LHCb EXPERIMENT

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1. Introduction

The LHCb experiment is aimed at detailed studies of *CP*-violation effects in various decays of *B* mesons and also at search for rare *B* decays suppressed in the Standard Model. These studies should check the predictions of the Standard Model on a high precision level and, in this way, may reveal some presence of the "new physics" beyond the Standard Model. At present, the main information in this research area is coming from the e^+e^--colliders (BABAR experiment at SLAC (USA) and BELLE experiment at KEK (Japan)). Also, some important results were obtained recently in the CDF and D0 experiments at Tevatron (1 TeV + 1 TeV $p\overline{p}$ -collider at FNAL (USA)). Compared to the e^+e^--colliders, LHCb will be much more abundant source of *B* mesons. Moreover, a larger variety of *b*-mesons and *b*-baryons will be produced. As concerns the CDF and D0 experiments, they are general purpose experiments, not optimized for *B*-decay studies. The LHCb experiment, being a dedicated *B*-physics experiment, will have serious advantages (forward geometry, particle identification) over the Tevatron experiments.

In the initial stage of formulation the physics program for LHC, there were three different proposals for dedicated studies of *B* physics. One of them (COBEX) proposed to use the *pp*-colliding beams, the other proposals considered two options of fixed target experiments. None of these proposals was accepted by the LHC Committee. Instead, it was recommended to the three collaborations to merge in one collaboration and to present a new proposal oriented on utilization of the *pp*-colliding beam. Following this recommendation, such collaboration (LHCb collaboration) was soon organized and started to work out the new project. The COBEX layout was considered as a starting point. The PNPI group, being a member of the COBEX collaboration, took an active part in development of the new project. In particular, the PNPI group suggested the most radical change in the COBEX layout: it was proposed to replace the COBEX magnetic system (a large quadrupole magnet followed by a small dipole magnet) by one large aperture dipole magnet. This proposal was based on simulation studies of the detector performance, including the background conditions. After hot discussions, this proposal was accepted by the collaboration. The Letter of Intent was presented in August 1995, and it was approved by the LHCC. Since then, the PNPI group focused the efforts on development of the LHCb Muon System.

2. LHCb detector

The Technical Proposal (TP) of the LHCb experiment was approved in September 1998. The LHCb detector was designed as a single-arm spectrometer with a forward angular coverage from 10 mrad to 300 (250) mrad in the bending (unbending) plane. The choice of the detector geometry was motivated by the fact that at high energies both $b(\overline{b})$-hadrons are predominantly produced in the same forward cone. The production rate of the $b\overline{b}$ -pairs being very high, the LHCb experiment plans to operate at reduced luminosity of 2×10^{32} cm^{-2}s^{-1}, still producing unprecedented amounts of the $b\overline{b}$ -pairs (10^{12} per year). This allows to study rare *B*-decay channels, under condition that these channels could be well separated from the background reactions. The strategy of the LHCb experiment was formulated as follows:

- powerful particle identification;
- high precision vertex detector;
- high momentum resolution for charged particles;
- efficient trigger for selected *B*-decay channels with *b*-tag;
- selection of the bunches with only one interaction per bunch.

These features should make the LHCb detector a unique facility for future *B*-physics.

The LHCb detector comprises a large aperture magnet, a vertex locator, a tracking system, two RICH counters, an electromagnetic calorimeter with a preshower detector, a hadronic calorimeter, and a muon system. It occupies space of 20 meters along the beam direction. One important parameter of the detector is the amount of material traversed by the particles before they enter the calorimeter. This material deteriorates the detection capability of electrons and photons, increases the multiple scattering of the charged particles, and increases occupancies of the tracking stations. Unfortunately, after completion of the Technical Design Reports (TDRs) by the end of 2001, it was realized that the material budget of the LHCb detector is a factor of 1.5 higher than expected in the TP. On the other hand, it was understood that the amount of material can be reduced to the TP values by reoptimizing some of the detector systems without deterioration of its performance.

Figure 1 shows the layout of the reoptimized LHCb detector. The basic layout remains unchanged from that of the TP. The main changes are in the number of tracking stations (4 stations instead of 11), in the number of stations in the vertex detector (21 instead of 25), in the thickness of the silicon sensors (220 μm instead of 300 μm), and in the number of detecting planes in the first muon station M1 (two planes instead of four). Also, there is some reduction of material in RICH1 (due to changing the mirror material) and in the beam pipe (due to replacing the Be-Al alloy by Be in the sections up to the calorimeters. The resulting material budget in front of RICH2 is now 20−30% of the radiation length X_0 and 12% of the nuclear interaction length λ_I, compared to the TP values: 40% of X_0 and 10% of λ_I.

