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The compact muon solenoid RPC barrel detector

A. Colaleo [a], F. Loddo [a], M. Maggi [a], A. Ranieri [a], M. Abbrescia [a,b], R. Guida [k], G. Iaselli [a,b], B. Marangelli [a,b], S. Natali [a,b], S. Nuzzo [a,b], G. Pugliese [a,b], F. Romano [a,b], G. Roselli [a,b], R. Trentadue [a,b], S. Tupputi [a,b], N. Lacalamita [a], F. Chiumarulo [a], C. Pinto [a], M. Franco [a], A.K. Abadjjev [a], M. Papagni [a], A. Clemente [a], L. Benussi [c], S. Bianco [c], D. Colonna [c], F.L. Fabbri [c], M. Giardoni [c], B. Ortenzi [c], C. Paris [c,1], L. Passamonti [c], D. Pierluigi [c], B. Ponzio [c], C. Pucci [c,2], A. Russo [c], F. Cassese [d], N. Cavallo [d,3], A. Cimmino [d,e], D. Lomidze [d], P. Noli [d,e], P. Paolucci [d,*], G. Passeggio [d], D. Piccolo [d], G. Polese [j,k], L. Roscilli [d], C. Sciacca [d,e], A. Vanzanella [d], P. Baesso [f,g], G. Belli [f,g], S. Bricola [f], A. Grelli [f,g], E. Imbres [f], G. Musitelli [f,g], R. Nardò [f,g], M. Necchi [f,g], S.P. Ratti [f,g], C. Riccardi [f,g], D. Pagano [f,g], P. Torre [f,g], A. Vicini [f,g], P. Vitulo [f,g], C. Viviani [f,g], A. Dimitrov [h], L. Litov [h], B. Pavlov [h], P. Petkov [h], T. Anguelov [i], V. Genchev [i], P. Iaydjiev [i], B. Panev [i], S. Stoykova [i], G. Sultanov [i], R. Trayanov [i]

[a] *Istituto Nazionale di Fisica Nucleare of Bari, Italy*
[b] *Università degli studi di Bari, Via Amendola, 173I-70126 Bari, Italy*
[c] *Laboratori Nazionale di Frascati dell'INFN, Via E. Fermi, 00044 Frascati, Italy*
[d] *Istituto Nazionale di Fisica Nucleare of Napoli, Italy*
[e] *Università di Napoli "Federico II, Complesso Universitario di Monte Sant'Angelo, Edificio 6, 80126 Napoli, Italy*
[f] *Istituto Nazionale di Fisica Nucleare of Pavia, Italy*
[g] *IUniversità degli studi di Pavia, Via Bassi 6, 27100 Pavia, Italy*
[h] *Faculty of Physics, Sofia University, Bulgaria*
[i] *INRNE Bulgarian Academy of Sciences 5, James Bourchier Boulevard, BG-1164 Sofia, Bulgaria*
[j] *Lappeenranta University of Technology, P.O. Box 20, FI-53851 Lappeenranta, Finland*
[k] *CERN, CH-1211, Genève 23 F-01631, Switzerland*

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ABSTRACT

Resistive Plate Chambers (RPC) have been chosen as dedicated trigger muon detectors for the Compact Muon Solenoid [CMS collaboration, Technical Design Report, CERN/LHCC 94-38, 1994. [1]] experiment at the Large Hadron Collider [The LHC project at CERN, LHC-project-report-36, 1996. [2]] at CERN.

Four Italian groups from Bari, Frascati, Napoli and Pavia and two Bulgarian groups from Sofia have participated in designing and constructing the RPC barrel system.

A sophisticated and complex production line has been organized by the collaboration to build the 480 RPC chambers, with a quality assurance (QA) test, made by 3 consecutive steps, in order to assure full functionality of the chambers. A final certification of the chambers has been made at ISR (CERN) with a month-long test. After that the RPCs have been coupled to the Drift Tube chamber and installed in the iron return yoke of the CMS solenoid.

The first chamber was produced in 2002 and last was installed in October 2007. The system is now completely installed and commissioning has been going on since the second half of 2005 to complete the Large Hadron Collider (LHC) startup in the summer of 2008.

The chamber construction, the test made, the main results achieved and a short description of all the services needed to run the RPC barrel system will be described in this paper.

