LHCb EXPERIMENT

A.A.Vorobyov, V.V.Astashin, M.Ya.Borkowski, B.V.Bochin, S.A.Guets, A.P.Kashchuk, V.I.Lazarev, N.R.Saguidova, V.M.Souvorov, E.M.Spiridenkov, A.Yu.Tsaregorodtsev, An.A.Vorobyov, N.Yu.Zaitsev

1. Introduction

The LHCb experiment [1] is aimed at detailed studies of CP-violation effects in various decays of B mesons. CP violation was first discovered in neutral kaon decays. The observed phenomenon was explained within the Standard Model, where it is generated by complex three-by-three unitary matrix introduced by Kobayashi and Maskawa. However, it is not excluded that some other physics beyond the Standard Model is responsible, at least partly, for this phenomenon. The further progress in understanding the nature of the CP violation is expected due to new possibilities to study various decays of B mesons. In the B-meson system there are many decay modes, and the Standard Model makes precise predictions for CP violation in a number of these. One of them have been recently corroborated in BARBAR and BELLE experiments at e^+e^--colliders (B-factories) which have observed CP violation in the $B_d^0 \to J/\Psi\ K_s$ decay.

Compared to the e^+e^--colliders, LHC will be far the most copious source of B mesons due to the high $b\overline{b}$ cross section and high luminosity. Moreover, a variety of b-hadrons, such as B_u, B_d, B_s, B_c, and b-baryons will be produced at high rate. This opens unique possibility to perform complete quantitative tests of the Standard Model predictions. In particular, it will be possible to measure the angles of the unitary triangle by measuring the CP asymmetries, for example in the following channels:

- $B_d^0 \to J/\Psi K_s$; $\pi^+\pi^-$; $\overline{D}^0K^{*0}$; D^0K^{*0}; D_1K^{*0} ;
- $B_s^0 \to J/\Psi\ \phi$; $D_s^\pm K^\mp$.

In addition, the physics programme of the LHCb experiment will include studies of $B_s^0 \to \overline{B}_s^0$ and $D-\overline{D}$ oscillations, rare B and τ decays, B_c-meson decays. In particular, studies of various decay modes generated by the $b \to s\gamma$ process should be possible which may yield surprising results.

2. Strategy of LHCb experiment

The LHCb detector is 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 the b- and $\overline{b}$-hadrons are predominantly produced in the same forward cone, a feature exploited in the flavour tag. 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. This condition dictated the strategy of the LHCb experiment:

– 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.

3. LHCb detector

The layout of the LHCb detector is shown in Fig. 1. It comprises a large aperture magnet, a vertex detector system, a tracking system, two RICH counters, an electromagnetic calorimeter with preshower detector, a hadron calorimeter, and a muon system. The LHCb detector occupies space of 20 meters along the beam direction.

