $10^9 s^{-1}$. The interaction between the beam and the gas in the interaction region, of $\sim 50 m$ of length, are in the order of $10^2 m^{-1} s^{-1}$. Thus, the dominant radiation source is represented by the particles produced in p-p collisions in the interaction vertex.

Although a part of these particles is absorbed in the calorimeters, a consistent fraction of small angle-produced particles is not intercepted along the beam pipe and interacts with the passive elements of the experimental apparatus close to the beam. The hadronic showers produced in the interaction of the particles with the passive elements are rapidly degraded and produce neutrons, photons, muons and low-energy charged hadrons.

Neutrons and photons are subjected to various diffusion prior to be captured, giving rise to an isotropic neutron gas (with energy $\geq 100 KeV$), photons (with energy $\geq 30 KeV$) and $e^+ e^-$ produced in the interactions with the experimental
area’s materials. It is, therefore, essential to adopt a good and hermetic shielding in order that counting rate and radiation damage are within tolerated limits.

In the inner detector, the main background source are the neutral and charged particles deriving from the interactions of the particles with the internal part of the calorimeter. The neutron flux can be reduced by interposing a layer of material with a low atomic number between the calorimeter and the detector. The calorimeter absorbs the great part of the particles generated in the shower, shielding in this way the rest of the detector, but the great energy left (in particular by the electromagnetic showers) can damage its parts most sensitive to radiation, the readout electronics. Passive shields need to be inserted in the areas not covered by the calorimeter. The proposed system involves an iron shielding, to be inserted between the barrel and the extended barrel part of the tile calorimeter and between the extended barrel calorimeter and the first muon station. the calorimeters provide an almost hermetic shielding up to $|\eta| < 4.9$. Further downstream, the copper collimator for the low-$\beta$ quadrupole acts as a backstop. The actual estimate of background in ATLAS is effected with simulation programs, DTUJET, which describes the particle production and FLUKA, which simulates the interaction of particles with the detector complex and, also, their effects on the detector.
Chapter 2

Introducing the Resistive Plate Chambers.

2.1 Historical remarks

The Resistive Plate Chambers (RPC), developed in 1981 by R. Santonico and R. Cardarelli [11] [12] [13], are devices capable of detecting ionizing charged particles, using as sensitive target, a gas layer enclosed between resistive plates electrodes.

The electronic charge, released by the passage of the ionizing particle, primes an avalanche charge multiplication that makes use of the energy of an opportune electric field, uniformly established in the gas volume through the resistive plates.

The common ancestor [10] of all parallel plate devices, is the Keuffel spark counters developed in 1949. This was made of two metal plates separated by a few mm gas gap and connected to high voltage through very high resistors. When the gas was ionized, the whole energy of the capacitor was discharged through a spark indicating the ionization position. This detector had by far a much better resolution then any Geiger-Muller counter. It had however two main limitations:

- after each count a long recovery time was needed to restore the electric field inside the capacitor;
- it was extremely unstable and was therefore unsuitable for practical applications.

For a long time period parallel plate detectors could not be used as continuous sensitive detectors. Instead they were developed in the form of pulsed detectors, which were, in the historical order the optical spark chambers, wide gap and streamer chambers. This was possible with the invention of the trigger: another
fast detector, typically a scintillator, was used to preselect potentially interesting events. This triggered the high voltage driver to pulse the detector plates while the ionized electrons were still free inside the gas.

An attempt of implementing a continuously sensitive parallel plate detectors is due to Yu. N. Pestov [14]. He introduced for the first time the idea of resistive electrodes, as to limit the energy available for the multiplication process to that contained in a small volume nearby the particle track. Since the plates electrodes reaction time becomes much longer than the multiplication process, the spark can not occur, thus preventing from long recover times and leaving the remaining of the sensitive volume still ready to detect a new event. The Pestov detector made use of a resistive glass electrode only for the anode, and it was sealed to work at high gas pressure. For the high operating difficulties and for the impossibility to make easily large size versions, it did not find practical application.

2.2 RPCs basic working principles

The RPCs (fig. 2.1) adopt resistive materials for both electrodes (typically phenolic resin laminates, commonly called bakelite), to enclose the gas at atmospheric pressure. This material has a low cost and very good mechanical properties, permitting the implementation of this detector also for large area experiments.

The typical thickness of the bakelite plates and of the gas volume is 2 mm. The operating voltage is applied uniformly on the external faces of resistive electrodes by a graphite coating, and thanks to the residual plates conductivity, the resulting electric field is wholly applied on the gas layer (if no ionization occurs). An insulating foil separates the graphite electrodes from the readout, that is usually constituted by a system of independent strip-shaped transmission lines, on which the signal is induced by the fast charge (electrons) moving in the gas and transferred to the front end electronics.

The field has intensity variable in the range of some tens of $KV cm^{-1}$, depending on the chosen gas, and permits to the free electrons to start the avalanche multiplication that constitutes the detectable signal. The avalanche population growth can be described in first approximation by the Townsend law [24] as a function of the distance $x$ from the initial position:

$$N(x) = N(0)e^{\alpha x}$$

2.1

where $N(0)$ is the initially released charge and $\alpha$, usually called the first Townsend coefficient, is a function of the applied voltage determined experimentally.
Given the typical RPC geometry, the whole avalanche process develops completely in \(\sim 10\,\text{ns}\) with a very sharp growing front, that gives to the detector a typical time resolution of \(\sim 1\,\text{ns}\). Also the spatial information is very precise since the avalanche can be localized on the electrode plate with a precision better then \(100\,\mu\text{m}\), with an analog readout.

When the avalanche reaches an electron multiplicity of \(\sim 10^6\) electrons, it slows down the exponential growth due to space charge effects, starting the so called saturated regime, which will be studied in detail in the next chapters.

For extremely high values of the electronic charge (established by Meek in \(\sim 10^8\) electrons for noble gases), the avalanche becomes the precursor of a new process called streamer. This is a plasma filament, establishing between the electrodes and producing an extremely intense current pulse in the gas, about 100 times larger than the typical avalanche.

The streamer is prevented to evolve in a spark thanks to the electrodes resistivity, and to propagate laterally, due to emission of UV ionizing photons by the slowed recombining electrons, by an opportune photon quencher in the gas mixture.

For this reason the first RPCs were operated in streamer regime.
The drawback of operating RPCs in streamer mode is the high cost paid in terms of released charge per count that limits the rate capability of this device to few hundred of $Hz cm^{-2}$ [25].

Recently a major improvement in the detector evolution [26] [27] [28], permitted to use the avalanche signal to detect the particles, thus opening the possibility of adopting the RPCs in the forthcoming hadron colliders experiments characterized by an high event rate.

The improvement consisted in adopting gas mixtures based on electronegative gases, which have the property to retard the appearance of the streamer in terms of applied electric field, with respect to the precursor avalanche total charge. Finally the introduction of $SF_6$ as streamer quencher removed completely the problem of the streamer, permitting a very comfortable avalanche mode [23].

This operative mode could also be adopted thanks to a new concept of the front end electronics and of the signal readout, designed to have the maximum performances with the fast avalanche signals. In fact the strips layout was greatly improved to decrease the coupling between strips and avoid the cross talk that can arise at the very low threshold needed for avalanche operation mode.

Furthermore in the front end was adopted a voltage amplifier [29], instead of a charge amplifier, more effective with fast induced signals collected on a purely ohmic transmission line.
Chapter 3

RPCs working at high rate

3.1 An RPC gamma irradiation test

The need of large area muon triggers in the forthcoming hadron collider experiments, brought a great attention on the R&D of low cost and robust detectors with good time resolution and tracking capability. Being those requirements met by RPCs, a big effort was spent in order to ensure the high rate capability required and a reliability adequate for so long lasting experiments.

In this chapter the result of an high rate irradiation test are presented for variable incident flux, illustrating the RPCs behaviour in a very high rate environment, along with the performances of the last development of the RPCs GaAs Front End electronics that were tested for the first time.

A detector description is here introduced, in terms of the ”global” parameters, based on experimental data such as current, total counting rate and $\gamma$ flux.

3.1.1 Introduction

In order to study the performance of RPCs equipped with the final version of the ATLAS 8-channel full-custom GaAs front-end board, we irradiated a $10 \times 10 cm^2$ RPC using our $\gamma$ irradiation facility, located at the INFN laboratories of the University of Roma "Tor Vergata". This facility was already used to perform irradiation and ageing tests on RPCs equipped with the previous version of front-end electronics.

We measured the total operating current and counting rate vs. the applied voltage for different distances of the source.

Two quantities derived from the data are introduced: $Q_\gamma$, the total charge per ionizing photon, and $Q_c$, the total charge per count, that behave like state ”functions” of $V_{gas}$ that is the high voltage actually applied on the gas once the ohmic drop across the resistive plates has been taken into account. This description permits
the evaluation of important detector parameters like total RPC plate resistance and charge multiplication inside gas, and is the starting point for a rate dependent simulation model that will be the subject of a forthcoming paper.

3.1.2 The experimental set up

The experimental setup (fig. 3.1) consists in an irradiation cubic lead cell (edge=1m), equipped with a nominal 4 mCi $^{60}$Co source, in which a $10 \times 10 \text{cm}^2$ RPC was placed. A direct calibration measurement made two years before the present data gave $3.8 \pm 0.3 \text{mCi}$, corresponding to the present gamma rate of $2.2 \times 10^8 \gamma/s$ over $4\pi$ accounting for the half life of $^{60}$Co of 5.271 years.

The calculation of the photon flux $\Phi_\gamma$ over a square surface of edge $l \text{ cm}$, produced by a source of intensity $I_\gamma \text{ s}^{-1}$, placed at distance $d \text{ cm}$ on the square’s axis, is easily given by:

$$\Phi_\gamma = I_\gamma \int_{-l/2}^{l/2} \int_{-l/2}^{l/2} \frac{dx\,dy}{4\pi \left(d^2 + x^2 + y^2\right)^{3/2}}$$

that gives:

$$\Phi_\gamma = \frac{I_\gamma}{\pi} \arctan \frac{l^2}{2d\sqrt{2d^2 + 2l^2}}$$  \hspace{1cm} (3.1)

this relationship for $d > l$ tend to the usual law $1/d^2$.

An RPC sensitivity calibration measurement was also performed on this apparatus, through the single photons signals counting plateau showed in fig. 3.2, that was obtained with all the possible precautions to exclude spurious signals like detector and electromagnetic noise and afterpulses that arise at higher voltage, close to the streamer limit$^1$. The plateau counting rate results to be $4.66 \pm 0.03 \text{ KHz}$. By comparing this result with the total calculated incident flux in that setup, that was of $520 \times 10^3 \text{ s}^{-1}$, we obtained for the sensitivity $S_{\gamma}$:

$$S_{\gamma} = 0.9\% \pm 0.1\%$$  \hspace{1cm} (3.2)

The RPC was filled with $97\%C_2H_2F_4$, $2.5\%C_4H_{10}$ and $0.5\%SF_6$ gas mixture, called Standard ATLAS Mixture from this point on. Its bakelite volume resistivity was $\sim 4.4 \times 10^{10}\Omega\text{cm}$ at room temperature. It was equipped with the ATLAS 8-channel front-end board 4 of which were connected to the 3cm wide readout strips. The threshold is given by the difference between an internal reference value (-1.5V) and an external input $V_t$ (see fig. 3.3). A $100K\Omega$ resistor placed in series with the HV return line, provided a precise V-A current readout.

$^1$notice that this measurement was performed before the introduction of $SF_6$ that substantially removes the problem of streamers and afterpulses in a wide voltage range.
Figure 3.1: Experimental setup
Figure 3.2: Photon single counting plateau vs. applied voltage

Figure 3.3: Scheme of the amplifier and of the threshold

Physical threshold (V) = \frac{(1.5V - V_{th})}{A}
The resistivity of the RPC, or better its total resistance, was directly measured since it is a fundamental parameter for our data analysis. The chosen method, for its nature, was applied at the end of the data taking, since it consisted in short circuiting internally the gas volume, filling it with pure water. The current driven was plotted vs. the applied voltage, obtaining a straight line, and the inverse of the slope gave the reported value of the resistivity by a geometric factor.

### 3.1.3 Data taking and experimental results

Before presenting the data about the RPC’s counting rate it is useful to make some consideration about the converted photon rate per unit surface.

The expected counting rate on a certain surface is given by:

$$\frac{dN}{dt} = I_{\gamma} S_{\gamma} \frac{\Delta \Omega}{4\pi} s^{-1}$$  \hspace{1cm} (3.3)$$

where $\Delta \Omega$ is the solid angle covered by the surface, viewed by the source. We can make an easy calculation imagining to put the source in the center of a cube having the interested (square) surface as one of the six faces, in such a way that $d = l/2$. In this case the covered solid angle is exactly $1/6$ of the total and the pulse rate density is given by $\frac{I_{\gamma} S_{\gamma}}{d^2}$.

For example if $l$ coincides with the edge of the RPC ($l = 10 \text{ cm}$, $d = 5 \text{ cm}$), the sensitive surface of the RPC coincides exactly with one of the faces so that the RPC receives $1/6$ of the total flux on its whole surface. The expected average pulse rate density is in this case $4.7 \cdot 10^3 s^{-1} \text{ cm}^{-2}$, and at this distance the uniform flux approximation is still acceptable. If we bring the source nearer, we will have the same flux on a smaller square, resulting in higher density of pulse rate, for example:

$$\begin{align*}
  d &= 3.5 \text{ cm} & \Rightarrow & & 9.6 \cdot 10^3 s^{-1} \text{ cm}^{-2} \\
  d &= 2.6 \text{ cm} & \Rightarrow & & 17 \cdot 10^3 s^{-1} \text{ cm}^{-2} \\
  d &= 1.6 \text{ cm} & \Rightarrow & & 46 \cdot 10^3 s^{-1} \text{ cm}^{-2}
\end{align*}$$  \hspace{1cm} (3.4)$$

We report these values, that were also used to take the following data, to remember that in these extreme cases the irradiation is both strongly non uniform and well above the normal RPC typical working rate at least in the central area.

In figure 3.4 are shown single RPC counting rates vs. high voltage for different source distances. The value of $V_{th}$ was set at $-1.45 \text{ V}$ with respect to the offset voltage $-1.5 \text{ V}$. The number of photons that produce gas ionization are also reported along with the source distance.

The total rate ranges from 3.6 KHz to 714 KHz on $10 \times 10 \text{ cm}^2$ for source distances ranging between 70.9 cm and 1.6 cm.
Each curve is corrected by subtracting the closed source measurement. We observe that the two curves corresponding to the higher rates do not reach the plateau in the present voltage range due to a very large effect of the plates resistance. However, it has to be stressed that in this case the rate of converted photons is \( \sim 50 \text{kHz/cm}^2 \) in the central region of the detector due to loss of photons’ uniformity.

As a first F.E. electronics benchmark we compared the present counting rates with those already obtained using the previous version of the F.E. electronics in the same set-up, finding good agreement.

In figure 3.5 are shown the measured currents, which are corrected with the closed source values, for different distances of the source. Notice the long, almost linear, growth of the current that is a typical feature of operation with SF\(_6\) [15], that keeps the pure avalanche regime in a wide voltage range.

**Figure 3.4.** Counting rates at various distances
3.2 Discussion of results

With reference to the simple model presented in the previous section, for a uniformly irradiated detector we can properly define:

\[ V_{gas} = V - \overline{T}R \]  \hspace{1cm} (3.5)

as the average voltage across the gas gap, \( V \) being the power supply voltage, \( \overline{T} \) the average current and \( R \) the total resistance of the detector plates. The use of \( V_{gas} \) instead of \( V \) allows to describe the system independently of the voltage drop due to the current flowing into the resistive plates.

We remark that we are allowed to make this simple statement, described by 3.5, only if the offset voltage represented by \( \overline{T}R \) corresponds to a well defined physical quantity, i.e. the local fluctuations are small with respect to the offset.

Average charge per ionizing photon  An estimator of the average charge per ionizing event can be obtained from the ratio \( Q_\gamma \), between the total current and the calculated rate of converted photons, regardless of the counted rate that is dependent on a threshold.

Fig.3.6 shows the dependence of

\[ Q_\gamma = \overline{T} / (\Phi_\gamma \cdot s_\gamma) \]  \hspace{1cm} (3.6)

on the applied voltage \( V \). The quantity \( Q_\gamma \), should depend only on the gas multiplication phenomena, as a function of the effective voltage in the gas. Indeed
Figure 3.6: Charge per ionizing photon: $Q_\gamma$

the set of different curves plotted in fig.3.6 "melt" into one, if the correct voltage scaling from $V$ to $V_{gas}$ is applied, as it is shown in fig.3.7. This was obtained by introducing $R$ as a free parameter and it was fixed by minimizing the distances of the curves in fig. 3.6. The obtained value, $R = 2.2 \cdot 10^8 \Omega$, should be interpreted as the plate total resistance and gives a resistivity of $\rho = 5.5 \cdot 10^{10} \Omega cm$. This result is in good agreement with the one obtained by the direct measurement described above, $\rho \sim 4.4 \times 10^{10} \Omega cm$, thus confirming the interpretation of the parameter $R$ as the electrodes resistance.

The result of this test shows that the detector resistance can be correctly monitored with the method explained above.

In figure 3.7 is also presented the comparison with the binary gas mixture, free from the $SF_6$ component. It is apparent that, after an exponential growth, the mixture with 0.5% of $SF_6$ presents a linear growth in a 1 KV range, that we attribute to a saturation mechanism [18] as it will be explained in chapter 4. On the other hand the mixture without $SF_6$ abruptly enters its streamer regime after a barely visible linear range.

It is important to note that the linear dependence of $Q_\gamma$ on the applied voltage enhances the validity of the 3.5: in fact an exact linear dependence, in presence of local voltage random fluctuations, distributed symmetrically around the average value $<V>$, would give an average value of the signals coincident with the average signal produced in presence of an effective voltage $<V>$ in absence of fluctuations:

The validity of 3.5, demonstrated above, is substantially unaffected by local
field fluctuations, because for a linear $Q_{\gamma}$ dependence on $V_{gas}$, as in fig. 3.7, the relationship is valid also for large fluctuations.

$$< Q_{\gamma}(V) >= Q_{\gamma}(< V >)$$

this is not true, for example, in case of exponential dependence.

The figure 3.7 highlights another feature of this technique: extracting information about the gas properties with a quick and simple procedure. In particular this plot gives the effective multiplication law that includes all the non linear effects due to the space charge and for that we used it as a starting point to develop a more complete detector model.