The design of the reoptimized LHCb detector was approved in 2003 [1].

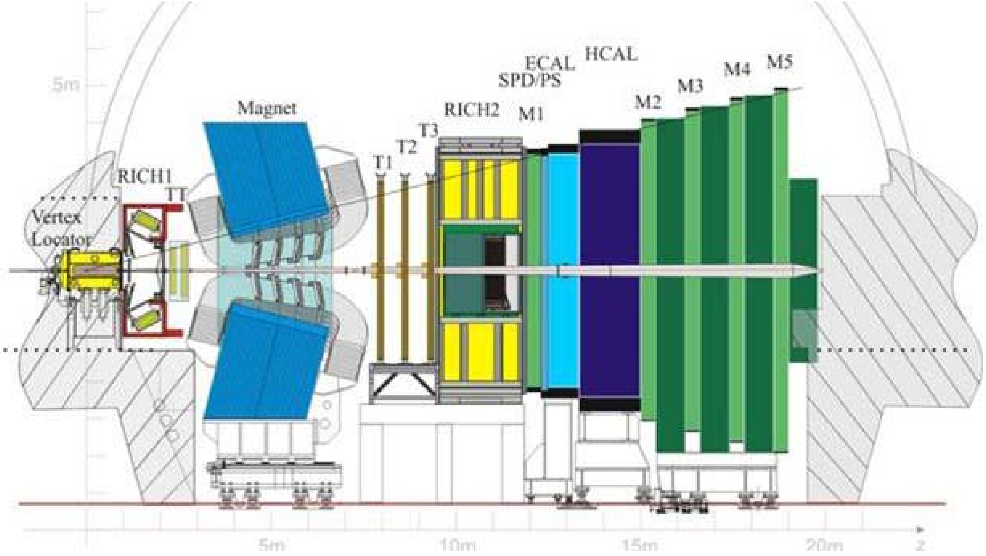

Fig. 1. Reoptimized LHCb detector layout showing the Vertex Locator (VELO), the dipole magnet, the two RICH detectors, the four tracking stations TT and T1−T3, the Scintillating Pad Detector (SPD), Preshower (PS), Electromagnetic (ECAL) and Hadronic (HCAL) calorimeters, and the five muon stations M1−M5

3. PNPI participation in design and construction of the LHCb Muon System

3.1. LHCb Muon System. General layout and principle of operation

The Muon System performs two functions: the muon identification and the Level-0 muon trigger. Also, it should provide matching of the selected muon trajectory to the Tracking System for precision measurement of the muon momentum. The principle of operation of the Muon System was formulated by the PNPI group in 1997 [2]. It was demonstrated that the Muon System can provide the muon trigger in a stand-alone mode using information only from the muon chambers. As it is described in the Muon TDR [3], the Muon System contains a longitudinally segmented shield to attenuate hadrons, photons, and electrons. The shield components comprise ECAL, HCAL, and four iron walls. The total weight of the iron shield is 1800 tons. Five muon stations, M1−M5, are located as shown in Fig. 1. Muon station M1 is positioned in front of ECAL Stations M2−M4 are embedded in the 40 cm space available between the iron walls, being mounted on movable platforms as illustrated in Fig. 2. The inner and outer acceptance (horizontal-vertical) of the Muon

System is 25 mrad × 15 mrad and 294 mrad × 250 mrad, respectively. The sensitive area of the muon stations varies from 42 m^2 (M1) to 106 m^2 (M5).