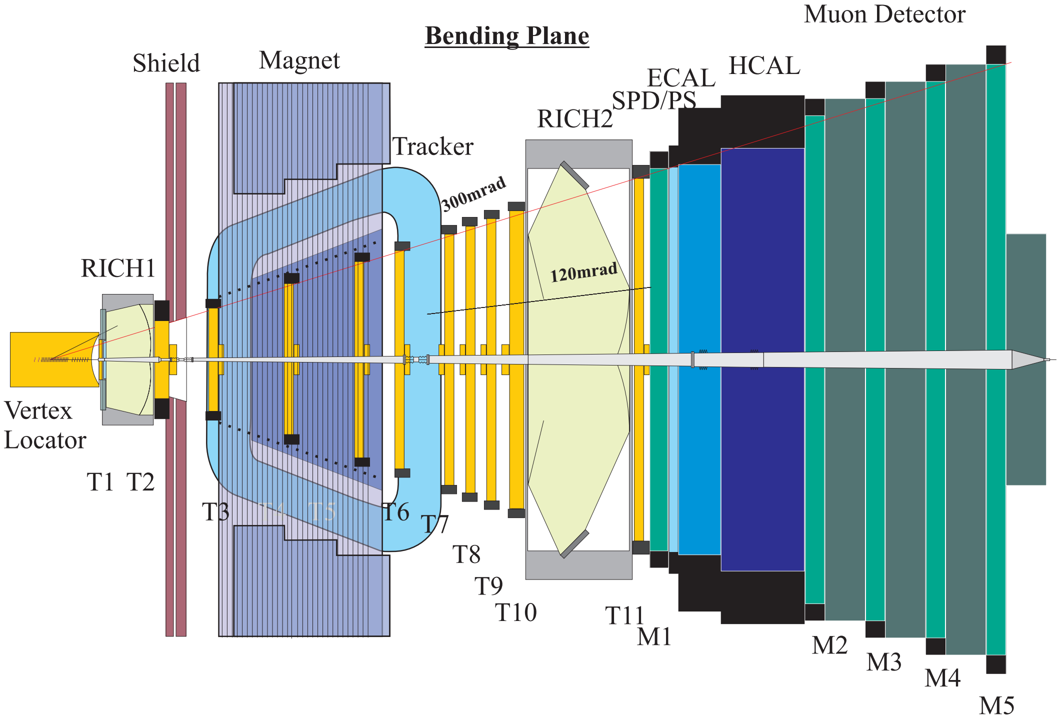

Fig. 1. The LHCb detector

3.1. Magnet

A superconducting dipole magnet is chosen to obtain a high field integral of 4 T·m with a short length. The field is oriented vertically and has a maximum value of 1.1 T. The polarity of the field can be changed to reduce systematic errors in the CP violation measurements that could result from a left-right asymmetry of the detector. The free aperture is 4.3 m horizontally and 3.6 m vertically. The coil is designed to maximize the field homogeneity.

3.2. Vertex Detector

A 1.8 m long section of the beam pipe around the interaction point has a large diameter of 120 cm. This accommodates the vertex detector system with its retraction mechanics inside the beam pipe. The Vertex Detector consists of 17 stations between Z = – 18 cm and

Z = + 80 cm. Each station contains two discs of 150 μm silicon detectors with circular (r) and radial (ϕ) strips, respectively. The discs are positioned perpendicular to the beam. Tracking coverage extends radially from 1 to 6 cm and provides at least three space points on tracks with polar angles down to 15 mrad. The detector will be operated at –10°C to decrease the radiation damages. The readout system contains 220,000 analog channels. All channels will be read out within 1 μs to provide information for the Level-1 trigger. The strip pitch varies from 40 to 100 μm. The resolution on the impact parameter will be 40 μm for high momentum tracks.

3.3. Tracking System

The Tracking System, consisting of the Inner and Outer Tracker, provides reconstruction and precise momentum measurement of charged tracks, track direction for ring reconstruction in the RICH, and information for the Level-1 and high-level triggers. The system comprises 11 stations (T1–T11) between the vertex detector and the calorimeter. The Outer Tracker will be based on straw tubes, while silicon strip detectors will be used for the Inner Tracker. Precise coordinates in the bending plane are obtained from wires or strips at 0° and ±5° with respect to the vertical. The expected momentum resolution is approximately 0.3% for momenta from 5 to 200 GeV/c. As an example, the mass resolution for $B_d^0 \to \pi^+\pi^-$ will be 17 MeV/c^2.

3.4. RICH detectors

The RICH system has the task to identify charged particles over the momentum range 1–150 GeV/c. Particle identification is crucial to reduce background in selected final states and to provide an efficient kaon tag. The system consists of an upstream (RICH1) and downstream (RICH2) detectors. RICH1 has a 5 cm-thick aerogel radiator and a 95 cm-long C_4F_{10} radiator, and it is tuned for the detection of low momentum particles. RICH2 is filled with CF_4 radiator with the length of 180 cm. The Cherenkov photons are focused by mirrors to detector planes positioned outside the spectrometer acceptance. The photons will be detected with Hybrid pixel photodiodes (HPD) or with multianode photomultipliers. A total image surface is 2.9 m^2, and the detector granularity of 2.5 mm × 2.5 mm is foreseen.

The RICH system will provide separation of pions from kaons over the momentum range 1–150 GeV/c with high efficiency and purity. This is an important advantage of LHCb if compared with other LHC-detectors (ATLAS and CMS).