Strictly speaking, the validity of this method for estimating the RPC resistance and the gas properties does not require to know the sensitivity. The plot 3.7 would be, in this case, charge per incident photon vs. $V_{gas}$.

**Average charge per counted photon** Combining the data from the current with the data of the counted rate, we can calculate the average charge per count.

Fig.3.8 shows the counting rate and the operating current vs. $V_{gas}$, with the source set at 16.5 cm. The average charge per count, defined $Q_c = \overline{I}/(counting\ rate)$, is also plotted in fig.3.8. This curve shows a minimum $Q_{th}$ at a voltage corresponding to about half of the maximum rate. The value of $Q_c$ grows at lower voltage since a bigger part of the events produce a signal under the set thresh-
old, so they are not counted while the associated current is measured as a "dark" current.

With reference to figure 3.9 we look at the prompt charge distribution of a set of pulses in relation to the fixed threshold: we can define the number of counted pulses as the cumulative of the distribution integrated between the set threshold and infinity. For increasing applied voltage we expect that the average value of the distribution moves toward higher charge. Experimentally we also observe that the distribution assumes a peaked form at higher voltage [18] [23], deviating from the exponential shown in fig. 3.9. When the peak coincides with the set threshold, the cumulative reaches its bending point corresponding about to 50% of efficiency. This should also correspond more or less to the minimum of $Q_c$, depending on the distribution type.

We therefore interpret the value of this minimum as the average total charge per count, produced in the gas, corresponding to a fast signal of amplitude equivalent to the front-end threshold. We demonstrate this statement in the hypothesis of exponential charge distribution:

the total charge distribution is given in this case by:

$$\frac{dP(Q)}{dQ} = \frac{1}{Q_0} e^{-Q/Q_0}$$  \hspace{1cm} (3.7)

where $Q_0$ is the average charge. Given a certain converted photons rate $r = \Phi \cdot S_\gamma$
Figure 3.9. Relation between prompt charge distribution and the minimum of $Q_c$ in arbitrary units, with $Q_{th} = .2$
the average total current $I$ is:

$$I = r \int_0^\infty \frac{1}{Q_0} e^{-Q/Q_0} Q \, dQ = r \, Q_0 \quad (3.8)$$

We introduce now the function $R_Q(Q)$ as the total charge to prompt charge ratio, already introduced in chapter 2 and extensively studied in chapter 4. A detected avalanche must produce a prompt charge larger then the set threshold $q_{th}$, corresponding to a total charge $Q_{th} = R_Q(Q_{th})q_{th}$. Thus the counting rate $C_r$ will be defined by:

$$C_r = r \int_{Q_{th}}^\infty \frac{1}{Q_0} e^{-Q/Q_0} Q \, dQ = r \, e^{-Q_{th}/Q_0} \quad (3.9)$$

while the average charge per count $Q_c$ is:

$$Q_c = \frac{Q_0}{e^{-Q_{th}/Q_0}} \quad (3.10)$$

We calculate the zero condition for the first derivative:

$$\frac{dQ_c}{dQ_0} = e^{Q_{th}/Q_0} \left( 1 - \frac{Q_{th}}{Q_0} \right) = 0 \quad (3.11)$$

that is satisfied for $Q_0 = Q_{th}$. This corresponds to the minimum point:

$$Q_c = \epsilon \, Q_{th} \quad (3.12)$$

As is apparent the minimum point value is proportional to $Q_{th}$ by a constant factor $\epsilon$. Since in the minimum $Q_{th}$ coincides with $Q_0$, that is also the average charge per ionization, $\epsilon$ represents the inverse ratio between $Q_0$, that includes the dark current contribution, and $Q_{th}$.

To explain this factor we make a further observation: looking at eq. 3.9 the efficiency $\epsilon$ for $Q_0 = Q_{th}$ is right equal to $1/\epsilon$, so the eq. 3.12 can be expressed as:

$$Q_c \cdot \epsilon = Q_{th} \quad (3.13)$$

but $Q_c$ can also be defined as:

$$Q_c = \frac{T}{\Phi_{\gamma} \cdot s_{\gamma} \cdot \epsilon} \quad (3.14)$$

so that eq. 3.13, recalling the 3.6, is identically true.

While is demonstrated experimentally a strong deviation from the exponential distribution, we insisted so much on this case since in the typical working situation the threshold is set to values corresponding to a still exponential and non saturated avalanche.
Figure 3.10: Calibration of threshold on F.E. electronics in terms of charge per count released in the gas.

It is so possible to make a threshold scanning at fixed source distance to determine the correlation between the minima positions and threshold $V_{th}$. This is shown in fig.3.10 where the source was at 6.5 cm and $V_{th}$ was ranged between -1V and -1.486V.

If the $V_{gas}$ variable is used the minimum position should not depend on the incident rate, as is apparent in fig.3.11.

Figure 3.11: The minimum position does not depend on gamma rate when plotted vs. $V_{gas}$

This gives another way to determine the RPC total plates resistance, imposing the alignment of the minima, and the result is the same as for the previous method.
Nevertheless we see that the minimum value depends on the source distance meaning that the calculated $V_{gas}$, is not sufficient to describe the detector in this voltage range.

![Graph showing the ratio of counting rate to estimated number of photons vs. V_{gas}](image)

**Figure 3.12**: Counting rate to gamma rate ratio.

In fig. 3.12 the ratio of counting rate to estimated number of photons is reported vs. $V_{gas}$. After an initial common slope, very similar to the one typical of minimum ionizing particles efficiency curve, the slopes spread at the knee, increasing with the source distance, to reach a roughly constant value at higher $V_{gas}$. This effect, if is not instrumental, could be due to the albedo photons, whose fraction increases with source distance.

The knee around 10KV corresponds to a sensitivity of 0.85% for the direct component of the photons emitted by the $^{60}Co$ source.
Chapter 4

The saturated avalanche regime

The simple exponential model, recalled in chapter 2, can describe with acceptable accuracy the electronic multiplication phenomena in the gas until one basic assumption cease to be valid: the requirement that the external electric field is not perturbed by the growing avalanche. This can be stated in other way saying that the exponential growth is obtained in case of independent electron scattering, i.e. the probability per unit length of a ionizing collision for the free electrons does not depend on the presence of the other electrons.

The falling of the previous strong requirement forces to abandon a comfortable linear description (eq. 2.1) of the problem when the non linearity is needed to describe the correlations between the electrons.

4.1 Short remarks on non linear systems

Non linear behaviour of physical systems is often associated with strange and peculiar classes of phenomena which subtract themselves to the "classical" approach of reductionism, based on the perturbation theory and on the superposition principle. Nevertheless our every day experience suggest that a linear description of natural phenomena is a rational abstraction that in many cases is false and misleading. This widely happens in many fields of the physics of matter concerning phase transitions, out of equilibrium systems, propagation of solitons in non linear media etc., but it is possible to find important examples in other fields where the reductionist and linear approach was most widely and successfully applied. For example the quark model in high energy physics, the General Relativity in cosmology are intrinsically non linear problems, but also without going so far Henry Poincaré, at about the turn of XIX century noticed the impossibility to describe in a perturbative way the problem of three bodies attracting each other with the Newtonian field.
Historically the study of non linear system is recent because of the intrinsic mathematical difficulties encountered, now partially overcome by the massive use of numerical calculation on powerful computers. One approach to these problems could be to follow each elementary component of the system, obtaining a large-dimensional nonlinear coupled problem that could be attacked with a finite element calculation strategy. On the other hand this way, often highly expensive in term of calculation time, presents also the risk to lose in the discretization the fundamental qualitative properties of the system. Investigation of interacting systems suggest a different approach, as strong correlation have one main consequence: they force the system to respond in a collective-like manner [20]. This introduce in the system new collective constituent objects that are not new fundamental physical entities: they are locked complexes of known elementary particles [21]. These objects are defined by their own space scale and follow a more or less simple set of pseudo-linear laws.

We come back now to the case of electronic avalanches in which the space-charge effects start to be non negligible. In this picture, we could think to describe its evolution in term of a self consistent object with its own properties, as much independent from initial conditions as much the non linearity is prevalent; so it would be possible to define its own proper space scale, independently on the microscopic properties of the component electrons.

4.2 Introduction: previous experimental results as starting point

Since the beginnings of the RPC operated in the "proportional" regime it was apparent that the size of the avalanches produced in normal working point, set not far from the normal limit for the transition to streamer, was well beyond the reasonable limits of validity of the exponential law. Moreover the streamer itself (which is not deeply investigated here), being a localized transition to plasma is a very clear example of a non linear system describing a saturated object which properties does not depend on initial conditions. The figure 4.1 shows how the charge distribution of a sample of triggered cosmic avalanche induced signals depend on the applied electric field. In the hypothesis of standard exponential law, it is well known (and it was also shown with montecarlo simulations [22]) that an approximately $\sim 1/Q$ distribution is expected (a decreasing power law). This figure, on the contrary, shows a gradual transition from exponential to a peaked distribution while the field and so the average avalanche size is increasing.

Moreover we remark, as a further indication, that the generally accepted explanation of the streamer is based on the emission of UV photons coming from
Figure 4.1: Prompt charge distributions of a sample of triggered cosmic rays for increasing applied electric field on a 2 mm gap containing the standard mixture with 1% of SF$_6$. (a)=9.2 KV, (b)=9.37 KV, (c)=9.55 KV, (d)=9.68 KV, (e)=9.9 KV, (f)=10.14 KV
Figure 4.2: Average prompt charge vs. applied voltage, for different percent of $SF_6$.

recombination of ionized electrons, slowed by the screening of the avalanche head that should lower the electrical field in the backward region.

The introduction of $SF_6$ in the mixture as a powerful streamer suppressor [23], made possible the study of deeply saturated avalanche regime. In Figure 4.2 are represented the relations between average avalanche induced signal vs. applied electric field for different quantities of $SF_6$ in the mixture. Here is apparent that, after an initial exponential growth the average induced charge tend to an almost linear path in analogy with the result of the previous chapter in Figure 3.7.

Some of this results about avalanches of high amplification are known since many years form the studies on proportional wire detectors [24], while the usual approach was based on forcing the exponential law, including in the Townsend multiplication coefficient usually called $\alpha$ all the deviation from linearity. Thus $\alpha$ becomes a function of the multiplication to be determined experimentally and loses its original clear physical meaning of multiplication coefficient.

Moving from the previously cited experimental results, we propose here a minimal model of avalanche growth that however preserves the qualitative feature of the non linear saturation mechanism. What we would like is to find the natural mathematical form for the model, introducing explicitly the non linearity in the system, avoiding to force it to be referred to the exponential model.
Figure 4.3: Fit of the experimental points of figure 3.7 with the logistic function’s cumulative

If we consider the points of fig. 3.7, before the start of the streamer, they represent the avalanche average charge per ionization as the electric field increase. In order to find a curve that fits this experimental data we look for a regular function gradually evolving from exponential form at weaker fields to a linear one at stronger fields, with the further request to have the smallest number of free parameters possible. The function:

$$Q(V) = K \ln(1 + \exp^n(V - V_0))$$  \hspace{1cm} (4.1)

fulfilling the stated requirements is applied to the data set with the results visible in figure 4.3.

Although function 4.3 has only 3 free parameters, it reproduces the data set with very good accuracy, meaning that those parameters have a clear physical meaning that will be discussed in the next section 4.3.2.

From the table in figure 4.3 we obtain for the three parameters:

$$K = 16.425 \text{ } pC$$  \hspace{1cm} (4.2)
$$V_0 = 9820 \text{ } V$$  \hspace{1cm} (4.3)
$$a = 3.92 \cdot 10^{-3}V^{-1}$$  \hspace{1cm} (4.4)

Let’s return for a moment to the idea of saturated avalanche. We can figure it in the following way: While the electric field gets stronger the avalanche can reach increasing values of the total charge, in the same drift space, until the space charge effect is strong enough to leave back a certain fraction of the multiplying
electrons, in a region with a weaker field. These electrons keep on moving about at the same average speed (until attached), but they are subtracted from any further multiplication process. Intuitively we can think that this process finds a dynamical equilibrium point when the number of electrons left behind is equal to the number of the newly generated one from the avalanche front. This equilibrium is stable because the space charge acts as a negative feedback on the fluctuations: an overproduction increases the space charge field that pushes backward more electrons and vice versa. So the intuition suggests that the avalanche front (i.e. the active electrons) reaches a stable maximum population and this is the meaning that we attribute to the word saturation. We can imagine an ideal saturated avalanche like a cluster of moving charge that propagates in the gas dissipating energy along the lines of electric field leaving a tail of inactive electrons, and, since the charge configuration is blocked in the reference frame of the avalanche, all the quantities that depend on the electric field tend to a constant in this reference frame. If so, it is apparent the usefulness to treat the avalanche front as a new and well identified independent structure to which the other observable are related.

On the other hand the total charge of the avalanche should tend to increase linearly with the electric field as confirmed in figure 4.3. In this case the function 4.1 can be interpreted as the integral of active population by a generating rate factor. The primitive of the function 4.1 happens to be the so called logistic curve.

4.3 Logistic avalanche model

The logistic equation was discovered by Pierre François Verhulst in the 1845, and was widely used in ecological applications to describe the growth of populations in presence of limited resources, but has universal validity for non linear dissipating systems with limited free energy supply.

Given a system which growth $N$ depends on the independent variable $x$, we can write the following first order non-linear differential equation:

$$\frac{dN}{dx} = \alpha N - \beta N^2$$

(4.5)

where $\alpha$ is the generation rate factor and $\beta$ is the "mortality" rate factor, meaning, in the case of avalanche, the rate at which the electrons are lost from the active avalanche front. $\alpha$ and $\beta$ are here considered constant in first approximation. We can rewrite the above equation in terms of:

$$\frac{dN}{dx} = \alpha N \left(1 - \frac{N}{K}\right)$$

(4.6)

$$K = \frac{\alpha}{\beta}$$

(4.7)
Figure 4.4: Solutions of the logistic equation for $N(0) > K$ (in red), and $N(0) < K$ (in blue) showing clearly that the growth rate tends to zero as $N$ reaches $K$. This is a stable stationary point whatever are the initial conditions. If $\beta = 0 \Rightarrow K = \infty$ this indicates that the growth is exponential and unlimited.

Integration of 4.6 gives the logistic function:

$$N(x) = \frac{K}{1 + C K e^{-\alpha x}}$$

where $C$ depends on the initial conditions. If the initial condition corresponds to a population above $K$, the solution decreases until $K$ is reached. In fig. 4.4 are shown the two possible branches of the solution, for initial condition corresponding to $N(0) > K$ (in red), and $N(0) < K$ (in blue).

We note here an important feature of this kind of equations: any power law on the right end of eq. 4.5, growing more then linearly, brings the system to the same stationary point$^1$. The quadratic non-linear term means that the non-linear effect increases linearly with $N$ and was chosen to have simple calculations, but the result should not change qualitatively also if the non linearity has a different power law.

We could imagine to have much more complicate non-linear terms such as

$^1$As the power of the non linear term increases there are other stationary points contemporary possible (and this, in dynamical systems is called bifurcation), but now we look at the only real and positive one.
polynomials with $n$ independent terms.

$$\frac{dN}{dx} = \alpha N - \sum_{i=2}^{n} k_i N^i$$  \hspace{1cm} (4.9)

In this case we can have more than one real and positive stationary point and the system can be brought to a chaotic behaviour. In fact for $n \geq 3$ the above equation is equivalent to a system of $n \geq 3$ non-linear differential equations in $n$ independent variables, and this is the minimal requirement for chaotic behaviour [19]. In our case we work with the first hypothesis because we saw that a single parameter non-linear term has a very good fit (the $\chi^2/\nu$ does not improve adding another term) and we have evidence of a well defined single stationary point of the system corresponding to the saturated charge of the avalanche front.

We can interpret the quadratic non-linearity in terms of electronic saturated avalanche: in this case we assume that the saturation phenomena are originated by the increasing space-charge field of the growing avalanche. This is generated between the moving avalanche front electrons and the standing ions, left behind, approximately in a double layer configuration [13]. Each of the $N$ electrons belonging to the front, feels all the other in terms of this field that increases linearly with the charge density (and so with $N$ in first approximation). Its effect is that some electrons find themselves in a screened field area, so that they are subtracted to the multiplication phenomena, while the others keep on multiplying. We will call the unscreened electrons the “active” avalanche.

Moreover has to be noted that this description is just an interpretation of the equation 4.6. This one is extremely schematic not including any detail about the charge distribution of the avalanche, but tries to describe the system in terms of few global parameters.

### 4.3.1 Spatial and field saturation

We rewrite now eq. 4.6 in the case of electronic avalanche running along the lines of a fixed external electric field:

$$\frac{dQ}{dx} = \alpha Q \left( 1 - \frac{Q}{K} \right)$$  \hspace{1cm} (4.10)

$$K = \frac{\alpha}{\beta}$$  \hspace{1cm} (4.11)

$$Q(x = 0) = n_0$$  \hspace{1cm} (4.12)

where $Q$ is a dimensionless variable proportional to the charge, $\alpha = \alpha(\nabla)$ and $\beta = \beta(\nabla)$ are multiplication factors per unit length related to the fixed electric field value, and $Q(0)$ is the ionization cluster size.
In this formulation the attachment is not included explicitly, but it can be done redefining $\alpha \Rightarrow \alpha - \gamma$, where $\gamma$ is the attachment probability per unit length, as the effective multiplication coefficient. When the attachment will be crucial for the model development $\gamma$ will be explicitly introduced.

We would like to bring the attention on the fact that the saturation phenomena, in this model, are not to be ascribed to the attachment effect, which acts as a linear term in the differential equation. Instead it is attributed to the self interaction of the multiplying electrons bunch as described by the quadratic term. The plot in figure 4.2 gives a strong confirmation of this description: different percent of $SF_6$, an extremely electronegative gas, has a very strong effect on the working point; nevertheless all the curves seem to be the same by a translation on the field axis, and the straight line slope, which is the signature of the saturation, does not depend on the $SF_6$ presence.

In these calculation we will suppose that the avalanche has one single starting point corresponding to a cluster with $n$ electrons released in a small volume. We suppose also to control the starting point in such a way that the total drift space is fixed by us. This is obtainable for instance with a collimated UV laser pulse. In our real case the cosmic rays, as ionizing particles, produce a path of many ionization clusters along the track inside the detector which positions are not under control, depending on the Poisson statistics. Furthermore there is little hope that the avalanches produced by the clusters behave in independent way one respect to the other. Anyhow we try to study the theory in the ideal case trying to apply its extrapolation to the real experimental case.