1. An introduction to the CMS RPC muon trigger system

The Compact Muon Solenoid (CMS) barrel muon detection and trigger system [3,4] is based on the muon stations [5], which are a sandwich of one Drift Tube and one or two Resistive Plate Chambers (RPC). They are placed in 240 positions in the CMS magnet return yoke. The yoke is a 13-m-long cylinder divided into

* Corresponding author at: I.N.F.N. Sezione di Napoli 80126, Italy. Tel./fax: +39 081 676839.
E-mail address: pierluigi.paolucci@na.infn.it (P. Paolucci).

[1] Scuola Ingegneria Aerospaziale Università di Roma "La Sapienza".
[2] Facoltà Ingegneria Università di Roma "La Sapienza".
[3] Università degli studi della Basilicata

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5 wheels along the axes direction and each wheel is divided into 12 sectors, housing 4 iron gaps or stations (Fig. 1).

The main unit of the RPC chamber is the double gap made by two gas gaps with a common readout plane of aluminum strips (from 80 to 96) in the middle.

An RPC gap is made by two parallel bakelite plates with a volume resistivity of $1–6 \times 10^{10}\,\Omega\,\text{cm}$ placed at a distance of 2 mm by a grid of polycarbonate cylinders and filled with the gas mixture (96% $C_2H_2F_4$, 3.7% i-C_4H_{10} and 0.3% of SF_6). The high voltage is applied to the outer graphite-coated surface of the bakelite plates in order to have an electric field inside the gas gap that can generate a charge avalanche along the track of an ionizing particle.

There are 10 different typologies of chambers but all of them are made by two or three double gaps assembled in a common mechanical framework. They are equipped with 6, 10, 12 or 18 Front-End electronic boards [6] each connected to 16 readout strips, one HV channel per double-gap, two LV channels and two gas connections (inlet and outlet).

2. From the single gap to the chambers: construction and test

The chamber production line has been structured in Italy with three specialized factories: the PanPla (Pavia), the General Tecnica (Colli) and the High Tech (Caserta).

The bakelite electrodes have been produced, tested and selected at the PanPla under the supervision of the Pavia group. A very accurate quality assurance (QA) test has been set up in order to select only the laminates plates with a bulk resistivity that determines the RPC rate capability, in a range from 1 to $6 \times 10^{10}\,\Omega\,\text{cm}$ and with a high uniformity over the plate.

The accepted bakelite electrodes have been sent to the General Tecnica where, under the supervision of the Bari group, the gas gaps are produced and tested following a very tight QA procedure. The *single gap* passes through a QA procedure in which tests for gas tightness (stability of an overpressure of 20 mbars in a fixed time), spacers tightness up to an overpressure of 20 mbars and dark current versus high voltage measurements (current $<3\,\mu\text{A}$ at 9.5 KV) are foreseen. About 2400 gas gaps have been built from 2002 to 2006 (40 months) with a rejection rate of 16%.

Also about thousand *double gaps* have been produced at GT with QA tests similar to the previous one where the stability of the dark current as a function of the high voltage is measured for a longer period. In total 956 double gaps have been assembled and tested from 2002 to 2006 with a rejection rate of 4.1%.

The accepted double gaps have, at this point, been sent to the 4 certified sites certified to be assembled: the Bari laboratory (140 assembling), the HiTec company (100 assembling–Napoli group supervision), the Sofia laboratory (20 assembling) and the General Tecnica itself (220 assembling—Bari/Pavia supervision). In almost all the sites a chamber was assembled in 1 day and tested from the mechanical and electrical point of view for a week.

When a chamber was built and certified [7], it was sent to one of the three test sites at the laboratories of Pavia, Bari and Sofia, where cosmic ray-based tests were carried out in about 3 weeks by the Pavia, Bari and Sofia groups. The standard QA test for the chambers was based on a set of cosmic ray runs taken at different HV values (at a step of 1 KV), with three different configurations (one gap at time ON and two gaps ON) and using the final gas mixture. For each step and configuration the dark current, the efficiency, the noise rate and the cluster size of the chamber were measured. The four stations were almost the same even if based on a different number of chambers to be tested in parallel and with few small differences used in the trigger. In all cases the environmental parameters were monitored in order to correct the results with pressure, temperature and humidity.

All data and results obtained during the chambers QA tests have been stored in the RPC construction database and are available for further studies. The most significant results, obtained on an almost complete set of chambers, are reported from here on.