3.5. Calorimeters

The main purpose of the calorimeters is to provide identification of electrons and hadrons for trigger and off-line analysis, with measurements of positions and energy. Furthermore, the calorimeters should enable reconstruction of photons and π^0 mesons. The structure consists of a single-layer Preshower detector followed by an Electromagnetic Calorimeter (ECAL) and a Hadron Calorimeter (HCAL). The polar-angle acceptance starts at 30 mrad from the beam axis and continues up to 300 mrad horizontally and 250 mrad vertically.

ECAL employs the "shashlik" technology of a sampling scintillator/lead structure. It has a cell structure. Each cell is constructed from alternating layers of 2 mm-thick lead, white reflecting paper, and 4 mm-thick plastic scintillator tiles. In total, there are 70 layers resulting in a total depth of 25 X_0. The light is read out *via* 1 mm diameter WLS fibers which penetrate the entire length of the module and transport the light from each cell to phototubes. The cell size varies from 4×4 cm^2 in the inner section, through 8×8 cm^2 in the middle, to 16×16 cm^2 in the outer section. The total number of cells (and so the readout channels)is around 6000. The total weight is 71 tones.

The Preshower detector is located immediately upstream of ECAL. The transverse segmentation of the Preshower detector matches that of ECAL. Each cell consists of a 14 mm-thick lead radiator (2.5X_0) followed by a 10 mm-thick plastic scintillator. The light is extracted from the scintillator by the WLS fibers and detected by 16-pixel phototubes mounted on the upstream side of the radiator. The Preshower detector serves to improve the π/e separation on the trigger level. The expected energy resolution of ECAL is $\sigma/E = 10\%/\sqrt{E} \oplus 1.5\%$. This energy resolution is enough to provide electron/hadron separation at a level of 100. It is also adequate for the π^0 reconstruction.

The HCAL cells are constructed from scintillator tiles embedded in an iron structure. The cells have square cross-section with sides of 8, 16, and 32 cm with 2:1 correspondence to the cell size in ECAL. The sampling structure of cells is 6 mm steel plate / 4mm steel spacer / 3 mm scintillator. In total, there are 1584 cells. The scintillation light is transferred by the WLS fibers to the rear of the calorimeter where it is detected by phototubes. The light is collected separately from the upstream and downstream halves of the cells making the total number of the readout channels 3144. The overall transverse dimensions of HCAL are 9.0 m $\times$ 7.0 m, and the depth of the iron is 1.5 m (7.3 λ_I). The total weight of HCAL is 597 tones. The design resolution of HCAL is: $\sigma/E = 80\%/\sqrt{E} \oplus 5\%$.

3.6. Muon System

Participation in design and construction of the Muon System is the main PNPI responsibility in the LHCb project. The PNPI group made most important contributions to development of the Muon System:

- It was proposed and proved a stand-alone mode of operation of the Muon System when the muon trigger is provided using information only from the muon chambers [2].
- Background calculations have been performed which determined the experimental conditions in which the muon chambers should operate [3].
- Based on physics requirements, a muon detector technology was proposed: fast-operating multiwire proportional chambers with cathode and anode readout [4].
- Ten prototypes of the muon chambers with readout electronics have been constructed at PNPI and tested successfully in the high energy beams at CERN [5].

The obtained results convinced the LHCb collaboration to select the proposed technology for construction the Muon System [6]. Furthermore, it was decided that nearly half of the muon chambers will be assembled at PNPI.

3.6.1. General description

The Muon System performs two functions: muon identification and the Level-0 muon trigger. Also, it should provide matching of the selected muon trajectory to the Tracking System for precision off-line measurement of the muon momentum.

The Muon System [6] contains a longitudinally segmented shield to attenuate hadrons, photons, and electrons. The components of the shield comprise ECAL, HCAL and four layers of steel. Five muon stations, M1-M5, are situated as shown in Fig. 1. Muon station M1 is positioned immediately in front of ECAL. The other four stations are embedded in the muon shield into the 40 cm space available between the steel shielding. The inner and outer acceptance (horizontal $\times$ vertical) of the Muon System is 25 mrad $\times$ 15 mrad and 294 mrad $\times$ 250 mrad. The total weight of the steel shields is 1800 tones. To penetrate this shield and reach station M5, a muon must have at least 6 GeV. In the regions M2–M5, an addition shielding is introduced around the beam pipe (from 10 mrad to 12 mrad) for protection from secondary particles which emerge from the beam pipe.