The eq. 4.10 represents the more natural idea we have of the saturating avalanche, in analogy with other physical systems which saturate moving in space or evolving in time. For the electronic avalanches in RPCs we have also the possibility to fix the total drift space, treating it like a parameter, and consider the evolution of total charge as a function of electric field expressed here in terms of applied voltage on a fixed distance. This is also the normal operation on this detector, used to obtain the data of figure 4.3, the cumulative of a logistic function that derives from the following differential equation:

$$\frac{dQ}{dV} = aQ \left(1 - \frac{Q}{K'}\right)$$

(4.13)

$$K' = \frac{a}{b}$$

(4.14)

$$Q(V = 0) = n_0$$

(4.15)

where $a = a(\pi)$ and $b = b(\pi)$ are multiplication factors per unit field related to the fixed drift space value. In principle it seems that the population limit in
case of field saturation $K'$ has nothing to do with the limit $K$ for field saturated avalanches. If now we suppose by hypothesis that $K = K'$ this would bring as a consequence that, when the avalanche front reaches its maximum population, $K$ does not change its value both for drift space increment and for field increment, but depends only on the gas composition:

$$\frac{\alpha(V)}{\beta(V)} = \frac{a(\pi)}{b(\pi)} = K$$

(4.16)

This is a very strong position and derives directly from the fact that we experimentally observed the field saturated avalanches, as it will be demonstrated at the end of this paragraph, by a sort of gedanken experiment.

A first consequence of eq. 4.16 is that $\alpha$ and $\beta$ must have the same functional dependence from $V$ as well as $a$ and $b$ from $x$, also if we are not making any supposition for the moment except that are increasing functions of their arguments.

The formulation in eq. 4.13 is important for two reasons: the first is that it represents the realistic experimental situation of a detector with a fixed drift space and a variable electric field. The second has more to do with the basics of the model, that interconnects the two pictures and permits to have information on the first investigating experimentally the second and vice versa.

If we now stay in the low charge limit, the eq. 4.10 and 4.13 describe an exponential law. Making a first order approximation, we can think that a variation of field $\Delta E$ at fixed drift space is equivalent to a global rescaling of the system in terms of multiplication average length $\lambda_m$ for the electrons. In other words, increasing the field means that $\lambda_m$ decreases, in first approximation in inversely proportional way respect to the field increment, so that the same drift space contains a proportionally increased number of $\lambda_m$. This should be equivalent to a proportionally bigger drift space $\Delta x$ with fixed $\lambda_m$ and field.

$$\Delta E \sim \Delta x$$

(4.17)

Of course there is a limit to this exercise because at lower field other field-dependent phenomena like electron attachment by electro-negative gases start to modify the situation.

We illustrate this connection in the low charge limit, taking the first order (linear) approximation in $\epsilon = \frac{Q}{E}$ of the 4.13:

$$\frac{dQ}{d\pi} \frac{dV}{d\pi} = \alpha(V)Q(1 - \epsilon)$$

(4.18)

equivalent to:

$$\frac{dQ}{d\pi} = \frac{\alpha(V)}{E}Q(1 - \epsilon)$$

(4.19)
where \( E = V/g \) is the applied electric field. In this case, if we suppose that \( \alpha = 1/\lambda_m \) is proportional to the electric field, the integration of 4.18 and 4.19 brings to identical results, introducing a new constant \( a = \alpha/E \).

This procedure is permitted by an understanding hypothesis, certainly verified in the exponential limit: that the applied electric field \( \frac{dV}{dx} \), from which depends \( \alpha \), coincides with its value inside the gas volume, point by point. This hypothesis unfortunately falls in the moment we suppose a non negligible influence of the space charge field, like in the case of logistic avalanche model.

Nevertheless we will see that this connection between the two equations keeps also in the opposite limit of saturated avalanches, as a consequence of the identification \( K \equiv K' \).

We now look at the field saturated avalanches that represents the part directly accessible with measurements in our system. If we suppose that the saturation is due to the space-charge effect, the relation 4.13 shows that the same number \( K' \) of electrons can saturate the electric field independently on its value. A basic explanation, of this unexpected feature, can be given considering that a field increment shortens the characteristic length scale of the avalanche front and, as consequence, increases charge density in the way needed to saturate the increased field.

We must insist on the saturation in terms of field since it is the key feature that characterizes this model. A priori one could expect that the value of \( K \) in equation 4.10 depends on the fixed value of the applied electric field. For example we can make an analogy with the classical system of a free falling body in a viscous medium: we have a body falling in a constant gravity field, that reaches after a certain path a maximum falling speed, that anyhow depends on the value of the applied field. The analogy stops here, since in our case the maximum value of the multiplying avalanche charge under a constant electric field does not depend on it, as it is shown by the experimental data, and the mechanism that produce this behaviour, like for example the one described above, it is one of our problems.

The consequences of this phenomenology are not obvious and recall the empirical Meek law [24] that binds the start of the streamer, for noble gases, to the reaching of a certain number of electrons (\( \sim e^{30} \)) in the precursor avalanche, regardless of the other experimental conditions like pressure, temperature and applied electric field. Looking at figures 4.2 and 3.7 we can see that the presence of \( SF_6 \) renders the start of the streamer quite independent from the total charge of the precursor, but what remains almost unchanged from the charge accumulated is the start of the linear slope that indicates the reach of the saturated regime.

Let’s consider now a fixed drift space system (\( \mathcal{E} = g \) can be the gap of an RPC) with a certain applied field (\( \mathcal{E} = V/g \)).
With the purpose of demonstrating the interconnection between field saturation and space saturation, assume a field saturated avalanche. In this case saturation means that the amount of "active" charge at the end of the anode plane is independent on the applied field and is equal to $K'$. This charge is the result of the avalanche multiplication along the drift space. This means that if we follow the avalanche along its evolution, it must reach the saturated size in some point $x_s$ inside the gap$^2$. As a consequence, during the drift motion from $x_s$ to $g$, the avalanche size must remain constant. As a conclusion the avalanche saturate also in terms of drift space, with the same active charge $K'$.

So we demonstrated that the eq. 4.16 is correct in the hypothesis of field saturation. The consequences of this on the relation between the coefficients are illustrated in the next section.

### 4.3.2 Active and total charge

Starting from eq. 4.6,4.10 we perform the integration with the given initial conditions $Q(0) = Q_0$, to obtain the evolution of active avalanche $Q_{act}$ as a function of $x$ or $V$:

$$Q_{act}(x) = \frac{K}{1 + e^{-\alpha(x-x_0)}}$$  \hspace{1cm} (4.20)

$$x_0 = \frac{1}{\alpha} \ln \left( \frac{K}{Q_0} - 1 \right)$$  \hspace{1cm} (4.21)

$^2$Saturation occurring exactly at the anode plane would require that the avalanche "knows" about the anode plane position, thing that we reasonably exclude by hypothesis.
\[ Q_{act}(V) = \frac{K}{1 + e^{-a(V-V'_0)}} \]  \hspace{1cm} (4.22)

\[ V'_0 = \frac{1}{a} \ln \left( \frac{K}{Q_0} - 1 \right) \]  \hspace{1cm} (4.23)

The 4.20 and 4.22 are logistic functions. The logistic function \( Q(V) \) is represented in fig. 4.5 along with the first derivative:

\[ \frac{dQ_{act}(V)}{dV} = \frac{aKe^{-a(V-V'_0)}}{(1 + e^{-a(V-V'_0)})^2} \]  \hspace{1cm} (4.24)

The derivative has a stationary point, occurring for \( V = V'_0 \), where \( Q_{act} = K/2 \).

It could be interesting to rewrite the 4.22 and 4.22 in terms of hyperbolic functions:

\[ Q_{act}(V) = \frac{K}{2} \tanh \left[ a/2(V - V'_0) + 1 \right] \]  \hspace{1cm} (4.25)

\[ \frac{dQ_{act}(V)}{dV} = \frac{aK \cosh \left[ a/2(V - V'_0) \right]}{2 \cosh \left[ a(V - V'_0) \right] + 1} \]  \hspace{1cm} (4.26)

the same apply for the variable \( x \).

The initial condition for 4.22 can be read as: \( V = V'_0 \Rightarrow Q_{act} = K/2 \). We would like to modify the expression 4.22, so that the initial condition can be referred to the real physical situation in which, for a certain \( V = V'_0 \), we have in the gas only the an average number of electrons equal to the primary ionization \( Q_0 \). In an ideal case we could think that \( V'_0 = U'_0 \), being \( U'_0 \) the gas ionization potential. The experience instead shows that for each gas a minimum field exists, of the order of \( 10^4 \text{V cm}^{-1} \), that permits to the multiplication to take place effectively.

The relations 4.22 becomes then:

\[ \frac{K}{1 + e^{-a(V-V'_0)}} \Rightarrow \frac{K}{1 + A_0e^{-a(V-V_0)}} \]  \hspace{1cm} (4.27)

\[ V'_0 \Rightarrow V_0 + \frac{1}{a} \ln A_0 \]  \hspace{1cm} (4.28)

\[ A_0 = \frac{K}{Q_0} - 1 \]  \hspace{1cm} (4.29)

this equation should now be read as for \( V = V_0 \) the free charge in the gas is only the initial charge \( Q_0 \), defined by \( A_0 \). This offset voltage can be explained with the attachment and the non-ionizing energy dissipating processes of the free charges accelerated in the gas. If for \( V = V_0 \) \( \Rightarrow Q_{act} = Q_0 \), it doesn’t mean that
the initially released electrons drift undisturbed toward anode, but instead that we have an equilibrium between produced and attached charges so that in average we have $Q_0$ free electrons in the gas.

On the side of spatial saturation a similar offset could be due to the multiplication length, that have to be smaller than the gap, but we don’t have experimental data about it and so it is not introduced.

**Relation between $a$ and $\alpha$** The functions 4.20 and 4.22 are the same by exchange of the argument of the exponential, being this possible thanks to the common value of $K$. In particular choosing two values $V = V$ and $x = \pi$ so that the saturation is substantially reached ($Q_{act} \simeq K$), in the limit of $x \geq \pi$ and $V \geq V$ the two equation become identical as a consequence of the saturation:

$$Q_{act}(x) \equiv Q_{act}(V) \Rightarrow \alpha_{\pi} \cdot x = a_{\pi} (V - V_0)$$  \hspace{1cm} (4.30)

Where the notation $\alpha_{\pi}$ and $a_{\pi}$ indicates parameters calculated for fixed values of the subscript variable.

It is possible to use the last relationship to estimate $\alpha_{\pi}$ once that $a_{\pi}$ has been extracted from experimental data, calculating 4.30 in the $x = \pi = g$ point that correspond to the real measurement:

$$\alpha_{\pi} = \frac{a_{\pi}(V - V_0)}{g}$$  \hspace{1cm} (4.31)

This demonstrate that the rescaling of multiplication length $\lambda_m$ with the applied field, already viewed in eq. 4.17 not only keeps to be valid in a fully saturated condition but it is also rigorous.

Before the calculation of the total charge it is opportune to spend some more words about the two multiplication coefficients $a$ and $\alpha$. Someone for example could object that $\alpha$, being a function of the field, can not be a constant parameter because the field is deformed by electrons space-charge, while the applied field is constant (and analogously for $a$).

What can be certainly said is that, for negligible space-charge, $\alpha$ is well defined and constant all over the drifting path and for all the free electrons. Moreover, when the avalanche is saturated we find that $\alpha$ is constant as well, by definition of saturation, being the charge distribution fixed in the reference frame of the avalanche. The question is if the two constants coincide or not, assuming for $\alpha$ an evolution law between the two constant values. These last options would contrast all the present strategy that consists essentially in finding a mathematical representation that introduces a minimum number of constant parameters, leaving the non linearities embedded in the very structure of the function. From this point of view it is possible instead to change the non linear term of 4.5 with a more
complicated one, containing further constant parameters, in equivalent way to the case of a variable $\alpha$. On the other hand we saw that is not very useful to complicate the minimal model introduced, since it describes very well experimental data; so we keep, with good approximation, the same constant values for multiplication coefficients in the linear and in the saturated traits.

**Calculation of the total charge**  The situation described is of a saturated avalanche moving with constant active charge and producing new electrons with a constant rate $\alpha$ (or $\alpha$) that is the same of the exponential trait. An increase of voltage produces a corresponding increase of $\alpha$ as stated in eq. 4.31.

Now it is easy to define the total charge of the avalanche as:

$$Q_{tot}(x) = n_0 + \int_0^x Q_{act}(x')\alpha \, dx' = n_0 + K \ln \frac{1 + e^{\alpha(x-x_0)}}{1 + e^{-\alpha x_0}} \quad (4.32)$$

and in the domain of field:

$$Q_{tot}(V) = n_0 + \int_0^V Q_{act}(V')\alpha \, dV' = n_0 + K \ln \frac{1 + e^{\alpha(V-V_0)}}{1 + e^{-\alpha V_0}} \quad (4.33)$$

notice that the initial ionized charge is added by hand to $Q_{tot}$, since the integral provides all the electrons ever produced by the active avalanche. This is zero for $x = 0$ or $V = 0$, because the initial charge is released by the ionizing particle and is considered the initial condition for the active avalanche.

These expressions do not distinguish the different stories of the electrons after production, if they arrive to the anode free or attached to atoms, but simply give the total charge produced in the gap as it can be measured on the voltage supply circuit.

In the case of attachment, substituting $\alpha$ with $\alpha - \gamma$ in $Q_{act}$ the expression 4.32 becomes:

$$Q_{tot}(x) = n_0 e + \int_0^x Q_{act}(x')\alpha \, dx' = n_0 e + \frac{\alpha}{\alpha - \gamma} K \ln \frac{1 + e^{\alpha - \gamma(x-x_0)}}{1 + e^{-\gamma(x-x_0)}} \quad (4.34)$$

obviously the production rate in the integral remains $\alpha$. This expression will be used further on in the chapter.

It is interesting to highlight at this point one of the consequences of the saturation on the dependency of total charge on initial conditions. As it is apparent observing eq. 4.33 and 4.22, $Q_{tot}$ depends in logarithmic way from initial cluster size (that is included in $V_0$), and not linearly as for the exponential avalanche. This is shown in figure 4.6, obtained from eq. 4.33, having everything fixed except the cluster size.
Figure 4.6: Total charge achieved by an avalanche vs. size of initial electrons cluster, for fixed field and drift space.

Figure 4.7: $Q_{act}$ and $Q_{tot}$ vs. applied voltage, calculated with the logistic model, in which the parameters were fixed by fitting the experimental data.
In fig. 4.7 $Q_{tot}(V)$ and $Q_{act}(V)$ are plotted together vs. applied voltage. In particular $Q_{tot}(V)$ is the same curve of fig. 4.3 since it is defined with the same values for the parameters that characterize the present gas mixture (see chapter 3): $V_0 = 9 \text{ KV}$, $K = 16.4 \text{pC}$, and $a = 0.0039 V^{-1}$. It is easy to notice that $V_0$ in 4.33 here corresponds to the intercept between horizontal axis and the $\lim_{V \to \infty}$ of the tangent.

Anyhow it is necessary to remark that the curve 4.3 refers to an experimental situation different from the assumption, used for calculations, of single ionization cluster. This aspect is treated in the following section.

### 4.4 Realistic case: multi-clusters

As already stated elsewhere, the typical ionizing events produces a track of charge clusters inside the gap of an RPC. The position and the size of these clusters fluctuates randomly with Poisson and by Landau statistics respectively.

In the case of exponential avalanche we already treated this case in chapter 2, applying the superposition principle and considering the total charge as the sum of avalanches each starting from the cluster position. Then, imaging of smearing the total primary charge uniformly along the track, that corresponds to an average on initial positions, the average total charge per event was obtained by integration.

Is not possible anymore to apply this technique for two main reasons: the first is that if the distance of two primary clusters is of the order of the length scale of the saturated avalanche, the two avalanches are not distinct at saturation from the point of view of the total active charge, that always worth the same $K$. So in this case the total charge is not the sum of charges but the charge of an avalanche with the sum of primary clusters as initial condition, that is much less as demonstrated in fig. 4.6. The other reason is that we cannot treat as independent also the clusters that remain separated along the path, due to the distortion on electric field they induce on each other.

Clearly it is not possible to handle this problem with the present approach since nor the charge structure of the single avalanche, neither the electric field effects are introduced explicitly in the theory. What is needed is a general propagation equation for the saturated avalanche, including the field effects, a solution of which is the charge spatial distribution of the avalanche. Although the problem is currently under study, it is beyond the target of this thesis.

In order to be able to interpret experimental data, we tried to find a reasonable extrapolation of the logistic model in which the above effects are treated in approximate way.
4.4.1 Analysis of the total charge experimental curve

Starting again from the figure 4.3 or equivalently from figure 4.7 we can make the following observations:

- The fit of experimental points is consistent with a single cluster avalanche, as we applied the model developed since now under this assumption (eq. 4.33), predicting that the total charge tends asymptotically to a straight line. From the fit it results that this saturated object is constituted by $\sim 16 \, pC$ of active electrons (corresponding to $\sim 2 \cdot 10^8$ electrons), producing charge with a rate of $3.92 \, KV^{-1}$.

- A charge of $16 \, pC$ corresponds more or less to the knee point that connects the exponential part to the linear part. In fact $Q_{tot}$ and $Q_{act}$ should coincide in the limit the avalanche is not saturated, if we neglect the fraction of attached electrons by electronegative atoms. At this point we can still say that each primary cluster contributes to the active (and so also to the total) charge with a weight that is exponential with the total drift space.

- From this point in which the active charge remains more or less constant, can organize itself in various ways, while evolving.

One possibility is to form certain number $n_0$ of ”super-clusters”, that do not necessary coincide with the initial ones, each tending to the same value of active charge $K_0 = 16/n_0 \, pC$ by definition of saturation. In fact, as we already said, if two initial clusters are too near, they melt in one with total active charge $K_0$. What we cannot say is the value of $n_0$ and $K_0$ knowing from the data only their product. The problem of establishing a relation between the initial primary clusters and the final saturated clusters involves the study of the evolution of a non linear dynamical system having initial random seeds. This is not developed here but is an important point, since it can gives information about the real saturated avalanche charge $k_0$, due to a single cluster, that is strictly bound to the gas properties. Furthermore, from measurements made with collimated laser pulses, it should be possible to measure such charge and extract information about the effective number of saturated avalanches $n_0$. This number is connected with the dynamic of such interesting system and with its parameters like the space length scale of the active avalanche.