From the current distribution, shown in Fig. 2, we can conclude that more than 92% of the chambers have a current less than $5\,\mu\text{A}$ (half of the acceptance limit) at 9.6 KV, with an average value of about $2\,\mu\text{A}$. The average noise rate, when the chamber is operated

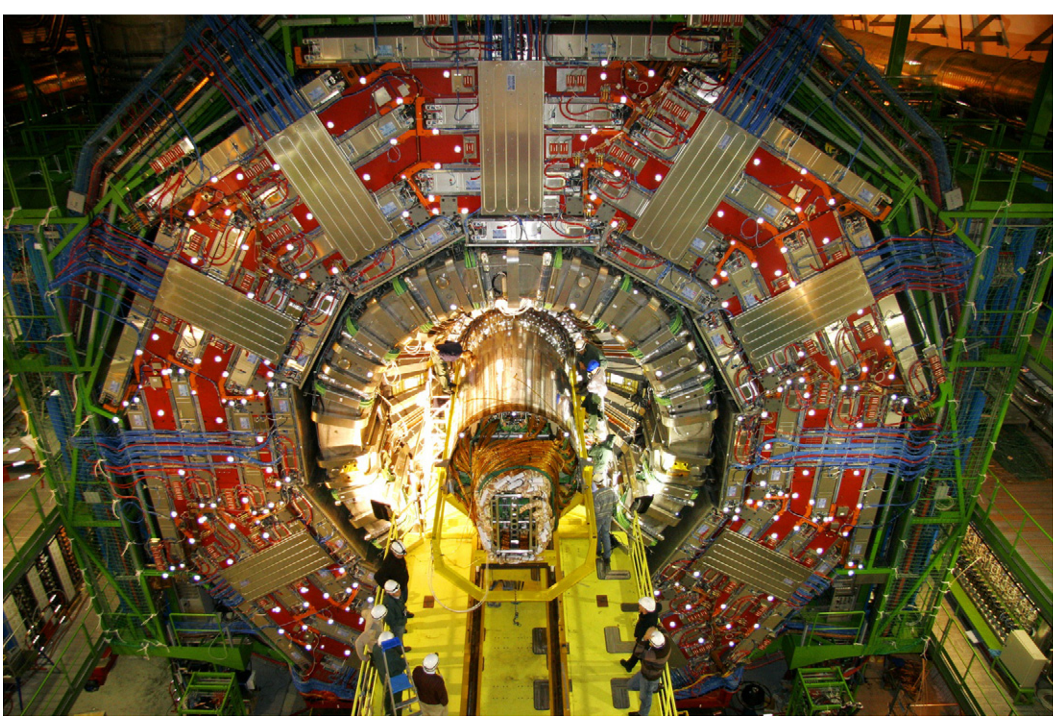

Fig. 1. A front-view picture of the CMS detector.

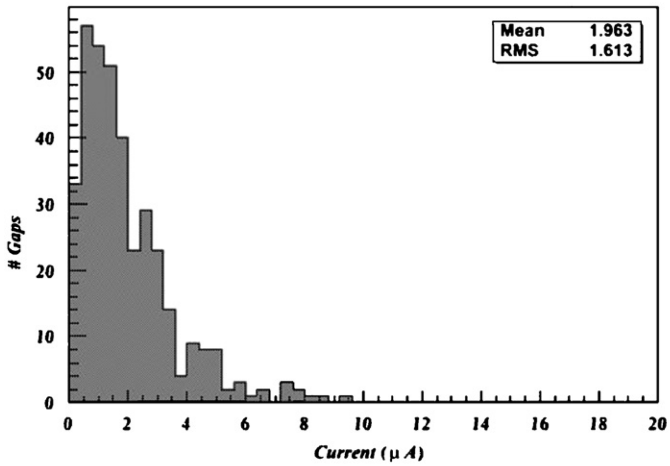

Fig. 2. The current distribution.