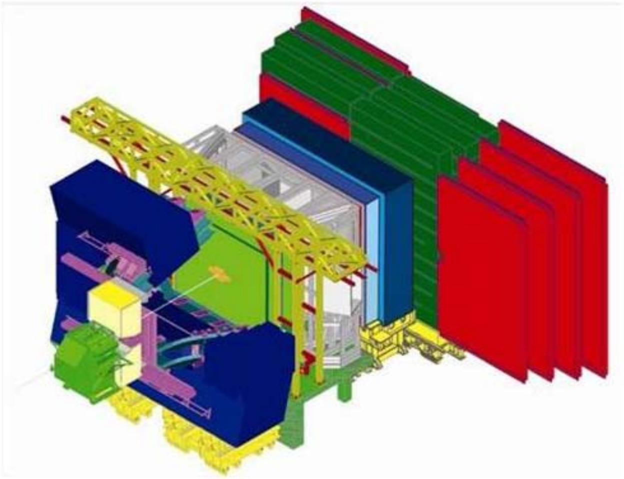

Fig. 2. Artist's view of LHCb.
The muon detectors in stations M2-M3 (red color) can slide sidewise the beam line to allow access. The figure shows the right-hand side detectors in maintenance position

As it was proposed in Ref. [2], the muon track finding procedure starts with detecting a hit in station M3. Then hits in the other stations are searched in the "fields of interest" close to the line connecting the hit in M3 with the interaction point. Finally, the muon trajectory is reconstructed using the hits in M2 and M1, while the hits in the other stations serve to reduce the background. Thus found muon trajectory is traced back to the interaction point. The deviation of the projected trajectory from the interaction point (impact parameter) is a measure of the muon transfer momentum p_t. The muon trigger selects events with p_t higher than a preset value (~ 1.5 GeV/c). The simulation shows that such trigger can provide ~ 40% registration efficiency for the $B \to \mu$ events with suppression factor of ~100 for the minimum bias events. The described above M1/M2 p_t cut exploits information from M1 station which is located in front of ECAL in most severe background conditions. However, in case of problems with M1, the muon trajectory could be determined using hits in M2 and M3. The performance of such M2/M3 p_t cut is still satisfactory: ~30% $B \to \mu$ efficiency with the same suppression factor for the minimum bias events. The described algorithm was implemented in Muon Trigger System which provides the Level-0 trigger signal in less than 3 μs time after the interaction.

3.2. Choice of the muon detector technology

A serious problem in the Muon System is the high background. Our studies with GCALOR simulation program [4] showed that fluxes of charged particles in station M1 vary from 200 kHz/cm^2 in the region close to the beam pipe to 10 kHz/cm^2 in the outer region. The background in stations M2−M5 is lower by nearly two orders of magnitude, but still it is very high. To a great extent, the high background level determines the choice of the detector technology. The detector should be fast and radiation hard. The trigger algorithm requires the very high detection efficiency in each muon station. It should be 99% in a 20 ns window to determine reliably the correct bunch crossing. On the other hand, the space resolution of the muon detectors might be rather modest, coherent with the muon track diffusion due to Coulomb scattering in the iron shield. To satisfy these requirements, a 2D-pad structure has been chosen with the pad dimensions in each station scaled so that the pad configuration in M1−M5 is projective to the interaction point. Each station is divided into four regions, R1−R4, with different pad sizes. Several technologies have been considered for the muon station detectors. The PNPI group suggested to use specially designed fast operating wire chambers with anode and/or cathode readout. The other technologies were so-called Thin Gap Chambers (TGC) and Resistive Plate Chambers (RPC). After extensive R&D studies, the LHCb collaboration has chosen the wire chambers proposed by PNPI for the whole Muon System except a small but the most "hot" region R1 in station M1 where GEM detectors will be used.

The proposed wire chambers have a rectangular geometry with the sensitive area $S = H \times L$, where the chamber height H varies from 20 cm (M1, R1−R4) to 31 cm (M5, R1−R4) and the chamber length L from 24−37 cm (R1, M1−M5) to 96−150 cm (R4, M1−M5). An important feature of this design is identical chamber height for all regions within one station. This allows to use the "ladder structure" and to avoid complications in boundary areas between different regions. This structure is illustrated by Figs. 3, 4.