The Muon system operates in a stand-alone mode, it provides the muon trigger using information from muon stations M1–M5. A muon should be detected in all five muon stations, and its trajectory should be traced back to the interaction point. The deviation of thus projected trajectory from the interaction point (impact parameter) is a measure of the muon momentum.

Fig. 2 illustrates the track finding procedure by the muon trigger. The muon trigger selects muons with a transfer momentum P_T higher than a preset value (around 1 GeV/c) with the goal to reduce the rate of minimum bias events by a factor of 30 to 100 while keeping the highest possible efficiency for $B \to \mu + X$ events. The muon trigger should be provided within 3.2 μs.

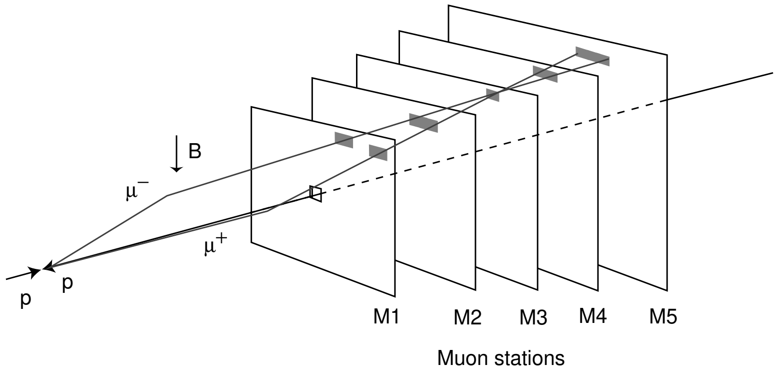

Fig. 2. Track finding by the muon trigger. For each logical-pad hit in M3, hits are sought in M2, M4 and M5, in a field of interest (highlighted) around a line projecting to the interaction region. When hits are found in the four stations, an extrapolation to M1 is made from the hits in M2 and M3, and the M1 hit closest to the extrapolation point is selected. The track direction indicated by the hits in M1 and M2 is used in the P_T measurement for the trigger, assuming a particle from the interaction point and a single kick from the magnet. In the example shown, μ^+ and μ^- cross the same pad in M3

A serious problem in the Muon System is the high background. It is especially high in station M1 where it varies 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 to reduce the occupancy in the readout channels, and it should be radiation hard. The trigger algorithm requires very high detection efficiency in each muon station. It should be better than 99% in a 20 ns time window to determine reliably the correct bunch crossing (the interval between bunch crossings is 25 ns). On the other hand, the space resolution of the muon station 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 a specially designed fast operating wire chamber (MWPC) 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, maybe, the most "hot" region R1 in station M1 where some other technologies are also under consideration (triple GEM in particular).

A schematic diagram of an MWPC is given in Fig. 3, and the principle chamber parameters are summarized in Table. The chambers have a symmetrical cell with the anode-cathode distance of 2.5 mm and the anode wire spacing of 1.5 mm. Such small wire spacing is an essential feature of the proposed MWPCs: it helps to improve the time resolution and eliminates the staggering effect in the multilayer chambers. All MWPCs have a rectangular geometry with the sensitive area S = H·L, where H is varied from 20 cm (M1, R1–R4) to 31 cm (M5, R1–R4) and L from 24–37 cm (R1, M1–M5) to 96–150 cm (R4, M1–M5).

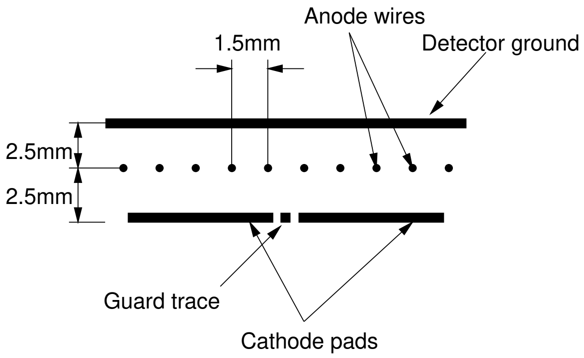

Fig. 3. Schematic diagram of one sensitive gap in a MWPC

Table

Main MWPC parameters

Parameter	Design value
Gas Gap	5 mm
Wire spacing	1.5 mm
Wire Diameter	30 μm
Nominal operating voltage	3.1 kV
No. of gaps	4
Gas mixture	$Ar/CO_2/CF_4$ (40:50:10)
Primary ionization	$\sim$ 100 e^-/cm
Gas Gain	$\sim 10^5$