Another possibility is that the charge evolves as a whole object, loosing completely the memory of the initial cluster distribution. In this case it should be treated as a single saturating avalanche, shaped on the entire gap.
A final note on the initial conditions: setting \( V = 0 \) in the eq. 4.22, with the present parameters values, \( Q_{act}(0) = 2.8 \cdot 10^{-18} \, \text{pC} \) is obtained which is difficult to be explained in physical terms. So is convenient to introduce a physical voltage offset \( V_0 \neq 0 \), at which the free charge in the gas is \( Q_{act} = Q_0 \), in order to fix correctly the initial condition, as is done in eq. 4.27. Looking at equations 4.27, we can calculate such offset as a function of total expected initial ionization:

\[
9820 = V_0 + \frac{1}{0.00392} \ln \left( \frac{16}{Q_0} - 1 \right)
\]

that gives

\[
V_0 = 9820 - \frac{1}{0.00392} \ln \left( \frac{16}{Q_0} - 1 \right)
\] (4.35)

In figure 4.8 this logarithmic dependency is plotted. A reference offset value of \( \sim 6500 \, \text{V} \) is also indicated for the average initial charge expected for \( 2 \, \text{mm} \) thickness of standard ATLAS gas mixture, that is of 15 clusters with 3 secondary electrons each. This offset is probably due to the attachment probability that is much higher for lower field due to the lowering of electron velocity distribution.

### 4.4.2 Calculation of \( Q_{act} \) in case of independent clusters

Now we suppose to have \( n_0 \) clusters, each producing an avalanche that tend to the same saturated charge \( 16/n_0 \, \text{pC} \), in function of applied field, and running in a drift spaces that depend on initial cluster positions. Supposing to ignore the field effect of each avalanche on the others we calculate the overall active charge in function of applied field:

\[
\frac{dN_i}{dV} = a_i N \left( 1 - \frac{N}{K} \right)
\] (4.36)

\[
Q_{att}(V) = \frac{K}{1 + A_0 e^{-a_i(V-V_0)}}
\] (4.37)

\( a_i \) is defined as the multiplication rate coefficient per unit field, for the i-th cluster of the \( n_0 \), starting from the anode, running for a space \( x_i \). Since this coefficient scales linearly with drift space:

\[
a_i = a \frac{x_i}{g}
\]

where \( a \) is the coefficient for the maximum drift space \( g \). Now we suppose to have regularly distributed primary cluster positions. We remember in fact that, if
two initial clusters are too near, they should be considered as one cluster, so the
distribution of the distances between clusters is not anymore exponential but has
a peak. In the approximation of equidistant clusters we have:

\[ a_i = \frac{i}{n_0} \]  \hspace{1cm} (4.38)

where \( i \) is the cluster index, increasing from 1 to \( n \), starting from the cathode. For
the overall charge we have:

\[ Q^{n_0}_{\text{act}}(V) = \sum_{i=1}^{n_0} \frac{K}{1 + A_0 e^{-\frac{a_i}{n_0}(V-V_0)}} \]  \hspace{1cm} (4.39)

In figure 4.9 \( Q^{n_0}_{\text{act}}(V) \) is plotted vs. applied voltage for \( n_0 = 1, 2, 4, 6 \) respectively. The lower is \( x_i \), the higher is the voltage for which we can recognize the
contribution of that cluster, since it refers to a smaller value of \( a_i \). The red curve
corresponds to the one derived from data (see figure 4.7), and the other cases are
clearly far away from a realistic description still compatible with the observed
saturation.

Figure 4.8. How the voltage offset \( V_0 \) depends on the supposed initial electrons cluster size,
being \( V_0' \) fixed by experimental data fit.

![Graph showing the relationship between Q0 (electrons) and V0](image-url)
4.4.3 Hypothesis of interaction between clusters

A way to generalize the equations 4.22 and 4.33 to the multi-cluster case, preserving the experimental result fitted in fig. 4.7, is to modify somehow the electric field that interests each cluster. We have to find the conditions under which the two members of equation below are identical:

\[
\int_0^V Q_{act}(V') a_g dV' \equiv \int_0^V \sum_{i=1}^n Q_{act}^i(V') a_{x_i} dV'
\]

(4.40)

where the sum is over the \( n \) clusters each having a drift space \( x_i \). In the saturated zone \( Q_{act}^i \), the active charges of single clusters are constants so the integration become trivial. Remembering that \( Q_{act}^i \) depends on \( a_{x_i} V \) and making the hypothesis that \( V \) is different for each cluster we rewrite 4.40 in the following way:

\[
Q_{act}(a_g V) a_g \Delta V \equiv \sum_{i=1}^n Q_{act}^i(a_{x_i} V_i) a_{x_i} \Delta V_i
\]

(4.41)

where \( \Delta V_i \) are related to \( \Delta V \) trough the introduction of \( f_i \) so that \( \Delta V_i = \Delta V \cdot f_i \). We introduced the index on \( Q_{act}^i \) to distinguish it from \( Q_{act} \), since now the dependence from \( i \) is inside the parameter \( a \). Now to have the equivalence of the two members we suppose that:

\[
a_{x_i} \cdot f_i = a_g \quad \forall i
\]

(4.42)
It is easy to find that under this hypothesis also happens that:

\[ Q^d_{act}(a_x V_i) = Q^d_{act}(a_x V_j) \quad \forall i, j \]  

(4.43)

because they depend on the same argument. So also the sum become trivial:

\[ Q_{act}(a_g V) a_g \Delta V = n Q^d_{act}(a_x f_i V) a_x f_i \Delta V \]  

(4.44)

from which the equivalence 4.41 is demonstrated remembering eq. 4.42 and imposing \( Q_{act} = n Q^d_{act} \). Since this is valid \( \forall V \) it’s easy to extend it to eq. 4.40.

The strong hypothesis introduced to demonstrate the previous equivalence is that the electric field, felt by each cluster, have to lower with respect to the applied field as \( a_x \) increase linearly with \( x_i \), due to the larger drift space, in such a way to exactly compensate it.

A possible effect that goes in this direction is based on how the clusters have influence on each other, moving on the same track. Now we will try to calculate such effect in a very simplified way.

We consider three contribution:

- the negative avalanches starting at \( x_i \) moving with constant velocity toward the anode. The avalanche charge increase linearly with space, until it reaches the anode, while the shape is fixed and described by a cylinder with same diameter and height.

- Each avalanche leaves behind a positive tail of ions, steady in the avalanche development times, with constant density since we consider the active avalanche already saturated. Also this charge distribution is described by a cylinder with the same diameter of the electron avalanche and a height corresponding to the distance between the initial cluster position \( x_i \) and the electron avalanche. The total positive charge belonging to the positive tail is obviously equal to the total negative charge of the electrons (in the case of negligible attachment).

- Finally, while the electronic avalanches arrive subsequently on the anode, their charge spread there on a small surface, generating a field contribution described by a charged disk placed on the anode. At the end of the process this disk will contain the charge of all the electrons generated.

We make the following conventions: \( g \) is the maximum drift space, \( n \) (indexed with \( i = 1, ..., n \) starting from the cathode) is the number of clusters, \( d = g/(n+1) \) is the average distance between clusters, \( E_{eq}(x_0, s_0, h_0, \rho) \) is the electric field calculated in the point \( x_0 \), on the axis of the described charge system, due to a charged cylinder of density \( \rho \), \( s_0 \) is the coordinate where its base is placed and \( h_0 \)
Figure 4.10: Schema of the charge distributions of a multicluster avalanche. In pale red is represented the positive ion tail, in light blue the free electrons (active and inactive), in dark blue the discharge zone.

the height. In figure 4.10 is represented the schema of this charge system. We call $R$ the radius of the cylinder, considered as a fixed parameter.

The electric field contribution on the axis, due to a charged disk of radius $R'$ placed on the anode with its axis coincident with the avalanche path is:

$$E_{\text{disk}}(x_0, \rho) = \frac{\rho (x_0 - g)}{2\epsilon_0} \left( \frac{1}{\sqrt{(x_0 - g)^2 + R'^2}} + \frac{1}{\sqrt{(x_0 - g)^2}} \right)$$ (4.46)

Now we can calculate the global effect of the various contributions using expression 4.45 as a building block for positive tails and negative avalanches, and
4.46 for deposited negative charge on the anode. It is also possible to include the
time dependence in the arguments of 4.45 and 4.46.

For positive tails in the approximation of equally spaced clusters:

\[
\begin{align*}
    s_0 &= i d \\
    h_0 &= vt \\
    \rho &= \rho_0 \quad \text{(constant)}
\end{align*}
\]

For the negative avalanches, having by hypothesis \( ss \) as a fixed width along \( x \)
coordinates:

\[
\begin{align*}
    s_0 &= i d + t \\
    h_0 &= ss \\
    \rho &= -\rho_0 \frac{v t}{ss}
\end{align*}
\]

Finally for the negative charge on the anode:

\[
\rho = -\frac{\rho_0 (g - i d)}{2\pi \epsilon_0 R^2 g} \xi(i d + t - g)
\]

where the \( i^{th} \) cluster’s charge contribution is added only when the relative avalanche
reaches the anode, thanks to the \( \xi \) function.

Summing over the index \( i \), the electric field along the axis of the avalanche is
obtained as a function of space and time:

\[
E_{axis}(x_0, t) = \sum_{i=1}^{n} \left[ E_{cyl}(x_0, i d, v t, \rho_0) + E_{cyl}(x_0, i d + t, ss, -\rho_0 \frac{v t}{ss}) +
E_{disk}(x_0, -\frac{\rho_0 (g - i d)}{2\pi \epsilon_0 R^2 g} \xi(i d + t - g)) \right]
\]

The twenty frames in figure 4.11 represent the value of the electric field generated
by all the avalanches on the axis, for successive time intervals of 1ns, supposing
to have a total drift time of 20ns on \( g = 2 \)mm. The parameters are arbitrary
set to reasonable values for the avalanches described since now, given that this
calculation is mainly performed for a qualitative study.

A positive value of the field means that the space charge field direction is
opposite to the applied field (the anode is on the right side). We observe that the
highest values are reached by the edges of the series of negative avalanches: on
the left side because of the discontinuity of the charge distribution, on the right
because of the accumulation of negative charge on the anode. The general effect
is that the more the cluster starts far from the anode respect to the others, the more
Figure 4.11: Electric field due to the internal charge distribution. On the horizontal axis is represented the $x$ coordinate in mm, on the vertical the electric field in V/mm. Each frame corresponds to a different time instant.

the average perturbation experienced by that avalanche is stronger. This goes in the right direction in order to confirm the relation 4.40, but this rough analysis doesn’t permit to give an exact demonstration.

The main limit is that we introduced the same charge growing rate for each avalanche, in order to calculate the electric field, ignoring the dependency of the growing rate from this last. So this calculation could be considered as the first step of a recursive procedure that tend to correct the growing rate of the avalanches, clearly favoring the ones with a lower average value of the perturbing electrical field.

Looking again at the figure 4.11 we notice that the clusters in the middle are the most favored, since they are both screened backward and enough far from the anode to have the maximum path with the lowest possible perturbation. To confirm this we can plot the electric field felt by the $i^{th}$ avalanche along its path, as represented in figure 4.12 and defined by $E_i(t) = E_{axi}(i d + t, t)$. 

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Let the external field $E_0$ to be $500 \, V/mm$ above the saturation knee ($V_0/g$ in eq. 4.33), normally corresponding to the full saturation. The field really experimented by the $i^{th}$ avalanche is then $E_i = E_0 - E_i(t)$. We suppose that for $E_i$ above $500 \, V/mm$ the avalanche total charge grows with a rate that is linear with $E_i$, below decrease exponentially according to the logistic model.

Performing a time integration for each avalanche, we can calculate the effective contribution for each cluster at the end of the story i.e. the charge of the avalanches arriving in sequence to the anode. The result of such calculation is shown in fig. 4.13.

As already remarked this should be considered just as the first step of a recursive calculation, where the lastly calculated electric field map should be used to correct the charge distribution from which another field map comes out to repeat the cycle. This is done in order to find, if exists, a stable self-consistent solution for the charge distribution density, that generates the perturbing field, representing the real avalanche “profile”.

Figure 4.12: Electric field perturbation (in $V/mm$) felt from each cluster along its path (in $mm$) toward the anode. Each frame is referred to a single cluster starting from the farther from the anode (up-left) up to the nearer (down-right).
**Figure 4.13**: Charge contribution at the anode (in arbitrary units) of each cluster (on the horizontal axis), for first order iteration on the electric field dependent production rate, in the hypothesis of a uniform cluster’s contribution at order-0. This plot represents the charge density profile of the avalanche.

We can say that the clear peak of fig. 4.13 should become more symmetric with further iterations, since the charge of the very first clusters should decrease respect to the initial hypothesis, resulting in a less effective screening of inner clusters and that let the charge to grow up more slowly than in fig. 4.13.

This result seems to be confirmed by the first step of the described calculation, the results of which are illustrated in figure 4.14. The starting point charge distribution is the first on top and any of the successive is obtained introducing the electric field correction due to the previous iteration. This perturbative procedure, anyhow, is not suitable for obtaining detailed results, since the system is highly non linear, and the recursive stepwise evolution of such systems could easily brings to a variety of possible orbits in phase space, also possibly toward chaotic behaviour, depending on system initial parameters and on the discretization used.

To make an extreme case let us take $d = h_0$, that means that the negative charge distribution is continuous. In this situation the individual avalanches loose their identity and we have a smooth negative charge distribution flowing from the first cluster position toward the anode, in which the linear density presents a peak that is modulated by the self generated field inside the distribution.

In this picture we loose any residual of a superposition applicability in avalanche description, since we are forced to describe avalanche like a whole object and not like the sum of avalanches from the single clusters. In this picture each part influ-
Figure 4.14: Some of the recursive calculation steps for the avalanche profile. On the horizontal axis is reported the cluster index, on the vertical the charge contribution at the anode in arbitrary units.
ences the other in a complicated way probably similar to the case of single cluster avalanche, since experimentally it behaves in a similar way, and the initial cluster positions can be considered as a sampling of a bigger object. This very interesting perspective is not further investigated here because the best way for carrying it out is to find the avalanche propagation equation, as stated before, in order to introduce explicitly the density function as its unknown solution.

4.5 Signal induction in the logistic avalanche model

Until this point we tried to describe the avalanche development in RPCs in terms of total negative charge of the average event produced in function of applied electric field an available drift space. In this section we are going to study the induction of the signal on a metallic readout strip-line, in case the avalanches follow the logistic model.

This point is crucial for the two following reasons: The first is that it is important to calculate the amplitude of the available signal respect to the total charge released in the gas for different values of detector parameters; this in fact helps to give a precise description of the detector in terms of dynamic range of the signal, simulated charge distribution, best working point and rate capability. The other reason is that this provides another independent information that can be easily compared to experimental results. We will be interested particularly in the calculation and measurement of total charge to prompt charge ratio, being this a powerful benchmark for the reliability of the model.

4.5.1 Fast and slow negative charge

Until now we did not make distinction between the different destiny of a negative charge produced in the gas: if it reaches the anode as free electron or attached to an electronegative gas atom. This is important mainly for the calculation of the fast signal picked up on the detector readout system, the so called “prompt charge” \( Q_{pr} \). In fact only the free electron component \( Q_{free} \) of the negative charge is considered to produce the fast signal since the ions are a factor \( \sim 10^3 \) slower.

In the exponential model the presence of the attachment introduces a distinction between \( Q_{tot} \) and \( Q_{act} \) (that in this case coincides with \( Q_{free} \)):

\[
Q_{act}(x) = Q_0 e^{(\alpha-\gamma)x} \\
Q_{tot}(x) = Q_0 + \int_0^x Q_{act}(x') \alpha \, dx' = \frac{Q_0 \alpha}{(\alpha - \gamma)} \left[ e^{(\alpha-\gamma)x} - 1 \right]
\]

where \( \gamma \) is the attachment probability per unit length.
In the logistic model, as we know, $Q_{act}$ do not coincides with $Q_{free}$. Making the hypothesis that $\gamma$ is the same both for the active charge and for the remaining free charge, that is certainly true along the exponential trait, $Q_{free}$ is defined by the following differential equation:

$$\frac{dQ_{free}}{dx} = \alpha Q_{act}(x) - \gamma Q_{free}$$

(4.52)

$$Q_{free}(0) = Q_0$$

(4.53)

where $Q_{act}$ has to be redefined to include the attachment. Since $\gamma$ and $\alpha$ have the same physical dimensions, we can simply replace $\alpha$ with $\alpha - \gamma$ in equation 4.10 and following, obtaining:

$$\frac{dQ}{dx} = \alpha Q \left(1 - \frac{Q}{K}\right)$$

(4.54)

$$K = \frac{\alpha - \gamma}{\beta}$$

$$Q(0) = c_0$$

and

$$Q_{act}(x) = \frac{K}{1 + e^{-(\alpha - \gamma)(x - x_0)}}$$

(4.55)

$$x_0 = \frac{1}{\alpha - \gamma} \ln \left(\frac{K}{Q_0} - 1\right)$$

Even though $Q_{act}$ depends on $\gamma$, this acts only modifying the effective value of $\alpha$ i.e. how fast the saturation is reached. This translates the fact that the exclusion of one electron from the multiplication charge $Q_{act}$, described in eq. 4.54, is not necessarily connected to attachment, from which instead depends the possible free path of the already excluded electron. The limit charge $K$ can be expressed by the ratio in 4.54 but is itself an independent parameter related only to the equilibrium between charge density and diffusion.

Here, $\gamma$ is considered constant, as it refers globally to the avalanche. For this we recall the considerations already expressed for $\alpha$ in section 4.3.2.

Another possibility is to consider different values, of the parameter $\gamma$ in $Q_{act}$ that we call $\gamma_{act}$, and in the equation 4.52: $\gamma_{ina}$. This last is applied to the inactive free electrons produced while the saturation is reached. This would reflect the
appearing of different electric field values inside the avalanche body. The limit case is to have a finite value for $\gamma_{act}$ and $\gamma_{ina} \gg \alpha$. This would describe an avalanche in which the free charge is essentially constituted by the active charge, given the very short free path for the attachment of the other electrons.