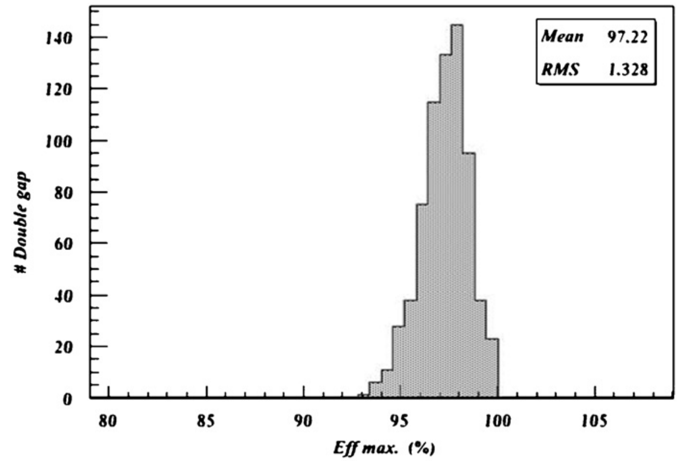

Fig. 4. The chamber maximum efficiency.

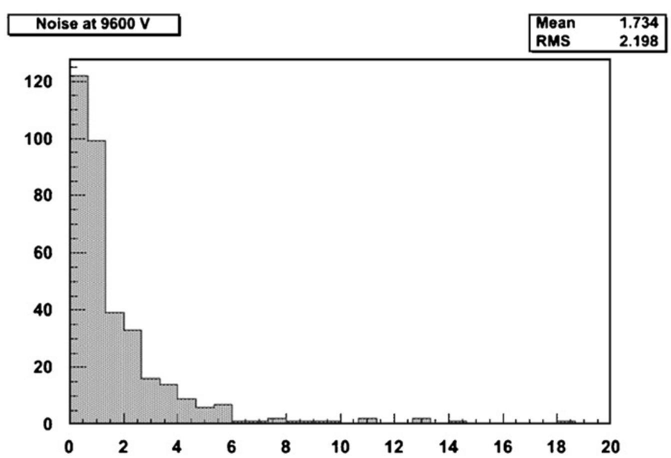

Fig. 3. Noise rate (right) in double-gap readout mode at 9.6 kV.

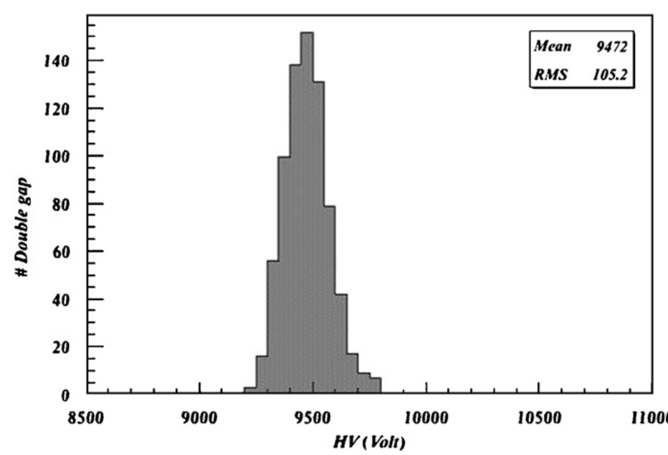

Fig. 5. HV working point at 95% of the max efficiency.

at the knee of the plateau (defined as 95% of the maximum efficiency value) (Fig. 3), is 2.2 Hz/cm^2, which is about half of the required rate and much less than the theoretical limit of 50 Hz/cm^2 after which the RPC trigger will not work properly.

The efficiency was measured extrapolating the impact point of the reconstructed cosmic track on the chamber and looking at a fired strip in a range of few centimetres. All the 480 chambers showed an efficiency greater than 95% at 9.5 KV with an overall average efficiency of 98% (Fig. 4). A very good uniformity of the chamber performance has been also shown by a very narrow distribution (rms of about 100 V) of the high-voltage working point at which the chamber reaches an efficiency of 95% of the maximum measured efficiency (Fig. 5).

3. From the Cosmic ray test at ISR to the chamber installation

From the test sites, the chambers have been shipped to CERN at the IS where they were completed with the installation of the Front-End cooling, the HV connection and temperature sensors and where they undergo further longer tests in order to fully characterize the chambers and eventually find some unusual behaviour over a long time.

The main test at that time is to keep a large set of chambers at the working HV point for a month and continuously monitor the dark current of every double gap and the noise strip by strip.

Almost all the chambers have shown a current stability in time with an average value similar to the one measured before. The current at 9.4 KV of 380 chambers is reported in the left plot of Fig. 6 where the average is of about 1 μA. The chambers that showed a non-standard behaviour of the current over a period of 2–3 weeks have been repaired replacing one double gap. The average noise rate measured at ISR (Fig. 7) was about 0.7 Hz/cm^2, about half of that measured in the QA tests, and this reduction was due to a different and improved grounding schema and to the use of the final LV and HV boards in which the noise of the single channel was reduced by a factor ten.