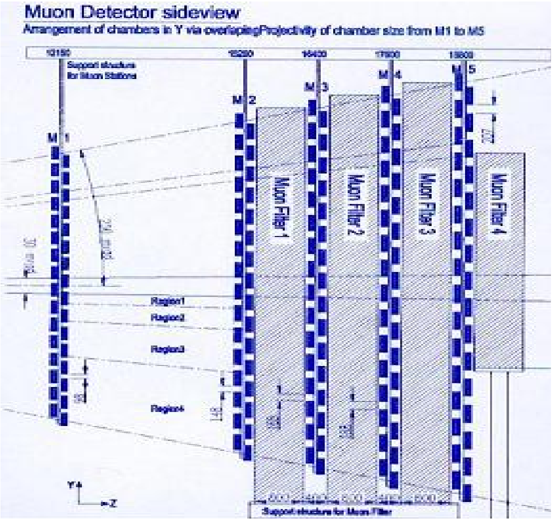

Fig. 3. Side view of the muon system in the YZ-plane

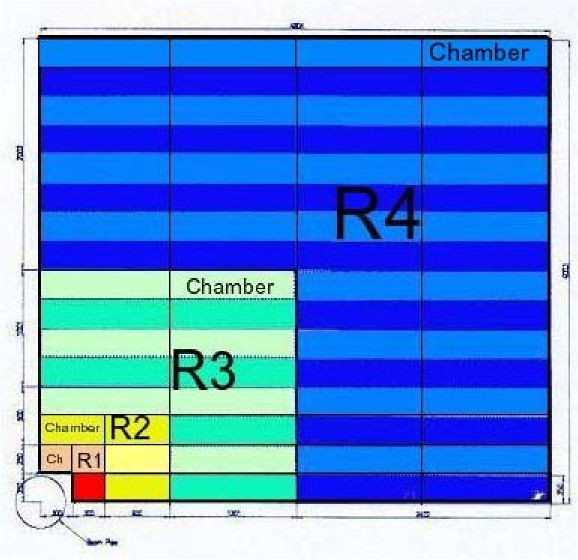

Fig. 4. XY-view of a quarter of station M2. Regions R4, R3, R2, and R1 are marked in blue, green, yellow and red, respectively

The wire chambers have symmetrical cells with the following geometry parameters:

- the anode-to-cathode distance − 2.50 mm ,
- the anode wire diameter − 30 μm,
- the anode wire spacing − 2.0 mm.

The wire is wound along the short side of the chamber in the vertical (Y) direction. In the region R4, the wire length coincides with the required pad size in the Y-direction. Therefore, wire pads are used in these regions by grouping several wires in one readout circuit. For example, the wire pad size in the region M3R4 is 54×270 mm^2. The other regions have cathode pads with the pad sizes reduced in both directions by the factors 2 (R3 region), 4 (R2 region), and 8 (R1 region). The pad size remains constant within each region.

Each chamber in stations M2–M5 contains four sensitive gaps which are connected as two double-gap layers. Such multi-gap structure helps to satisfy the requirements of fast operation and high detection efficiency. Also, it should provide a sufficient redundancy of the Muon System designed for many-years operation of the LHCb experiment. Note, however, that the station M1 contains only one double-gap, due to space and material budget constraints for this region.

3.3. Study of muon chamber prototypes

During the period 1998−2002, a series of muon chamber prototypes (10 prototypes in total) were constructed at PNPI and tested in a pion beam at CERN [5] − see Fig. 5. These R&D studies allowed to optimize the chamber geometry parameters, the gas mixture, and the front-end electronics parameters. Also, simulation studies of the muon chamber performance were carried out.

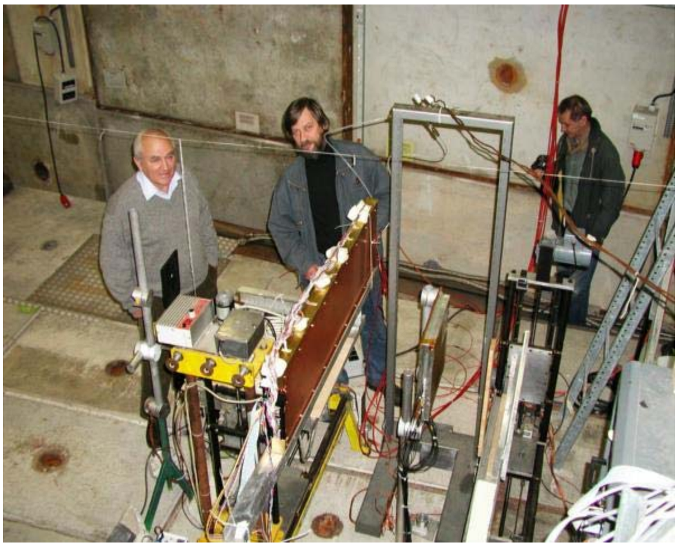

Fig. 5. One of the muon chambers constructed at PNPI in the T11 test beam area at CERN. In total, 10 muon chamber prototypes have been constructed at PNPI and tested in the 3 GeV/c pion beam at CERN. The results of these tests were decisive for selection of the proposed detector technology for the LHCb Muon System

Various gas mixtures have been tested, and the mixture of $Ar/CO_2/CF_4$ (40:50:10) was recommended. This gas mixture provides high electron drift velocity (~100 μm/ns), increased stability again discharges, and good aging properties. Note that these studies were performed with 1.5 mm wire spacing in the chambers. The conclusions from these studies were as follows.