In this case the eq. 4.52 becomes more much more complicated since we would like to describe a situation in which the parameter $\gamma_{act}$ undergoes an evolution and so it is no a parameter anymore. Following the guidelines given in the previous sections about having all the dynamical effects in the mathematical structure and keeping the parameter constant, we would be forced here to deeply modify the equation, in order to include such variability.

This is not done here but is introduced instead a variation in the previous equation that distinguish between $Q_{free}$ and $Q_{ina}$, the part of $Q_{free}$ describing the non multiplying fast electrons behind $Q_{act}$, to whom $\gamma_{ina}$ is referred:

\[
\frac{dQ_{ina}}{dx} = \alpha Q_{act}(x) - \frac{dQ_{act}}{dx} - \gamma_{ina} Q_{ina} \quad (4.56)
\]

\[
Q_{ina}(0) = 0
\]

\[
Q_{free} = Q_{ina} + Q_{act}
\]

\[
Q_{free}(0) = Q_0
\]

In this way it can be well described, an avalanche that experiments two different values of $\gamma$ in its two different parts: the active head and the tail that, as seen, feel different electric field intensities. If such distinction is really necessary it will be seen later. In table 4.5.1 some of the quantities introduced until here are summarized. We can determine $Q_{ina}$ in the limit of saturation that is when $Q_{act} = K$ and $\frac{dQ_{act}}{dx} = 0$. In this limit the 4.52 simply tends to a stationary point defined by:

\[
Q_{free} = \frac{\alpha}{\gamma} K \quad (4.57)
\]

This is the same both for 4.52 and 4.52 except for the definition of $\gamma$. For $\gamma = 0$ this quantity diverges coherently with the fact that a stationary point does not exist anymore.

We have different scenarios produced by 4.52 and 4.56 depending on the value of $\gamma_{act}$, $\gamma_{ina}$ and $\gamma$ (referring to 4.52):

- if $\gamma_{ina} = \gamma_{act} = 0$ the 4.52 and 4.56 are equivalent to 4.32, i.e. no of the produced electrons is attached and $Q_{free}$ coincides with $Q_{act}$ that tend to increase linearly;

- if $\gamma_{ina} \gg \alpha > \gamma_{act}$ then $Q_{ina}$ is negligible respect to $Q_{act}$ so $Q_{free} \simeq Q_{act}$.
Table 4.1: Summary of the main defined quantities. (1) is refers to the case of a single given value for $\gamma$. (2) indicates the free charge calculated in the case of different $\gamma$ for active and inactive charge.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Equation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{\text{act}}(x)$</td>
<td>$Q_{\text{act}}(x) = \frac{K}{1 + e^{-(\alpha - \gamma)(x-x_0)}}$</td>
<td>active charge</td>
</tr>
<tr>
<td>$Q_{\text{tot}}(x)$</td>
<td>$Q_{\text{tot}}(x) = n_0 + K \ln \frac{1 + e^{\alpha(x-x_0)}}{1 + e^{-\gamma(x-x_0)}}$</td>
<td>total charge</td>
</tr>
<tr>
<td>$\frac{dQ}{dx}$</td>
<td>$\frac{dQ}{dx} = \alpha Q \left( 1 - \frac{Q}{K} \right)$</td>
<td>for $\gamma = 0$</td>
</tr>
<tr>
<td>$n_0 + \int_0^x Q_{\text{act}}(x') \alpha dx'$</td>
<td>$n_0 + \int_0^x Q_{\text{act}}(x') \alpha dx'$</td>
<td>for $\gamma = 0$</td>
</tr>
<tr>
<td>$Q_{\text{act}}(x)$</td>
<td>$Q_{\text{act}}(x) = \frac{K}{1 + e^{-(\alpha - \gamma)(x-x_0)}}$</td>
<td>active charge</td>
</tr>
<tr>
<td>$\frac{dQ_{\text{free}}}{dx}$</td>
<td>$\frac{dQ_{\text{free}}}{dx} = \alpha Q_{\text{act}} - \gamma Q_{\text{free}}$</td>
<td>for $\gamma \neq 0$</td>
</tr>
<tr>
<td>$Q_{\text{free}}(x)$</td>
<td>$Q_{\text{free}}(x) = \alpha Q_{\text{act}} - \gamma Q_{\text{free}}$</td>
<td>Total free charge$^{(1)}$</td>
</tr>
<tr>
<td>$Q_{\text{free}}(x)$</td>
<td>$Q_{\text{free}}(x) = Q_{\text{ina}} + Q_{\text{act}}$</td>
<td>Total free charge$^{(2)}$</td>
</tr>
<tr>
<td>$Q_{\text{ina}}(x)$</td>
<td>$Q_{\text{ina}}(x) = \alpha Q_{\text{act}} - \gamma Q_{\text{ina}}$</td>
<td>The free inactive charge</td>
</tr>
<tr>
<td>$Q_{\text{ina}}(x)$</td>
<td>$Q_{\text{ina}}(x) = \alpha Q_{\text{act}} - \gamma Q_{\text{ina}}$</td>
<td>Total free charge$^{(2)}$</td>
</tr>
</tbody>
</table>

- if $\gamma_{\text{ina}} \sim 0 > \gamma_{\text{act}}$, the electrons of $Q_{\text{ina}}$ are attached to atoms at the same rate they are produced, and $Q_{\text{ina}}$ tend to $Q_{\text{act}}$, that tend to the constant value $K$, so $Q_{\text{free}}$ tend to $2K$;

- if $0 \leq \gamma < \alpha$ we are in the intermediate case. This the only case permitted by equation 4.52 since $\gamma$ can not be greater then $\alpha$ otherwise the avalanche extinguishes itself.

- if $\gamma_{\text{ina}} > 0 > \gamma_{\text{act}}$ then $Q_{\text{ina}} < Q_{\text{act}}$.

In figure 4.15 these cases are represented, plotting $Q_{\text{free}}$ vs. drift space, having the parameters fixed in a realistic way to reproduce the typical experimental case analyzed until now (in particular we take $\alpha = 12 \, mm^{-1}$), except $\gamma_{\text{ina}}$ which varies, while $\gamma_{\text{act}} = 0 \, mm^{-1}$. The black curve is $Q_{\text{act}}$ (coincident with $Q_{\text{free}}$ for $\gamma = 0$), the blue one is the case $\alpha = \gamma$, the red one is for $0 < \gamma < \alpha$ and the green, coincident with $Q_{\text{tot}}$ is the case $\gamma = 0 \, mm^{-1}$.

In figure 4.16 is reproduced a similar situation, except for the fact that the red and the blue curves, identical to the one in figure 4.15 represent now a situation in which the coefficient $\alpha$ is substituted by $\alpha - \gamma_{\text{act}}$, including the attachment contribution on the active avalanche $\gamma_{\text{act}} = 2 \, mm^{-1}$ but keeping the same numeri-
ical value, thus $\alpha = 14$. For confrontation are shown the curves obtained for for $\gamma_{act} = 0$ with this fixing, in the cases of $\gamma_{ina} = \infty$ and $\gamma_{ina} = 0$. As expected the action of $\gamma_{act}$ is essentially to translate the curve along the $x$ axis, while $\gamma_{ina}$ regulates the maximum free charge after saturation. In case $\gamma$ is the same, the two actions take place at the same time.

We can summarize this scenario as follows: we have an active avalanche that tends to its limit value $K$. As said, part of its electrons are certainly attached to atoms but it can all be comprised in the effective value of $\alpha$, diminished by $\gamma_{act}$; anyhow, in presence of a strong enough electric field, could be a good approximation to consider the attachment for the active avalanche, small and constant, since by definition here the electric remains high for all the avalanche story. The active avalanche produces charge with rate $\alpha$, that while considered "fast", is subtracted to further multiplication, staying in a shielded field region. Due to the lower field value the attachment is here more effective so we tend to consider $\gamma_{ina}$ to become greater than $\gamma_{ina}$ as the avalanche saturate, while at the beginning the must coincide.

Notice that while the production process tends to a linear law, the subtraction is exponential since it depends directly on $Q_{ina}$, so this race tends to the equilibrium point of eq. 4.57. Thus, behind a saturated $Q_{act}$ there is a population of $Q_{ina} - Q_{act}$ inactive but free electrons, tending also to a limit value, taking part in signal induction.

Figure 4.15: $Q_{free}$ for $\gamma_{act} = 0$, in the various cases analyzed.
Figure 4.16: If the blue and the red curves represent here $Q_{free}$ in the case we substituted $\alpha \rightarrow \alpha - \gamma_{ina}$, the curves with $\gamma_{ina} = 0$(in black and green) result translated with respect to the previous. The values for $\gamma_{ina}$, which determines the aspect of the curve are respectively the same of figure 4.15. $\gamma_{ina}$

4.5.2 Calculation of $Q_{pr}$ and $Q_{tot}$ to $Q_{pr}$ ratio

Here the calculation of $Q_{pr}$ and $R_{Q} = \frac{Q_{tot}}{Q_{pr}}$ is performed in the different presented cases, and it is compared to the results of the simple exponential model.

We consider to have for simplicity the idealized system in which the pick up electrodes are very near to the gas gap but still insulated, that means to have a resistive electrode of negligible thickness. In this situation an electron drifting along the whole gap will induce in the pick up electrodes exactly one electron, and in general a charge $q$ moving in the gas will induce on the electrodes a charge that corresponds to the fraction of crossed drift space respect to the total [16].

We will also treat the avalanches produced by a charged multi-cluster track like a single object (except for the exponential case) as suggested by experimental data and by the calculations of the previous section.

Finally, being in a saturated drift velocity situation, we will forget about velocity and time in favor of spatial variable $x$.

In general given a certain expression for $Q_{free}(x)$ the prompt charge induced for a drift path $g$ is given by:

$$Q_{pr,\text{comp}} = \frac{1}{g} \int_{0}^{g} Q_{free}(x) \, dx$$  \hspace{1cm} (4.58)
so the ratio $R_Q$ is given by:

$$R_Q = \frac{Q_{\text{tot}}}{Q_{\text{prompt}}} = \frac{g \int_0^x Q_{\text{act}}(x) \, dx}{\int_0^x Q_{\text{free}}(x) \, dx} \tag{4.59}$$

**In the exponential case** all the electrons take part in multiplication process and we consider $\beta = \gamma = 0$ since all the space charge field effects are neglected. Standing the relation $Q_{\text{act}} = Q_{\text{tot}} = Q_{\text{free}} = Q_{\text{ina}}$ we have [16]:

$$Q_{\text{prompt}}(x) = \frac{1}{g} \int_0^x Q_0 e^{\alpha x'} \, dx' = \frac{Q_0}{\alpha g} (e^{\alpha x} - 1) \tag{4.60}$$

$$Q_{\text{tot}} = Q_0 e^{\alpha x}$$

$$R_Q = \frac{Q_0}{\alpha g} \quad \forall \, x < g$$

The eventual presence of attachment can be easily calculated from eq. 4.51 and brings to the same result.

In [16] it is also demonstrated that this result keeps to be valid in the case of uniformly charged track but it is possible to demonstrate that the validity is extended, whatever is the initial charge distribution, as an immediate consequence of the validity of 4.60 point by point and of the superposition principle.

**The logistic case with $\gamma_{\text{ina}} \to \infty$** is surprisingly similar to the previous one. In fact, since $Q_{\text{free}} = Q_{\text{act}}$:

$$Q_{\text{prompt}}(x) = \frac{1}{g} \int_0^x \frac{K}{1 + A_0 e^{-\alpha x'}} \, dx' = \frac{1}{\alpha g} Q_{\text{tot}}$$

$$R_Q = \frac{Q_0}{\alpha g} \quad \forall \, x < g$$

The free charge coincides with the active charge that tend to a constant value, while the total charge increases with rate $\alpha$. The eventual presence of $\gamma_{\text{act}} > 0$ is treated as above. Notice that this case only make sense if we distinguish the two $\gamma$, otherwise the avalanche would not develop at all.

**The logistic case with $\gamma = 0$** is characterized by $Q_{\text{free}} = Q_{\text{tot}}$ so we have:

$$Q_{\text{prompt}}(x) = \frac{1}{g} \int_0^x Q_{\text{tot}}(x') \, dx' = \frac{1}{g} x x (Q_0 - k \log[1 + A_0]) + \frac{K}{g} [\text{PolyLog}(2, -A_0) - \text{PolyLog}(2, -A_0 e^{\alpha x})]$$

$$R_Q = \frac{1}{g} \int_0^x Q_{\text{tot}}(x) \, dx \tag{4.61}$$

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where \( \text{PolyLog}(n, z) = \sum_{k=1}^{\infty} \frac{z^k}{k^n} \). The above expressions are complicate, while still treatable in algebraic way. Anyhow we can say that \( R_Q(x) \) starts from the value \( \alpha g \) for such \( x \) or \( \alpha \) that the saturation is negligible (exponential approximation). On the opposite side, neglecting the transition trait to saturation, it is easy to approximate \( Q_{tot} \) to its linear part:

\[
Q_{tot}(x) \simeq K \alpha x
\]

In this limit is easy to verify that \( R_q = 2 \), by substitution of the above expression inside the 4.61, that is just the weighted average of a uniformly increasing charge in the gas. This number depends only on the problem geometry and does not depend on any other parameter, so it can be considered an inferior limit for \( R_Q \).

**The logistic case with \( \gamma > 0 \) and finite** is intermediate between the two last cases. We won’t give the explicit algebraic expression of \( R_Q \) since is quite complicate and of little use, but we will reason on the limits. We have already seen that \( Q_{ina} \) tend to \( \frac{\alpha}{\gamma} K \) (4.57) so that \( Q_{free} \) tend to \( K(1 + \alpha/\gamma) \) (4.56). The limit of \( R_Q \) for big values of \( x \) or \( \alpha \) is then:

\[
R_Q = \frac{Q_{tot}(x)}{\frac{1}{g} \int_0^x Q_{free}(x) \, dx} \approx \frac{K \alpha x}{\frac{K}{g} \left(1 + \frac{\alpha}{\gamma}\right) x} = \frac{\alpha g}{1 + \frac{\alpha}{\gamma}} \quad (4.62)
\]

This limit is unaffected by the eventual presence of \( \gamma_{act} \). The opposite limit is simple since, as usual, everything returns into the exponential approximation for which \( R_Q = \alpha g \).

In figure 4.17 \( R_Q \) is plotted in these cases vs. the drift space, having fixed \( \alpha = 12, g = 2 \) and \( \gamma_{act} = 0 \). In particular the red curve represents \( R_Q = \alpha g \) for the exponential model and for the logistic model with \( \gamma_{ina} = \infty \), the black one represents the logistic model in absence of attachment and the intermediate blue curve is the logistic model in presence of the attachment given by \( \gamma = 7 \).

The prompt charge was already encountered at the beginning of this chapter in fig. 4.2, plotted vs. applied voltage for different percent of \( SF_6 \), a strongly electronegative gas used in small quantities to suppress the streamer. In that case was presented as one of the experimental evidences of saturated avalanches. Now we can say something more about this plot using the mathematical instruments illustrated to have some indications about the right choice of the parameters.

Looking at figure 4.15 and remembering the definition 4.58 of \( Q_{prompt} \) we can certainly exclude the case with \( \gamma = 0 \) since \( Q_{prompt} \) would tend asymptotically to a parabola and not to a straight line as is apparent from figure 4.2. On the other side we still have to determine what value of \( \gamma \) is present, that is not indicated by experiment at this point.
Figure 4.17: Total to prompt charge ratio vs. drift space, for the exponential model or logistic with $\gamma_{int} = \infty$ (red line), logistic model without attachment (black curve) and intermediate situation (blue curve).

We are now interested to express the previous quantities and graphs in terms of the conjugate variable $V$ with the purpose of verify experimentally which is the most favorable scenario.

Recalling the 4.27, 4.31, 4.33 and 4.35, we can calculate $\alpha (V)$ for $x = g$ leaving $\alpha$ as the independent variable. Then we apply the linear relation that binds $\alpha$ and $V$ using the parameters values derived from the data:

$$\alpha (V) - \gamma_{act} = \frac{a_0 (V - V_0)}{g} = 0.0022(V - 6500) \text{ mm}^{-1} \quad (4.63)$$

We added here the possibility to introduce $\gamma_{act}$, and it is clear, from above expression, the role it has in moving the operating voltage. We assume that the parameters extracted from experimental data refers to a certain unknown value of $\gamma_{act}$.

We want to remark here that, fitting the data with the logistic theory, we observe is the difference $\alpha - \gamma$ that appears in the logistic equation, and the product $K \alpha$ that appears in the total charge expression. It is apparent that there are infinite ways to fix these quantities to certain values, adjusting $\gamma$ with $K$. In absence of other experimental results we can even suppose that when the multiplication starts, at $\alpha = \gamma$, they are really much bigger but we observe only the difference. This, for instance, could explain in part the existence of a big $V_0$, also because it is widely observed that small quantities of strongly electronegative gases (such as $\text{V}_2$...
$S F_{0}$) translates appreciably the operative voltage.

Now we can make an hypothesis just to fix $\gamma$ (for example $\gamma_{act} = 2 \text{ mm}^{-1}$) so that an expression for $\alpha$ is obtained, purified by the $\gamma$ contribution:

$$\alpha(V) = \frac{a b_d (V - V_0)}{g} + \gamma = 0.0022 [V - (6500 - 909)] \text{ mm}^{-1} \quad (4.64)$$

Having this fixed, we can try to see the effect of eventual electronegativity variation in the base gas mixture, with respect to the reference value $\gamma_{act} = 2$, on the $R_q$ plot.

In figure 4.18 $R_q$ is plotted vs. applied voltage for some of the different cases described above, characterized by a single value for $\gamma$ (eq. 4.52). In particular we have two groups of curves: in the upper $R_Q$ is presented for $\gamma = 0, 2, 4 \text{ mm}^{-1}$ respectively, having fixed the voltage scale using the 4.64 ($\gamma = 2$ is the reference); the lower group represents instead the case where $\gamma = 0 \text{ mm}^{-1}$ was introduced in the 4.63 as a reference to calculate the voltage scale (no attachment hypothesis). The two straight line are $R_Q = \alpha g$ in the two cases, as expected.

![Figure 4.18](image-url)  

**Figure 4.18.** $R_q$ vs. applied voltage in the case characterized by a single value for $\gamma_{act}$ and $\gamma_{ina}$ (eq. 4.52): in the upper group the voltage scale is fixed by $\gamma = 2$, the lower by $\gamma = 0$. The values for $\gamma$ are $0, 2, 4 \text{ mm}^{-1}$ respectively.