The ISR tests represented the very final certification of the RPCs before the mechanical coupling of the RPC and DT chambers and the following installation in the wheels.

The operation to couple the DT and the RPC chambers in a unique mechanical framework was examined closely by the two collaborations and was always done in ISR area from July 2004 to October 2007. After a learning period, the coupling was done at a speed of about 2 h including a final fast test in order to check the integrity of the chambers.

The muon chambers were sent to the CMS installation area placed on the surface of the CMS pit (SX5), where they were installed in the iron gaps. 90% of the chambers have been installed in surface while the last 10% were installed in horizontal sectors down in the pit. The installation of the 480 muon chambers was completed at the end of 2007. In the meanwhile the commissioning of the muon system and of CMS has been going on since 2006.

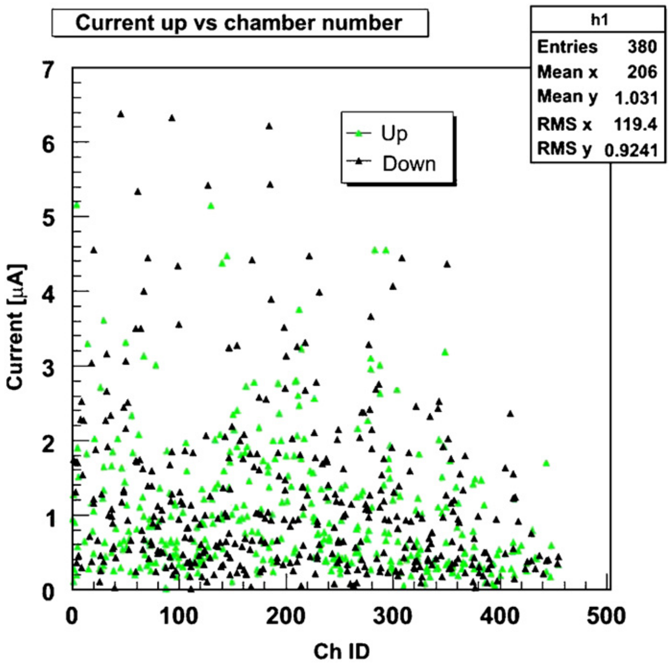

Fig. 6. The current distribution per layer.

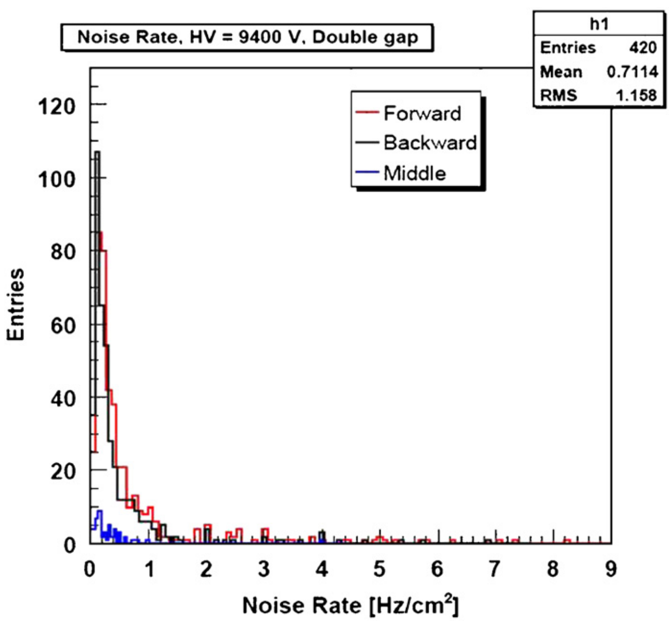

Fig. 7. The noise rate per double gap at 9.4 KV (ISR test).

4. The design and construction of the RPC services

4.1. Power system

The main requirement of the Large Hadron Collider (LHC) power system is to work in a very "unusual" hostile environment due to the high magnetic field and high radiation flux. For the muon system the idea was to have a large part of the power system close to the detector and in particular on the racks placed around the barrel wheels. In this area, the magnetic field can reach up to 0.8 T while the radiation is around 5×10^{10} proton/cm^2 and 5×10^{11} neutron/cm^2.