- One double-gap layer of the muon chamber can provide the required 99% detection efficiency in a 20 ns time window in the high voltage (HV) range from 3.15 kV to 3.35 kV, the efficiency being not so sensitive to staggering of the wire planes and to the incident angle of the muons.
  With two double-gap layers, the 99% efficiency can be obtained starting from HV = 2.95 kV.
- The gas gain was around 10^5 at HV = 3.15 kV. Its variation over the whole chamber area was measured to be within ±20% (equivalent to ±30 V variation in HV).
- The chambers could operate at high beam intensity. The tests with a 150 kHz beam did not show deterioration of the detection efficiency.
- The total cross talk probability in a double-gap layer was measured to be less than 10% at HV $\leq$ 3.2 kV, and it was dominated by the cross-talk to the neighbor pads.

These results demonstrated that the designed muon chambers can satisfy the requirements of the LHCb experiment with the redundancy which was considered even as excessive. That is why the collaboration decided to increase the wire spacing from 1.5 mm to 2.0 mm, thus reducing the cost and simplifying the assembling procedure. Further tests showed that the chamber performance was not deteriorated significantly. After that, the chamber technology was fixed, and the construction of the Muon System has been started.

3.4. Assembling of muon chambers at PNPI

The LHCb Muon System contains 1380 muon chambers in total, 600 of them were to be assembled at PNPI. These are the four-gaps chambers with the wire pad readout for the region R4 in the stations M2, M3, and M4. They cover 75% of the total area of these stations (Fig. 4). The sensitive area of each chamber is 120 × 25 cm^2 (M2R4), 130 × 27 cm^2 (M3R4), 140 × 29 cm^2 (M4R4). In total, they contain about 1500000 anode wires.

According to the specifications, the gas gain should be uniform over the chamber area within ±30%. This is translated to the following constraints: the gap size of 5.0 ± 0.1 mm, the anode wire spacing of 2.0 ± 0.1 mm, the anode wire tension of 65 ± 5 g.

The chambers have no frames. The chamber planes are glued together, so the chambers could not be opened after assembling. This requires a reliable assembling technology with control at at each step. Such technology has been developed at PNPI, and it was approved by the collaboration after the Production Readiness Review on January 30, 2004. Then chamber assembling was started in a specially prepared assembling facility (PNPI-1) − see Figs. 6, 7. From mid of 2005, the second facility (PNPI-2) − see Figs. 8, 9 − joined this activity. More than 40 PNPI specialists were involved in this project. A clean area (800 m^2) was prepared for this work. Both facilities were equipped with special tooling: six bar-gluing tables, two automated wiring machines, an automated wire-soldering machine, two wire-spacing and wire-tension control machines, two γ-rays test stands, various test equipment. This tooling was designed and fabricated jointly by the PNPI and CERN teams.

Fig. 6. Bar gluing tables at PNPI-1 facility

Fig. 7. Automated wire soldering and wire pitch and tension measuring machines at PNPI-1

Unprecedented production rate has been reached: up to one chamber per working day in each facility. By the end of 2006, all 600 chambers have been assembled and tested. According to the tests, all chambers were well within the specification requirements.

Fig. 8. Automated wiring machine at PNPI-2 facility

Fig. 9. The PNPI-2 team in front of containers with the last muon chambers assembled at PNPI and prepared for the transportation to CERN on November 20, 2006.

All results from the tests are stored in the CERN Oracle Database Server accessible *via* Internet by any member of the LHCb collaboration – see Fig. 10.