In figures 4.19 and 4.20 is instead described the behaviour of $R_Q(V)$ according to the hypothesis $\gamma_{act} \neq \gamma_{ina}$, described in equations 4.56.

In particular in 4.19 $\gamma_{act}$ is varied between $0 \text{ mm}^{-1}$ and $3 \text{ mm}^{-1}$ while $\gamma_{ina}$
was kept fixed at $4 \text{ mm}^{-1}$. The red curve is $\gamma = 0$ that is the only one following the right exponential limit for low multiplication, as we already noticed.

![Graph](image)

**Figure 4.19**: $R_Q(V)$ according to the hypothesis $\gamma_{act} \neq \gamma_{ina}$ (equations). $\gamma_{act}$ is varied between $0 \text{ mm}^{-1}$ and $3 \text{ mm}^{-1}$ while $\gamma_{ina}$ was kept fixed at $4 \text{ mm}^{-1}$.

In figure 4.20 it is illustrated the complementary case of figure 4.19: $\gamma_{act} = 0$ and $\gamma_{ina} = 0, 4, 8, 12, 20$. We observe that all the curves has the right exponential lower limit, and the more $\gamma_{ina}$ is bigger, the more they tend to the same behaviour (straight line $R_Q = \alpha(V)g$).

The summarizing observation we can make, looking at every of these graphs is that, after saturation, the value of $R_Q$ decreases anyway to relatively small values, compared to the prediction of exponential model that moreover ask for an increasing $R_Q$ with the voltage. This fact is quite independent from $\gamma$ and happens whatever is the model we used to introduce it, being a effect that depends directly on saturation.

All this calculation are carried out in the hypothesis of $\gamma$ independent from $V$. This is almost qualitatively correct in the case we study the dependence of $R_q$ from the drift space, where $V$ is set at a fixed value (supposing, as usual, that all the dependencies from the local value of the electric field, biased by the space charge, are included into the mathematical structure).

Remarkably different could be the course of $R_Q$ as a function of applied voltage, at fixed drift space, if we suppose a direct dependence of $\gamma$ from $V$. This can be justified in various ways especially in presence of electro-negative gases.
These are mainly based on the fact that the attachment is a threshold process so that the attachment cross section could depend critically from the applied field, biased form the internal charge distribution, in way already described in the present section. An sensible indication is given from the existence of the measured physical field offset $V_0$ corresponding to a field $E_0 = 32500 \text{V cm}^{-1}$ for the ATLAS standard gas mixture. The study of this model modification is carried out in a further section, upon the suggestions of the experimental data.

As is shown in figure 4.18, the saturation carries a clear signature since $R_Q$ remarkably deviates, decreasing for high values of the field, while the exponential model gives a linearly increasing value. Furthermore a decreasing value would also exclude the logistic model with a very strong role of attachment also in the high field limit (case of $\gamma \gg \alpha$).

### 4.6 Measure of the ratio of total charge vs. induced charge

With the purpose of testing the Logistic Electronic Avalanche Model described in the present chapter, we designed and performed an experiment to measure $R_Q$ in function of the applied voltage. The method chosen consisted in the acquisition of triggered signals, produced by cosmic rays, using a digital oscilloscopes system.

The innovation in this kind of measure is the possibility of having information
directly on the total current pulse waveform, associated to each event, along with the usual induced pulse waveform.

The cathode current readout method, already applied in chapter 3 for the average current measure, is here applied for the first time on RPCs, for the current pulse acquisition. This information is clearly required with good precision for $R_Q$ determination, and this was made possible thanks to an RPC especially designed built and optimized for this purpose.

### 4.6.1 Experimental setup

The RPC used was built with high resistivity bakelite ($\rho \sim 10^{12}\Omega \text{cm}$) to have the lowest possible noise due to eventual imperfections on the borders. It was of rectangular shape with a sensitive area of $50 \times 2.5 \text{ cm}^2$, covered by a single readout aluminum strip, glued on the anode side. The strip was terminated on the back end side on its own impedance ($40\Omega$), carefully measured with the reflections method, and adapted on the front end side to the input impedance of the amplifier ($50\Omega$). All the terminations were made with SMD resistors. The signal was injected in two cascaded identical amplifiers, each with a factor 5 of amplification and a flat bandwidth from $DC$ to $1.1 \text{ GHz}$. The signal was carried through $1 \text{ m}$ long $10 \text{ GHz}$ coaxial cable to a $1 \text{ GHz} - 5 \text{ MSample/s}$ digital oscilloscope for the DAQ. These very good features of the apparatus were chosen also to permit a precise and a minimum bias avalanche waveform measurement.

The current pulse waveform associated to the triggered cosmic ray was picked up onto a trimmer in the range 1-100 $K\Omega$, connected in series to the power supply circuit, before the cathode connection to the HV supply, and read onto the oscilloscope high impedance input ($1M\Omega$). The signal amplitude is therefore proportional to the parallel between the trimmer and the oscilloscope input impedance.

This signal was acquired on a second digital oscilloscope, triggered by the first one. The use of two oscilloscopes was necessary because of the very different time scales of the prompt and of the current signal, of the order of few $\text{ns}$ the first and tenth of $\mu\text{s}$ the second. The description of these signals is the subject of the section 4.6.2.

In figure 4.21 the experimental setup is illustrated, together with the trigger system. This is constituted by a triple scintillators coincidence, with a fourth scintillator placed out of geometry and vetoing cosmic showers triggers.

In order to be able to measure with good precision and reliability the current pulse associated to the event, we introduced some modifications in the typical RPC layout. In particular we wanted to avoid that the current pulses, originating in different points of the detector surface, would experiment different resistances to arrive to the electrodes through the graphite layer. Another requirement was also
Figure 4.21: Experimental setup for the measure of the ratio $Q_{tot}/Q_{prompt}$

to lower the total resistance viewed by the current pulse in series on the graphite layer.

The adopted solution consisted in painting a thin strip of conductive epoxy resin on the border of the graphite layers, along the major edges as illustrated in fig. 4.22. This conductive strips do not face the gas volume, but are positioned upon the RPC frame, to avoid the screening of the signal.

The main effect of this technical feature is that the surface resistance seen between any two points on the graphite layer do not depend on the points distance. We remark that the invariance of the resistivity, experimented by different pulses, is also helped by the rectangular shape of the detector: in the limit of one edge much longer then the other, the sum of the paths of the current pulse on the anode and on the cathode electrodes is constant, since the electrical contacts are placed on opposite sides respect to the long edge (see figure 4.22).
Figure 4.22: Technical details of the RPC used. Is evidenced the role of the conductive strips and of the rectangular shape.

The rectangular shape, in addition to the reasons above, was also chosen so to permit a single strip readout, so to avoid signal dispersion on lateral strips. Furthermore the length of the strip was chosen properly to ensure a transmission-line like behaviour of the readout, so to treat it as a pure resistor, equivalent to its characteristic impedance.

Since the duration of the current pulse depends also on the series resistance of the circuit, the readout trimmer was regulated to find the better compromise between signal to noise ratio and total signal duration. In fact a too long lasting current pulse could pile-up more easily with other signals.

If we consider a decreasing exponential pulse $I(t) = A e^{-t/R_{tot}C}$ of total charge $Q$ we can determine how its amplitude depends on the resistance set on the trimmer:

$$I(t) = \frac{Q}{R_{tot}C} e^{-t/R_{tot}C}$$

where $R_{tot}$ is the series between the graphite resistance $R_g$ and the readout resis-
The tension on the readout is:

\[ V(t) = A' e^{t/R_{\text{tot}}C} = \frac{Q}{C} \frac{R_0}{R_g + R_0} e^{t/R_{\text{tot}}C} \]

The amplitude \( A' \) tend so to the maximum value \( Q/C \) for \( R_0 \gg R_g \). Moreover is clear that, for example, for \( R_0 = 2R_g \) the amplitude is already 2/3 of the asymptotic value. A larger value would increment the total signal duration for a modest gain in the signal amplitude.

### 4.6.2 Description of the current pulses

In this section are explained some of the charge movements involved in RPCs operation, with the support of experimental data obtained by the current pulses waveforms. In the signal production process we can determine at least four independent time scales:

- **the fast signal scale**, of the order of tenth of \( \text{n} s \), is determined by the electron speed in the gas. This is mainly involved in determining the shape of the prompt signal.

- **The slow signal scale**, of the order of \( 1 \mu s \), is determined by the movement of ions. It determines the ramp-up time of the current pulse.

- **The power supply and current readout circuit time constant** depends on the capacitances of the system layers and cables and on the graphite and readout resistances. It describes the reaction of the power supply circuit to the internal charge movement and deposition, in order to restore the graphite electrode potential. It influences the growing part shape of the current pulse and determines the return to zero. Using a trimmer as a readout resistor we made this constant to range between few \( \mu s \) and several tenth of \( \mu s \), so this time scale is comparable with the slow signal scale.

- **The plate charge rearrangement scale**, of the order of tenth of \( ms \), is determined by the plate resistivity and dielectric constant, as seen in chapter 2, and describes the compensation of charges, internally to the resistive plates, occurring after the graphite electrodes restored their initial potential. At the end of this process all the plate volume become equipotential and all the electric field is applied on the gas.

In figure 4.23 is represented the same current pulse due to an avalanche with different zoom factor on the time scale. The readout resistance is set to 50 \( K\Omega \).

The growing part presents a sharp initial front of few hundreds of \( \text{n} s \) followed by a sort of ramp-up of about 12 \( \mu s \) ending in a rounded maximum. From there the
pulse returns to zero with a characteristic exponential law. We attribute the sharp front to phenomena correlated to the fast charge development and the slower ramp to the ions movement as explained below.

In figure 4.24 are represented many avalanche signals of different amplitude, showing that the total duration of the growing part does not depend on the amplitude, since it is connected only to the charge movements in the gas. Furthermore we will see that the sharp front of the growing pulse does not depends neither on the value of the readout resistance (fig. 4.25), as we should expect.

In order to better understand the growing part of the current pulse, we studied also streamer and multi-streamer pulses with the same method. The higher value of the charge released permitted to drastically decrease the readout resistance to about 1 $\Omega$ still having a good noise to signal ratio. This made possible to study the signal shape with very different values of the readout resistance and to correlate the fast growing part of the pulse to a better visible fast signal. The streamer charge production is very different from the case of the avalanche and a complete explanation is beyond the aims of the present work, nevertheless we consider these data to have a better point of view on the problem.
In figure 4.25 is presented a double streamer event. In black is plotted the prompt signal, in red the current pulse. There is a clear correspondence between the peaks (clipped in the figure) of the prompt charge and the kinks of the current pulse, which rise time is therefore bind to the prompt signal timing. Looking at figure 4.26 we see, from the decreasing part of the pulse, that the circuit time constant is of about $\frac{1}{\text{BE}}$, $\frac{1}{\text{AM}}$, $\frac{1}{\text{D7}}$, so that the $\frac{1}{\text{BD}}$, $\frac{1}{\text{BE}}$, $\frac{1}{\text{D2}}$, $\frac{1}{\text{D7}}$, ramp visible in fig. 4.23 here is suppressed. Nevertheless the present rise time is of the order of the sharp front of the avalanche in figure 4.23.

**Relation between $Q_{\text{col}}$ and the current pulse**  From the previous discussion follows that the current pulse is too fast to be related to the collected current through the bakelite plate, but is the consequence on ions moving in the gas and inducing a certain charge on the graphite electrode, as happens for the electronic fast signal on the metallic strip line.

We already know that the prompt signal contribution of an electron is proportional to the fraction of drift space effectively covered from the ionization point to the anode (unless attached). In the same way the remaining part is contributed, much slowly, by the positive ion left behind, traveling in the opposite direction for a distance that is complementary to the electron’s one; another contribution can arise in case of electron attachment, proportionally to the path fraction covered as negative ion. Anyhow the sum of the two contributions is always equal to one electron, i.e. to the total charge.
Figure 4.25: Prompt signal and current pulse associated to a double streamer

Figure 4.26: Prompt signal and current pulse associated to a double streamer
In the case the electrodes do not coincide with the drift space boundaries a geometric correcting factor is needed as explained in chapter 2. Notice that if we consider coincident the graphite electrode and the readout strip (neglecting the 80 $\mu$m insulating film), the geometric correction is identical for the two contributions.

The graphite electrodes and the strip line readout of an RPC behaves then like a system of two selective filters: the first are designed to be transparent to the fast signal that is then intercepted externally by the second; on the other side the current pulse is slow enough for the reaction of the power supply circuit, that pumps current in the graphite electrode to restore them equipotential, producing the current pulse.

### 4.6.3 Data taking and results for the $Q_{\text{tot}}$ to $Q_{\text{pr}}$ ratio measurement

To measure the $Q_{\text{tot}}$ to $Q_{\text{pr}}$ ratio, we acquired the prompt and the current pulse signals at the same time for each triggered pulse, for different values of the applied voltage. We repeated the measure both for the ATLAS standard gas mixture, with and without the 0.5% of $SF_6$. The final values for the charges and their ratio were obtained from the oscilloscope waveforms in the following way:

- The total prompt signal area was automatically calculated by the oscilloscope in $V \cdot s$ units. The offset value from the ground to the base level of the signal, along with the integration gate was also acquired to subtract the offset contribution. The net area furnished then the prompt charge once divided by the strip line impedance, taking into account also the amplification factor 25 and the factor 2 due to the charge division on the strip.

- The current pulse charge was similarly acquired, dividing its net area by the readout impedance. The value of $Q_{\text{tot}}$ is then obtained adding to this the contribution of $Q_{\text{prompt}}$, according to the previous paragraph.

- Finally $R_Q$ was obtained simply by dividing $Q_{\text{tot}}$ and $Q_{\text{prompt}}$ since the correction factors due to the bakelite thickness eliminate each other the ratio.

In figure 4.27 and 4.28 $Q_{\text{tot}}$ and $Q_{\text{prompt}}$ are plotted respectively one vs. the other, along with their ratio, putting together all the points of each applied voltage data set. The two data sets were obtained respectively with the standard ATLAS mixture with and without the 0.5% of $SF_6$. For each data set are reported the generic power law trend lines, represented by the black curves.

On these two plots we make the following observation:
The prompt charge was chosen as independent variable for the plots since it depends only on the fast moving electrons. We saw in figure 4.2 that different quantities of SF$_6$ just produce a prompt charge curve translation on the axis of applied voltage, so its shape is invariant if the main components of the mixture are unchanged. It is then possible to use it as an absolute scale to compare the two considered plots, independently from the applied voltage.

In presence of the 0.5% of SF$_6$ results that both $Q_{tot}$ and $R_Q$ values tend to increment up to $\sim 30\%$ than in the case of the binary mixture, for increasing values of $Q_{prompt}$. This is shown in figure 4.29 were the data sets trend lines are represented for both mixtures, along with the calculated percent increment in red. The increment is probably due to the attached fraction of the produced charge by the SF$_6$, thus not participating to the prompt signal production.

It is apparent that the points belonging to data sets of different applied voltages dispose themselves along a the same trend line, since the trend lines of the single sets are substantially compatible one another. This means that the represented quantities do not depends explicitly on the applied voltage: if happens that two events, belonging to different data sets, produce the same prompt charge, the resulting values of $R_Q$ and $Q_{tot}$ are the same, independently on the applied voltage. This means that the avalanche describing variables are bind together and depends only on present development stage of the process, influenced both by the applied field and by the useful drift space, that fluctuates with the Poisson statistics. Observing in detail the single data sets we notice anyhow a small displacement of the trend lines, that could be weakly correlated with the applied voltage, also if the experimental error is to large to appreciate it.

This notwithstanding, we can consider these data a very strong confirmation of the equivalence between drift space and applied field predicted in eq. 4.16, 4.17 and 4.30.

Finally we analyze the behaviour of $R_Q$ in relation with the logistic model predictions. In the lowest limit reached for the applied field, the value of $R_Q$ is around 50 for the ATLAS standard mixture, decreasing for increasing values of the avalanche amplitude. In the opposite limit we have a ratio value slowly decreasing toward a value little above 10. For the other mixture we have the same low field value (extracted from the trend lines extrapolation in figure 4.29), from there it proceeds quasi parallel to the other curve with smaller values.
To compare these data to the theoretical predictions we report in figure 4.30 the average value of $R_Q$ in function of the applied voltage, along with the statistical error on the points and the power law fit.

The exponential model is certainly excluded from this plot in the explored range of avalanche development, since it predicts an increasing value of $R_Q = \alpha(V)g$ (eq. 4.60). For the same reason also the logistic model with immediate excluded electron capture is to be abandoned (eq. 4.61 and fig. 4.20).

On the other side the $R_Q$ experimental curve shape is compatible to the descending part of the prediction of the intermediate case, described by equations 4.52, 4.54, 4.20 and 4.62, and represented in fig. 4.18; The main difference is that the experimental $R_Q$ increases faster then the theoretical prediction by about a factor 2, for decreasing values of the applied voltage, while the numerical value is compatible for extremely saturated avalanches. We do not observe any trace of the linear increasing part, that should be the signature of proportional regime, in the present voltage range.

The plots in figure 4.18 are obtained thinking to the avalanche as generated by a concentrated initial cluster that evolves along the whole gap $g$. In the real case we should average on the initial positions of ionization, so that the effective average path is only a fraction of the whole gap. This also correspond to the picture, given in section 4.4.3 of a multicluster avalanche treated as a single object, more or less symmetric respect to the initial charge distribution.

Another approximation present in those calculations is the fact that $\gamma$ is kept constant also if we expect a certain dependence on the electric field.

Therefore we repeated the calculations including a linear decrease of $\gamma$ with the electric field and an ”effective” value for the drift space. Moving these two parameters is possible to improve the fit between the data and the model as shown in fig. 4.31.
Figure 4.27: $Q_{tot}$ and $R_Q$ vs. $Q_{pmt}$ for different applied voltages, for the standard ATLAS gas mixture.
Figure 4.28: $Q_{tot}$ and $R_Q$ vs. $Q_{prompt}$ for different applied voltages, for the binary gas mixture, without $SF_6$
Figure 4.29: Trend lines of the data sets in fig. 4.59 and 4.28, calculated with a generic power law $y = ax^b$. In red is represented the percentile increment of the data fit (the same for $Q_{tot}$ and $R_Q$) for the two gas mixtures examined.