To fulfil this requirement, the power system has been designed as a master–slave system. The master is supposed to control and monitor the slaves and is placed in a safe and accessible area such as the electronic room, while the slave is where the power is generated and was designed to be modular, multifunctional and radiation tolerant in order to be placed around the detectors.

The whole power system consists of about 25 km of cables, 6.000 connectors and 220 electronic elements.

It has been designed by the group of Napoli and built by the CAEN Company and has been installed in all the parts (cables, distributions and electronics) from the end of 2006 to April 2008 and was used extensively to commission the RPC detectors.

Low Voltage: The LV power boards have been placed close to the detectors (max distance of about 15 m) in order to minimize the noise pickup and the high voltage drop along the cables and to reduce the cost of the whole power project. The total number of LV channels needed is 720 corresponding to 60 LV boards (A3009) with 12 channels each.

High Voltage: The experience made in the past experiments with the RPC detectors suggested the use of a different configuration for the HV system where both the master and slaves are placed in an accessible and safe area (electronic room), to easily fix any problem regarding the connection and the distribution of the HV.

Every chamber has been equipped with two independent HV channels in order to keep the upper and lower gaps of the chambers separate. The present configuration, reduced to one channel per chamber for financial reasons, has 8 or 9 HV channels per sector for a total of 490 corresponding to 82 boards (A3512N).

4.2. Gas system

The RPC detector uses a four-component non-flammable gas mixture made on 94.7% $C_2H_2F_4$ (R134a), 5.0% iC_4H_{10}, 0.3% SF_6 and water vapour. Water vapour is added to obtain a mixture with a relative humidity of about 40–50% allowing to maintain the bakelite resistivity constant and therefore to avoid degradation in the rate capability.

The large detector volume (18 m^3) and the use of a relatively expensive gas mixture ($\sim$85 CHF/m^3) have obliged to implement a gas re-circulation system (the RPC gas system has been developed by the C.E.R.N. PH-DT1-Gas Section).

The CMS RPC gas system consists of several modules: the primary supply, the mixer, the humidifier, the closed-loop circulation, the gas distribution to the chambers, the purifiers and the pump. The full system extends from the surface gas building to the service cavern and to the experimental cavern.

The purifier module is a crucial component since it has to clean the gas mixture from the impurities produced inside the chambers during operation before the mixture is sent again to the detector. The injection of fresh mixture into the system is foreseen to be at the level of 5% at regime, in order to keep the operational cost acceptable.

The mixture composition and quality are monitored by two independent systems [9]: the gas quality monitoring and the gas gain monitoring. The former is based on chemical analysis (mainly gas chromatography, pH and fluoride monitoring [8]) while the latter is based on several 50×50 cm^2 single gap RPC supplied with a mixture coming from different points (i.e. fresh gas, supply to the chambers, return from the chambers, etc.). In case significant difference is observed between the performances of the different RPC, a warning will be sent to the DCS.

4.3. Front-End electronic system

The RPC Front-End electronics has been designed and developed by the Bari group and is based on chip, called RPC_FEC, developed in the AMS 0.8 μm technology and implementing 8 channels of amplifier, discriminator and LVDS line driver. Two of these chips are housed on the barrel Front-End Boards (FEB), where ancillary electronics provide the remote control interface and some testing features. FEB are connected to the readout strips through a kapton foil, whose shape is optimized to obtain the right impedance and to have the same arrival time for all channels

The barrel is fully equipped with about 4600 boards for a total amount of 74,000 channels. The Front-End Boards send the amplified and discriminated signals to the Link Boards, located on the detector periphery, where they are compressed and sent on optical link to the Trigger Electronics, housed in the CMS Counting Room, for further processing.

5. Conclusions

The CMS RPC muon trigger project was officially approved in 1998 and many years have been devoted by the collaboration to design, build, test and install the 480 chambers and the relative services necessary to run the system.

The RPC chamber construction began in 2002 in Bari and the last chamber was assembled in December 2006. In the meanwhile, a great and collaborative effort was done by the collaboration to design and build the power, gas and Front-End electronics systems, to draw the cable and gas line routings and to plan all the operations, from the installation to the commissioning, needed to assure the perfect functioning of the whole system.

The RPC system installation began in 2004 and was completed in 2007 and in the meanwhile the commissioning of the system is still going on and it will be over in June 2008 when LHC will be ready to close the doors and to begin the first physics runs.

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