Fig. 10. Special Web-Application was developed in order to implement all test results into the CERN Oracle Database Server. The database contains full information on chamber tests at all stages from the beginning of construction till the installation into the LHCb Muon System

3.5. Testing of muon chambers at CERN and installation into LHCb Muon System

By the end of 2006, all 600 muon chambers assembled and tested at PNPI were transported to CERN. At CERN, the tests were repeated (gas leak tests and HV tests). After that, the chambers were installed in a storage area and permanently flushed with dry nitrogen. Then the chambers were dressed with Faraday cages and with low voltage and high voltage lines, and were passed the final “pre-installation” tests on a special cosmic-rays test stand. Some chambers were also tested in the CERN high-flux gamma-rays facility GIF. All this work was done by the PNPI team.

After the pre-installation tests, the chambers were sent to the LHCb pit for installation into the Muon System. The installation process required tremendous efforts from the PNPI team. This procedure included preparation of the gas lines, tracing the HV, LV, and readout cables, fixation of the chambers in their positions in the muon stations, alignment of the chambers, gas leak tests, and tests of the readout electronics. A team of 10 people from PNPI participated in this work from mid of 2006. The installation and commissioning of the muon chambers should by finished by the end of 2007, when the Muon System should be prepared for the pilot run of LHC.

All the above mentioned stages of testing of muon chambers at CERN and their installation into LHCb Muon System are illustrated by Figs. 11−16.

Fig. 11. Muon chambers in containers after arrival at CERN

Fig. 12. Muon chambers in storage area at CERN

Fig. 13. Preparing of muon chambers for final tests

Fig. 14. Testing of muon chambers at cosmic-rays test stand

Fig. 15. Installation of muon chambers into the LHCb Muon System.

Fig. 16. PNPI team participating in installation of the LHCb Muon System

3.6. Design and construction of multi-channel high voltage system for LHCb Muon detector

The LHCb Muon System contains 1380 muon chambers with about 5000 detecting layers. For better redundancy of the system, it would be important to have independent high voltage supply (up to 3 kV) for each layer. However, the cost of such multi-channel HV system available on market proved to be unacceptable for the LHCb collaboration. A much less expensive HV system for 11000 channels has been constructed recently by joined efforts of PNPI and Florida University for the CMS detector. The LHCb collaboration offered PNPI to build a similar HV system for most part of the LHCb Muon detector (for 4000 channels). Taking into account the critical situation in construction of the HV system for the LHCb Muon detector, PNPI agreed with this proposal, though this work was not in the initial PNPI responsibilities. As the first stage, it was decided to build a system for 2000 channels in 2007 with further extension up to 4000 channels. The designed HV system provides in each channel the voltage control with 1 V resolution and the current control with a resolution of 2 nA (for $I < 1\ \mu$A) and 100 nA (for $I > 1\mu$A). The maximal current in one channel is 100 μA. During 2006, a 108-channel prototype of the HV system was constructed at PNPI and tested at CERN. Construction of the 2000-channel system is planned to be completed by the end of 2007. A block scheme of this HV system is presented in Fig. 17.

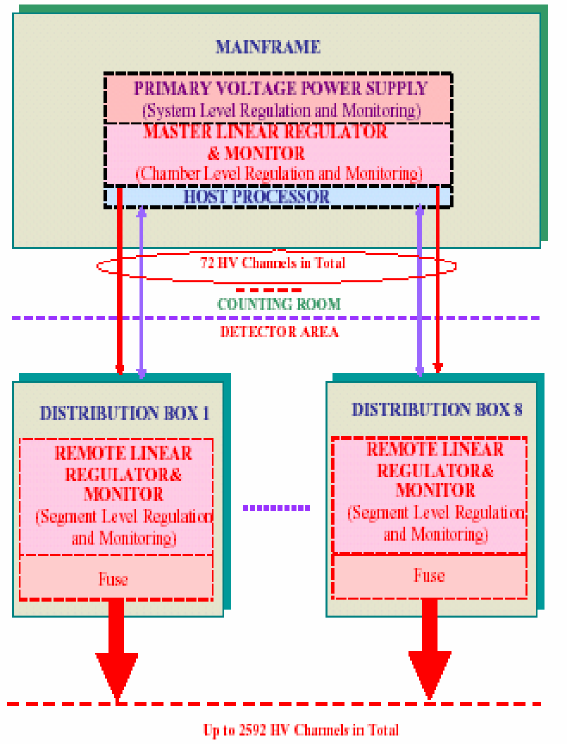

Fig. 17. Block scheme of designed multi-channel HV system for the LHCb Muon detector.

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