Figure 4.30: Average value of $R_Q$ in function of the applied voltage for the standard ATLAS mixture
**Figure 4.31:** Comparison between the experimental data fit (in red) and the model predictions (in black), corrected for the "effective" drift space and with $\gamma$ linearly decreasing with applied voltage in kV.
4.7 Summary, conclusions and further developments

In order to summarize the main results and the most important nodes in the Logistic Saturated Avalanche Model exposed in the present chapter, this section will briefly go over again the logical path followed by the author.

The experimentally observed prompt charge distribution (fig. 4.1), increasingly peaked for higher applied electric fields, suggests that the electronic avalanche growth should depart from the simple Townsend law, that indeed predicts a $\sim 1/Q$ distribution, with the typical MIPs particles ionization statistics [22]. The representation of the averaged distributions values vs. the applied field can be described as a transition from exponential to linear behaviour (fig. 4.2).

Since the prompt charge does not directly represent the avalanche growth, the average total charge per ionizing event was measured from the detector’s operating current, showing a trend similar to the one in of the prompt charge. This trend was fitted in fig. 4.3 with a three parameters function, providing all the qualitative needed properties (eq. 4.1), that happens to be the cumulative of the so called "Logistic Function" (eq. 4.8).

The Logistic function was introduced originally to describe the evolution of a biological population in a limited resources environment, bringing to a stationary population from an initially exponential growth. An ideal parallelism can be established with the saturated avalanche, where the role of resources limitation is played by the space charge density of the growing avalanche, that in first approximation acts as a screening of the backward electrons. The introduction of an explicit non linearity in the rate differential equation force to treat this problem in the framework of the non linear dynamical systems in which the usual assumptions based on the superposition principle cease to be valid.

As usually happens in the study of such systems, it is convenient to find out if a natural structure exists in terms of which the description is particularly meaningful and simple. In our case we indicated in the Active Avalanche the electrons having enough energy to perform further ionization, in analogy with the biological case. Since a stationary state is reached, all the charge distribution shapes, influencing somewhat the ionization process, should freeze, permitting to give a precise physical meaning to the equation parameters. Starting from saturation the active avalanche is conveniently described like a well identified object in terms of electron density distribution. This is transported along its course while continuously other electrons are produced in the same quantity they are left behind in a lower field area.
A key feature of the logistic growth model applied to electronic avalanches in uniform field is that the experimental observation of the saturation in terms of applied field, implies the saturation also in terms of drift space, as demonstrated. This introduces a strong binding between field and drift space (eq. 4.17), from which follows a linear relation between $\alpha$ and the applied field, valid in a fully saturated regime (eq. 4.30,4.31).

Other important features of the model are:

- the saturation does not depend on the attachment, that acts as a negative linear term in the rate differential equation, but on the space charge screening effect. What is the destiny of an excluded electron is then regulated by the attachment coefficient of that gas, determining its mean capture path;

- The saturation depends on reaching the right value for the charge density in order to saturate a given electric field with the established number of electrons. This implies that for field saturated avalanches the electron density have to increase to balance the increasing field;

- The total charge generated depends on the logarithm of the initial electron number, so the dependence on the initially deposited charge is weak and the associated fluctuations tend to be small.

- An offset voltage seems to exist independently from the initial conditions, that accounts for the energy dissipating an non-ionizing phenomena.

While the theory is developed under the hypothesis of a pointlike initial condition, it well describes also the real case where many charge clusters deposited along the particle track initiate as many initially independent avalanches. The simple summation of the avalanches charge certainly contrasts with the non linear principles applied until now and does not bring to anything compatible with the data. On contrast we demonstrated that a many cluster avalanche can be approximately described by a single saturating object if the interaction between clusters is taken into account.

In order to perform a falsifying test of the theory we predicted the trend of the total charge to prompt charge ratio as a function of the applied field, in various hypothesis for the attachment, including also the classical exponential case. This last predicts an increasing trend while the logistic model a decreasing one.

A direct measure on triggered cosmic signals of the ratio gave a good agreement with the logistic model.
Furthermore this result is also relevant from the detector point of view, since this measure, the first of its kind, attests that the more the avalanche is saturated, the more the charge induction is efficient.

In conclusion we have established for the first time some theoretical and experimental bases for a rigorous study of the saturation process in electronic avalanches, trying to put in evidence its intrinsic non linear nature.

Future perspectives can be the introduction of a more formal approach that makes use of a transport equation of which the active avalanche is a particular solution. This could bring to the description of avalanches in terms of gas to plasma transitions propagation, that could help also for a better comprehension of the streamer development.
Chapter 5

Ageing tests of RPCs

LHC muon trigger detectors are supposed to work for ten years under an intense flux of radiation. Therefore the problem of ensuring the required LHC detectors performances would not be degraded during about 10 years operation, is the central problem for all the LHC detectors. In the framework of ATLAS, the performance of full and reduced size RPC prototypes, heavily irradiated with gamma sources, were measured for variable incident flux. The measure was performed after the detector, exposed to the source, integrated the equivalent of 10 ATLAS years, with a safety factor of 10, in terms of rate and driven current.

These experiments evidenced that the the plate resistance has a tendency to increase with the total charge that has flowed through the chamber, thus reducing gradually the detector rate capability, although the detector performances remained comfortably above the ATLAS experiment requirements.

In addition to the tests performed on fully assembled chambers, we also studied the plastic laminate plates conduction properties, aimed to explain the observed ageing effects. The results are presented in the last section of the present chapter.

5.1 Small size RPCs ageing test

Ageing tests on small RPC prototypes were carried out by the Author since 1996, in order to study the reliability of this detector for the ATLAS experiment [22]. The obtained results, attesting the ATLAS requirements fulfillment, were reported in the ATLAS Muon Spectrometer TRD published in 1997 [7].

A summary of these results, in addition to further tests performed to increase the ageing statistics, are presented in this section.

A description of ATLAS requirements respect to RPCs performances, along the general criteria used to evaluate the results are also introduced here.
5.1.1 The ATLAS reliability requirements and the ageing criteria

The main source of background present in the barrel region of the ATLAS experiment is constituted mainly by photons and neutrons as reported in chapter 1. The montecarlo simulation of the background indicates an average counting rate for RPCs of about $10 \, Hz \, cm^{-2}$, that already accounts for the detector sensitivity to these particles. The main reliability requirement for the RPCs in ATLAS is to ensure continuous operation for the entire experiment with a efficiency better than 97%, without degrading time resolution and cluster size performances [7].

To perform an ageing test we must establish some criteria to define the equivalent of the 10 years of ATLAS operation in terms of a much shorter accelerated test. If we identify in the background induced counting rate the possible source of performance degradation, two possible "age" indicators can be identified with the total integrated counting rate and the integrated current driven by the detector. With respect to the ATLAS environment we define:

- a reference level for the rate density of $100 \, Hz \, cm^{-2}$, corresponding to the calculated value of $10 \, Hz \, cm^{-2}$ multiplied by a safety factor of 10;
- a total ATLAS running time $10^8 \, s$ over the 10 years;
- a total number of counts per unit surface of $10^{10} \, cm^{-2}$;

The total charge per count delivered in the gas by an RPC depend on the operative point chosen, according to the curve in fig. 3.7 experimentally established in chapter 3 and parametrized in chapter 4. This choice depends on the threshold set on the F.E: electronics needed to discriminate efficiently the particles signal from the electromagnetic noise, that ultimately depends on the layout project and crafting quality, on the electronics S/N ratio and on the electromagnetic noise level present in the ATLAS experimental hall. As we can see this question can not be answered in a univocal way.

Our experience indicates that in the present condition we can safely set a detector working point that produce an average value of $30 \, pC$ of total charge per count, with the present gas mixture, as indicated in figure 3.7. Thus a realistic ageing figure for the RPCs in the barrel region is $0.3 \, C \, cm^{-2}$.

As a conclusion, a successful test is one in which the tested chamber keeps full efficiency, at rate of at least $100 \, Hz \, cm^{-2}$ after integrating a charge of $0.3 \, C \, cm^{-2}$.

5.1.2 Experimental setup

The tests on small RPC prototypes of $10 \times 10 \, cm^2$ were performed using the same irradiation facility described in chapter 3, completed with an RPC based tracking
trigger. For the ageing period the source was set at about 2.6 cm from the RPC gap, corresponding to an expected converted photon rate of ~ 600 $KH$ overall.

**The trigger setup** The trigger was constituted by 6 $50 \times 50$ cm$^2$ RPCs each read on a single coordinate, assembled in thee X-Y trigger stations. One was positioned under the lead box floor and the other two suspended on a metallic frame upon the box, respectively at 170 cm and 220 cm from the floor. The trigger signal was given by the coincidence of the readout planes fast-or. For each event was also acquired a sample of the RPC signals out of coincidence, by generating a random trigger immediately after the cosmic event data acquisition.

**The test chamber** Tests were performed on various prototypes with different value of initial plate resistivity and different treatment of internal surfaces. Here we report the results of a $10 \times 10$ cm$^2$ prototype with plate resistivity $\sim 1 \times 10^{10}$Ω cm and the standard thickness of internal surfaces oil layer, as reported in [5], similarly to the module-0 RPC reported in the next section.

The RPC was read by 4 strips of pitch 2.5 cm, with one end connected to a double stage amplifier, based on commercial components. The other end was terminated on 50 Ω. A threshold of 30 mV on the amplified signal was set on a CAMAC discriminator.

During the test the chamber worked with a gas mixture of $96$, 7% $C_2H_2F_4$, 3% $C_4H_{10}$ and 0.3% $SF_6$. The RPC working point was set to 9700 V at cosmic ray flux, and to 10100 V when the chamber was exposed to the source.

**The DAQ** The data acquisition system is based on a computer controlled CAMAC crate containing a TDC module to read the test chamber, a STAS to read serially the strips pattern of the trigger stations, a scaler to acquire the instantaneous total rate of the tested RPC, and an output register driven by the acquisition program to generate the control signals.

In order to minimize time jitter of the trigger coincidence, the time difference between the AND and the OR of all trigger planes fast-or was also acquired on a separated TDC channel. In this way it was possible to correct off-line the time distribution of the test chamber, by using as reference time the OR signal that has a lower jitter.

The signals generated by the test chamber were transferred after amplification to the CAMAC discriminator with 100 ns delay, the discriminated signals where read by the TDC set in common start mode. The discriminator fast-or output was also used to measure the RPC counting rate.

With the purpose of monitoring the ageing progress, the program suspended the cosmic rays acquisition every 10 minutes, for a 10 s sampling of the total
rate. Other data like air temperature and total driven current were recorded by a continuous feeder plotter.

5.1.3 Data analysis and results

In figure 5.1 is shown the course of irradiated RPC counting rate along the ageing period, between April and December 1998, in terms of counting rate averaged on one day, and total integrated counts. As visible on the figure the test was often paused for other measurements run in parallel. We observe an initial fast decrease of the rate capability followed by a substantial stability of the counting rate. This behaviour was already observed in some of the previous tests [22].

In figure 5.2 is reported the detailed counting plot for the first 700 hours of ageing, with resolution of 1 hour. The initial average rate capability of more than $8 \text{kHz/cm}^2$ quickly decreases to about $3 \text{kHz/cm}^2$ after about 5 ATLAS equivalent years (see picture 5.1). Successively the rate capability decreased again, still remaining above $100 \text{Hz/cm}^2$, until 10 ATLAS years were integrated.
We could explain this behaviour considering that:

- initially the chamber working point was chosen in order to compensate for the voltage drop on the bakelite plates, but then was fixed for the rest of the test;
- with the increase of the plate resistance, the working point moved, leaving an increasing part of the signals distribution under the set threshold;
- if the resistance finds a stationary value, or varies slowly due to the reduced working rate, also the counting rate seems to be stable.

In the ATLAS module-0 ageing test, presented in section 5.2, a more complete analysis is performed thanks to the temperature and driven current monitors, that was not provided in these early ageing tests.

In figure 5.3 is reported the total rate vs. applied voltage (calculated for 22°C) at the beginning of the test, for a source distance of 2 cm. With reference to the right vertical scale are also reported the counting rates at various distances, taken at the end of the ageing test. Here the single counting plateau demonstrates that, at the beginning, this RPC could work with high efficiency with average rate up to $5 \, kHz$. Due to the ageing, this feature is not conserved for long operating times, being the residual rate capability between 200 and 300 $Hz$. 

Figure 5.2: Detailed counting plots for an RPC of initial plate resistivity $\rho \approx 7 \times 10^9$
Figure 5.3: Total rate vs applied voltage reported at the beginning and at the end of the test (90% of ATLAS)

**Efficiency and performances measurement**  The RPC efficiency, along its time resolution was measured at the end of ageing period in presence of a flux of $100 \text{ Hz cm}^{-2}$.

Since the tested chamber is closed inside the lead box showed in figure 3.1, the cosmic particles, tracked by the two upper trigger stations have to cross $\sim 20 \text{ cm}$ of lead, before being revealed by the tested chamber, and further $\sim 10 \text{ cm}$ before reaching the lower station. As a consequence the multiple scattering cause the particle track to kink in crossing a lead layer, so that the reconstructed hit on the tested chamber can be faked as explained in fig. 5.4.

In the worst case a track missing the chamber is reconstructed in the expected sensitive area, producing a fake inefficiency. To limit this error we selected among the collected events tracks with adequate requirements on the three points alignment. The selecting criteria were based on the maximum tolerated angle between the two reconstructed tracks in figure 5.4 and the maximum tolerated difference between the reconstructed hit positions.

The system tracking capability on the selected tracks is measured from the distribution of residual on the track, defined by the differences between the reconstructed hit position and hit-cluster center of gravity. From figure 5.5 results a tracking resolution $\sigma = 0.9 \text{ cm}$ corresponding to one standard deviation.

A safety external frame dependent on the tolerated difference is then excluded by the sensitive surface for the efficiency calculation. In the present case, by excluding a guard frame of $2.5 \text{ cm}$ width which is consistent with the multiple
Figure 5.4: Hit point reconstruction error, due to multiple scattering in lead
Figure 5.5: Hit point reconstruction error, due to multiple scattering in lead

scattering, we obtained a detection efficiency of:

$$\epsilon = 97\% \pm 3\%$$

The large statistical error is due to the big cut of about 90% on the accumulated statistics, needed to ensure the above conditions.

The reliability of this method depends also on how precisely the chamber position is known in the trigger chambers reference frame. This was achieved using the acquired data, by requiring that all the distributions of reconstructed impact point and angle differences (see fig. 5.4), and the residual distribution gives an average value compatible with 0.

For each trigger the hit-cluster was reconstructed looking for all strips firing within 10 ns after the first strip following the trigger signal. The measured time resolution of 2.8 ns was the same before and after the ageing, and was dominated by the trigger jitter.
5.2 The ATLAS RPC module-0 ageing test

The typical experience with small size RPCs, described in the previous section shows that the plate resistance tends to increase with the total charge that has flowed through the chamber, thus reducing gradually the detector rate capability. With the purpose of studying this effect in a realistic case, a full size Atlas chamber heavily irradiated with a 20 Ci (740 GBq) $^{137}\text{Cs}$ was operated during about 15 months at the CERN irradiation facility X5 GIF.

5.2.1 The GIF irradiation facility and the X5 beam

The GIF (Gamma Irradiation Facility) is situated at CERN West Area test beam complex. It is served by the X5 beam that can provide hadrons, electrons or muons of energy between 10 and 250 GeV.

The x5 beam is derived by the 450 GeV/c primary proton beam of the SpS accelerator, directed on the primary target with typical intensities of $2 \times 10^{12}$ protons per bunch.

The resulting beam, mainly constituted by pions is split between various users. The X5 muon beam is obtained by the fraction of pions decaying in flight (about 1.5%) in the 100 m long trait after the last bending. The GIF facility that is situated downstream the X5 beam area, is usually protected from pions by a beam stop. A typical obtained muon beam has energy of $\sim 100$ GeV with muons spills of about 10000 muons per SpS cycle, distributed on a surface of $\sim 10 \times 10 cm^2$.

The GIF irradiation facility was studied and simulated in detail [30]. Here we summarize the results of interest for our measurements, basing on the review found in [35].

The Gamma Irradiation Facility (GIF)(see figure 5.6) is provided by a $^{137}\text{Cs}$ radioactive source of 740 GBq nominal activity, emitting in 80% decays a single photon of energy $E_\gamma = 0.66$ MeV. The photon flux is made uniform over large plane surfaces in front of the source, by a properly step shaped lead filter. This is 4 mm thick in the center and positioned in front of the irradiation opening. The photon flux is regulated by several overlapping filters from the maximum value ($S = 1$) to zero ($S = \infty$), moved by a remote control system.

The RPC sensitivity to photons is mainly due to the Compton electrons produced in the electrode bulk, having enough energy to penetrate inside the gas. Experimentally was observed a roughly linear dependence of the sensitivity from the photon energy in the range below 1 MeV, of 0.1%/100 KeV [31]. In a realistic environment like the GIF facility, the photon spectrum is far form being monocromatic, thus it is important to study the photon flux and energy distribution in the different points of the area.

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The total photons flux is made of a direct component $E_\gamma = 660$ keV and a scattered one. The latter is due to an X fluorescent peak on Lead ($E_\gamma = 85$ keV), to scattering on collimators and filters ($E_\gamma > 180$ keV) and to albedo due to diffusion.
on the concrete hall’s walls. The ratio between direct and scattered components
decrease with the distance from the source. Figure 5.7 shows the results from
an accurate simulation [30]. The simulated spectrum with absorption factor I=1
(ABS=1) 155 cm far from the source is shown in figure 5.8.

5.2.2 The experimental setup

The ATLAS RPC module-0  The module zero RPC is constituted by two inde-
pendent 2 mm gas gap of 1.42 m² (80 cm x 176.7 cm) sensitive area and initial
plate resistivity of ~ 2×10¹⁰ Ω cm. The gas mixture is constituted by $C_2H_2F_4$, $C_4H_{10}$, $SF_6$
in fraction respectively of 96.7%, 3%, 0.3%. In the present chapter only one gas
gap is considered for the measures¹

The readout is performed on both views by metallic strip-lines 29 mm wide

¹The prototype suffered for a damage concerning the high voltage supply distribution over the
electrodes of the other gap.
with 31 mm pitch [7]. The X view is readout by the short vertical strips, the Y view by the long strips.

The F.E. electronics is based on 8-channel GaAs integrated circuit described in chapter 3. The X strips are equipped with seven F.E. boards and the Y strips with three boards. The resulting instrumented area is $\sim 1.3 m^2$.

**Readout, monitoring and DAQ**

The F.E. electronics output signals are brought by 14 m long unshielded flat cable to a line receiver. Are thenreshaped to 60 $ns$ differential TTL signals, by a CAMAC discriminator, to be driven in the counting room 35 $m$ away. There the signal, reformed by a double output shaper, are both sent to a multihit TDCs for the beam events acquisition, and to a cascaded fan-in fan-out bank for the counting rate acquisition. This last permits to have access simultaneously to each channel, to the OR of each board an to the OR of the entire view. The TDC is a 32 channel 16 hit, with a 1 $ns$ time resolution, so 16 strips per view are connected for beam acquisition, defining a $50 \times 50$ area centered on the beam.

Using a separate system for the detector control DCS we monitored and acquired continuously the applied voltage, total driven current, total counting rate of the two views and of a chosen single board, along atmospheric pressure, detector temperature and composition of the gas mixture. A sketch of the DAQ is shown in fig. 5.9, in red are represented the scheduled updates.

### 5.2.3 Initial rate capability and driven current

In figure 5.10 is shown the single counting rate for distances $d$ of 345 cm, 198 cm and 148 cm of the RPC from the source, keeping the filter factor $S = 1$. The counting rate is corrected for the dead times calculated on the base of the different devices between the RPC and the scaler. It is clearly visible the knee indicating the beginning of the plateau. The currents at 9400 V are reported in the figure. Is apparent that at the very beginning of the ageing, this RPC could work to up to counting rates of a few $KHz cm^{-2}$ over all the surface, in spite of the extremely high value of the driven current (near to the limit of the present HV power supply) needed for sustaining this extremely high rate.

In order to evidence an eventual rate effect (apart from the voltage drop on the bakelite plates), we compared the plateau counting rates with the law $1/d^2$ expected for the photon flux intensity. Assuming a negligible rate effect at large distances from the source, we used the counts in the farther case to calibrate the expected counts at lower distances. In figure 5.11 the counting rate, measured at the beginning of the plateau is compared to the expected value. Is also reported their ratio, in order to estimate if the reachable efficiency depends on the photon
intensity. This efficiency is referred only to the net effect of the photons, since all
the other systematic effects due to the detector are cancelled by considering the
lower rate point as the reference value. With reference to figure 5.7, that presents
the total photon counting rate as a function of the distance, it is possible to estimate
the present detector overall sensitivity to GIF in about 0.2%, by comparison with
the reported counting rates values. This value is not changing very much, as long
as the two curves substantially agree with the $d^2$ law, as it seems to be the case.

The total currents, for different distances from the source, are reported in figure
5.12 vs. applied voltage, besides the total charge per expected ionization vs. $V_{gas}$
(see chapter 3). We found that a value of the total plate resistance of $\sim 0.48 \, M\Omega$
at $25^\circ C$, corresponding to a resistivity of $1.68 \times 10^{10} \, \Omega \, cm$ brings to the correct
value of $V_{gas}$.

The figure 5.13 shows the plot of the total charge per count $Q_{count}$ besides the
total current for $d = 348 \, cm$. The minimum value of $31.7 \, pC$ corresponds to a set
$V_{th} = 1 \, V$, in agreement with the calibration plot of figure 3.10. In the present
setup we were forced to set a value so high for the threshold, due to the very high level of the experimental area electromagnetic noise, besides some imperfections.
5.2.4 Ageing progress and rate capability

Here we present the collected data over the 15 month ageing period, from July-1999 to October-2000. The data present some gaps, due both to temporary shut down and to DCS computer failures. The unmonitored periods were recovered trough the automatic source logbook and the HV monitor that was separated from the DCS.

During the ageing and for the efficiency measurement the detector was placed at 220 cm from the source with a nominal photon rate of $6.2 \times 10^5 \, Hz \, cm^{-2}$ that
Figure 5.14: Charge cumulative and instantaneous current vs. ageing time.

gives a counting rate of $\sim 1.6 KHz cm^{-2}$, given the detector sensitivity to the GIF source of $\sim 0.26 \%$, determined with the non aged detector.

In figure 5.14 the charge cumulative and the instantaneous current readout are represented over the ageing period. The mid-term and final performances measurement are also reported. The current plot is a highly reliable indicator of the effective detector status, given the applied voltage, being non affected by electromagnetic noise and being recorded by two independent systems. From this plot the very variable working condition experienced by the detector is clear.

In figure 5.15 is reported a sample of the main data monitored: the total rate, the total current and the detector temperature. The correlation between temperature and the working point is revealed by the synchronized oscillations of counts and current, as is apparent from the 24 hours period due to the night-day temperature excursion. The working point displacements are due both to the gas density variation with temperature and to the effect of temperature on the resistivity of the bakelite plates (see section 5.3). By knowing this last relation it would be possible to monitor the bakelite resistivity, as it was done for the early ageing tests on small prototypes. [22].

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5.2.5 Final performances measurement

The detection efficiency was measured with the X5 muon beam after 3 and 10 Atlas equivalent years, using multi-hit TDCs to read a surface of $50 \times 50 cm^2$ on both coordinates, centered on the beam. Before the ageing the efficiency of the chamber was measured with cosmic rays [33]. The mid-term measure is already reported in literature [34], and we refer to this work for further details on the data analysis, since the same software and setup were used.

The efficiency measure is based on the cluster recognition: given a 10 ns acceptance window centered on the muon beam time peak, we recorded for each event all the hits clusters. An event is considered efficient if at least one cluster is found in the area concerning the beam in the quoted time window. The efficiency is measured separately on both views, along with the AND and the OR of the views, in order to separate the intrinsic detector contribution from the F.E. possible electronics faults.

In figure 5.16 are reported the efficiency plots for different source intensities, vs. applied voltage, reported to 1010 mbar and $20^\circ C$, and vs. $V_{gas}$. Filter factors 5, 10, 20 were used, corresponding respectively to an expected converted photon rate of 320, 160, 80 $Hz/cm^2$ respectively. In addition to these rates, the beam rate, ranging in tens of $Hz/cm^2$, should also be taken into consideration.

Figure 5.15: Total rate, total current and detector temperature vs. ageing time.
Figure 5.16: Efficiency for various source intensities vs. applied voltage and vs. $V_{gas}$

Figure 5.17 shows the time distributions of two adjacent strips centered on the beam, for source closed, filter 10 and filter 5, taken at plateau efficiency working point corresponding to applied voltages respectively of 10200 V, 11800 V and 11500 V.
In Figure 5.18 is presented the average cluster size vs. applied voltage for the considered source intensities.

5.2.6 Current and resistivity analysis

The study of the current for different known source intensities gives a way of monitoring the RPC status, periodically during the ageing time. This permits in particular to monitor the detector plate resistance evolution, and to look for eventual anomalies in the V-A characteristic, assumed to be known for the actual gas (see chapter 3).

In the following schedule we report the main measurements of current and total resistance normalized to $20^\circ C$:

1. Jun-1999 at the beginning of the test. These data are already illustrated above. $R = 0.48 \, M\Omega$

2. October-1999, within the mid term performance measurement after about 3 ATLAS years. $R = 2.2 \, M\Omega$

3. May-2000 when we were forced to suspend the test due to a major damage of the plastic pipes on the gas system. $R = 5 \, M\Omega$

4. July-2000, within the 10 ATLAS years final performance measure. $R = 8.4 \, M\Omega$

5. October-2000, at the definitive end of the test. $R = 15.6 \, M\Omega$

The current measurements were extremely useful for understanding the problem mentioned in point 3.

We observed in May-2000 a sudden large increase of the detector current, following a gradual increase, registered since the October-1999. The test was interrupted and a close inspection revealed that some of the plastic pipes, used for internal junctions and for the gas control system where broken. A deeper inspection showed that all the plastic pipes appeared to be degraded and extremely fragile.

A possible interpretation of these facts is that, for reasons still under study, the plastic pipes were progressively damaged by some component of the gas mixture, and the air started to pollute the detector gas volume, displacing the working point.

In fact we remark that the counting rate always increased besides the current showing a values compatible with the current, also at voltage below 8 KV, at which the counts should be negligible with the standard mixture. Therefore we consider
Figure 5.17: Time distributions on both views taken, at plateau efficiency working point for various source intensities: on top source closed, in the middle $s=10$, bottom $s=5$. 
Figure 5.18: Average cluster size vs. applied voltage

A big part of the current increase due to avalanches or streamers produced in the gas.

In May, the definitive breakdown of an upstream pipe caused the massive air income. Unfortunately the detector worked in these last condition (11500 was the applied voltage) for many days before we did recognize the problem from our site in "Tor Vergata" University, due to a fault in the remote control system.

After the problem was completely fixed we measured the current plots of figure 5.19.

The upper curves refers to a scanning performed short after the pipe fixing, and evidence still a very high current. As a reference we take the current value at 8 KV \( I(8000) \) since at this point the physical events in the gas start to be visible in the standard condition.

The lower curve is taken one week after, showing a current drop by a factor 3. In the successive weeks we observed a progressive and slow \( I(8000) \) current decrease with operation time.

A similar operation was done in July within the final performance measure with result shown in figure 5.20. Here the current \( I(8000) \) lost another factor 2.

Due to the progressive decrease of the \( I(8000) \) current we prosecuted the test until October where the \( I(8000) \) current was less of the initial value, as we expect for the ohmic contribution, due to the observed increase of the plates total resistance. This is shown in figure 5.21, together the plot of \( Q_{\gamma}(V_{Q1,s}) \) used to estimate
Figure 5.19: Total currents in May 2000: upper curves may 19, red curve may 27

Figure 5.20: Total currents in July (after 10 ATLAS years)

the final value of plate resistance which was $R = 15.6 \ M\Omega$. 119
5.2.7 Conclusions and remarks to the ageing tests

After 10 ATLAS years (0.3 $C \text{cm}^{-2}$) the ATLAS module-0 still has a rate capability of $200 - 300 \, Hz \, cm^{-2}$ which is largely above the ATLAS requirements, this result agrees with the ageing test on a small detector reported in figure 5.3. The cluster size and the time resolution appear not to be appreciably affected by the ageing.

In both cases, looking also to the results of chapter 3, we demonstrated that the diminishing of the rate capability has to be correlated to the increase of plate total
resistance, that amplify the effect of the ohmic voltage drop on the electrodes, causing the displacement of the working point.

We remark that the diction "diminishing of the rate capability" has only a practical but not intrinsic meaning. In fact we have shown that the correct description of the observed detector behaviour is that, the more the detector get aged (in the defined meaning), the more the same rate capability is achieved at higher applied voltage. This is obviously limited by technical insulation problems at very high applied voltages, with the present setup.

On the current side our experience, based also on many tests on small detector, shows that the current has a general tendency to diminish, due to the increasing plate resistance. This is also bound to a diminishing of the detector noise single rate, probably due to a further conditioning of the internal electrodes surfaces.

As a first confirmation we remark that the plot in figure 3.2 was obtained with the aged detector described in section 5.1.

As a further confirmation we observe that also for the ATLAS module-0, in spite of the episodic current increase of May-2000, the current at voltages below the threshold of gas amplification is $< 2 \mu A$, showing a decrease with respect to the initial value. This behaviour is followed also by the spontaneous counting rate, $< 2 Hz cm^{-2}$ at the very end of the test.

5.3 Studies of conduction in bakelite plates

In order to study the the origins of the observed ageing phenomena, systematic studies were carried out on single detector components, with particular attention to the bakeite plates and to the graphite electrodes. Here are reported some of the achieved results, that already had an impact on the actual detector layout.

The test on $10 \times 10 cm^2 2 mm$ thick bakelite electrodes started in July-1998 and is still running. Nearly 20 bakelyte samples, in various conditions of initial resistivity and type of electric contact, have been tested so far.

The setup is simply constituted by three high voltage distributors each providing several supply lines, which are equipped with a current readout. The currents were automatically acquired every 2.8 minutes by an array of ADC connected to a dedicated computer, along with the room temperature and, recently, the air relative humidity.

The temperature was measured by a semiconductor device with a precision of $0.4^\circ C$ and a sensitivity better than $0.1^\circ C$. 121
5.3.1 Ageing tests with water and graphite based electric contacts

The first measurement was performed on two bakelite plates of different resistivity: $10^9$ and $4 \times 10^{10} \ \Omega \cdot cm$. One side was painted with the standard graphite layer, except for a guard frame, and protected by a PET insulating foil glued on the graphite. On the other side the electric contact was performed with a pad, wet with distilled water. We applied a voltage of 1 KV corresponding to an RPC having a 2 KV voltage drop on the two plates.

In figure 5.22 is shown, for the low resistivity plate, the plot of measured resistance (reported in terms of plate resistivity), the air temperature and the resistivity reported to a reference temperature $(T_0 = 20^\circ C)$ by the empiric law:

$$
\rho(T_0) = \frac{\rho(T)}{e^{0.06(T_0-T)}}
$$

that was tested on a wide range of bakelite resistivity values.

In the upper plot is reported the first part of the test that shows a quick initial resistivity increase, followed by a long plateau until about 1 "ATLAS equivalent charge" (from now AEC) of $30000 \ mC/100 \ cm^2 = 0.3 \ C \ cm^2$. From this point the resistivity seems to increase regularly reaching $\sim 12 \ G\Omega \ cm$ after 1.5 AEC. Here we observed a sudden and large resistivity increment up to values of several tens of $G\Omega \ cm$, characterized by fast and irregular variations.

We observe that the temperature correction of bakelite resistivity reported above, seems not to work anymore after the initial plateau, thus the observed current oscillations are to be attributed to some other system component, contributing to total resistance with a different dependence from temperature. We attribute this extra effect to the graphite coating electric contact, since experience shows that the water contact is much more stable. In this case it seems inappropriate to refer to the bakelite resistivity, since the graphite contribution cannot be neglected, and therefore we will speak in the following of total plate resistance.

To test the hypothesis that the graphite contact is the very responsible of the observed phenomena, we removed it substituting with another wet pad. The results is shown in the lower plot where is apparent an immediate decrease of the resistivity (properly named in this case) to the very initial value of $10^9 \ \Omega \cdot cm$. In this conditions the plate resistivity seems to be stable, within the explored charge range, because the observed peaks are proved to depend on the pad drying. We conclude that after removing the graphite the measured resistance depends only on the bulk of the bakelite plate. This is confirmed by the fact that the temperature correction works again.
Figure 5.22: Ageing of a low resistivity bakelite plate, with graphite/wet pad contact (upper) and double wet pad (lower)

Graphite-graphite electric contacts test. This test was repeated on 5 identical plates with various combinations of electric contacts on the two faces. We report
in figure 5.23 one of the two samples with a double graphite contact, without the PET protection. The plots of figure 5.23 represent a result compatible with the previous one. Starting from about \(0.32 \text{ cm}^2\) the measured resistance shows a large increase which disappears when the graphite coatings are substituted with wet pads.

**Further observation on graphite resistance** Since in this last test the graphite layer was accessible, we measured its surface resistivity, between two highly conductive graphite cords painted on opposite edges of each graphite layer.

The initial value was around \(100 \, \Omega/\square\), for all layers, which is the standard value for RPCs [7]. At the time of the sudden resistance increase we found for the two plates:

1. \(1.6 \, M\Omega/\square\) on the anode graphite contact and \(110 \, K\Omega/\square\) on the cathode.
2. \(4.2 \, M\Omega/\square\) on the anode graphite contact and \(147 \, K\Omega/\square\) on the cathode.

This asymmetric behaviour is also confirmed observing visually the graphite layers aspect: the anode became lighter and nearly transparent, while on the cathode appeared some superficial irregularities, still conserving its original thickness. The graphite layer effectiveness as electrode coupled to bakelite seems to be progressively compromised by some effect bound to bakelite conduction mechanism at the anode\(^2\).

The causes of these phenomena are presently under study, but anyhow the contribution of graphite in the total plate resistance seems to be confirmed and non negligible.

**5.3.2 Confrontation of plates performances with different graphite coating**

In order to achieve better RPC ageing performances we implemented another graphite coating type, that differs from the previous for the increased graphite quantity deposited per square \(\text{cm}^2\), with the same value of surface resistivity.

In figure 5.24 ”fake” resistivity measured with the new ”heavy” graphite coating is compared to the old one, on identical bakelite plates vs. the integrated charges.

The resistance of the two samples appear to be very similar until both integrated \(0.4 \, \text{cm}^{-2}\). From this point the old graphite plate presents an ever increasing resistance with respect to the new graphite, reaching quickly ”fake”

\(^2\)Tests concerning current conduction in the graphite layer only, shows that the graphite resistivity doesn’t depend on the integrated charge.
Figure 5.23: Ageing of a low resistivity bakelite plate, with graphite/graphite contact (upper) and double wet pad (lower).

resistivity values over $2 \times 10^{11}$. After integrating $0.75 \, C \, cm^{-2}$ also the resistivity new graphite sample shows a rapid increase.
Figure 5.24: Ageing comparison of the "heavy" graphite (upper) and old graphite coated plates (lower)

In figure 5.25 is reported the scatter plot of of the integrated charges along with the new "heavy" to the "light" old graphite plate resistance ratio, that evidences
Figure 5.25: Scatter plot of the integrated charges along with the "heavy" to old graphite plate resistance ratio.

The measurement of the graphite surface resistivity is also reported:

1. at the beginning:
   - new-graphite: 61 $K\Omega/\square$ for the anode and 45 $K\Omega/\square$ for the cathode:
   - old-graphite: 135 $K\Omega/\square$ for the anode and 150 $K\Omega/\square$ for the cathode

2. After about 0.3 $cm^{-2}$
   - new-graphite: 108 $K\Omega/\square$ for the anode and 56 $K\Omega/\square$ for the cathode:
   - old-graphite: 980 $K\Omega/\square$ for the anode and 178 $K\Omega/\square$ for the cathode

3. After about 0.76 $cm^{-2}$ for the new graphite and 0.48 $cm^{-2}$ for the old one
   - new-graphite: $> 20 M\Omega/\square$ for the anode and 60 $K\Omega/\square$ for the cathode:
   - old-graphite: $> 20 M\Omega/\square$ for the anode and 160 $K\Omega/\square$ for the cathode
The direct measurement of the graphite coating resistivity confirms therefore the strong asymmetry between anode and cathode behaviour, along with the already observed visual effects.

5.3.3 Conclusions

These measurements evidence that a possible cause of most of the ageing effect, measured on small and large size RPCs, is to be attributed to the degradation of the electric contact between bakelite and graphite, on the anode side. Some attempts of improving the RPCs ageing performances consisted in adopting a new graphite, that was proofed to be more robust than the previous one. Other tests on fully assembled detectors are in progress.
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