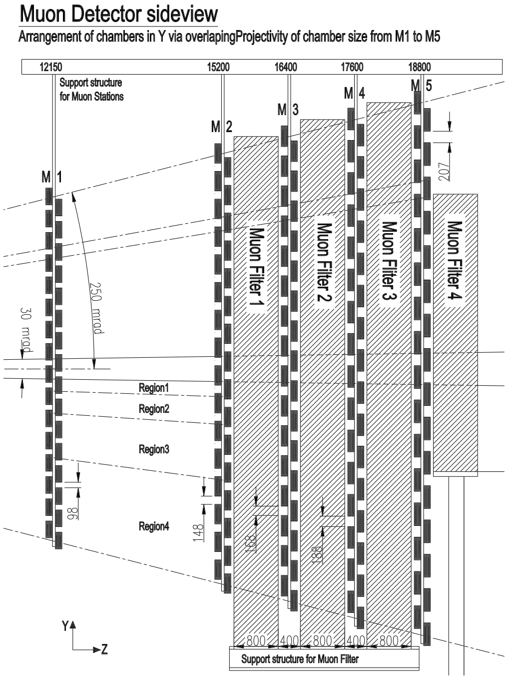

Fig. 4. Side view of the muon system in the y,z plane

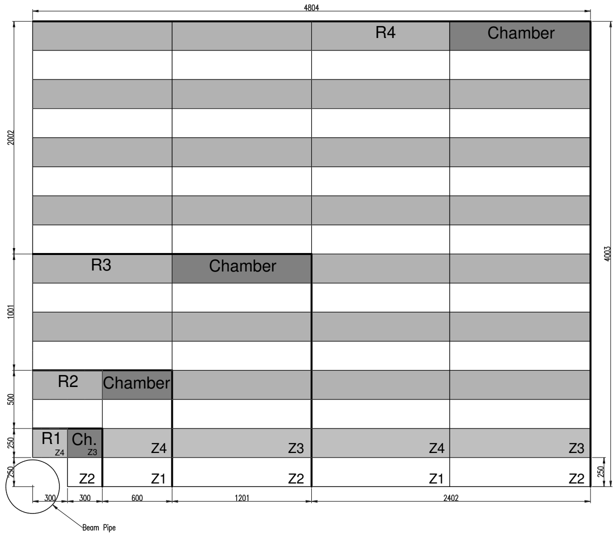

Fig. 5. x,y view of a quarter of station M2, one chamber in each region is highlighted

The wire is wound along the short side of the chambers that allows to avoid any wire supporting structure in the sensitive volume of the chamber. The MWPC gas is a non-flammable mixture of $Ar/CO_2/CF_4$ (40:50:10) which is characterized by high electron drift velocity and by good aging properties. Also, this gas mixture has low sensitivity to neutrons as it contains no hydrogen. Each chamber contains four sensitive gaps which are connected as two double-gap layers. Chambers are read out differently, depending on their position in the Muon System.

In region R4 the chambers have the anode-wire readout (wire pads with sizes ranging from 4×20 cm^2 in M1 to 6×31 cm^2 in M5). In region R3 the chambers have the cathode-pad readout (cathode pads with sizes raging from 2×10 cm^2 in M1 to 3×15.5 cm^2 in M5).

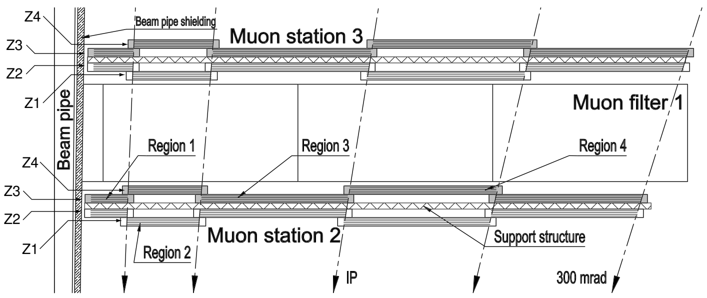

Fig. 6. Partial view of the muon system in the x, z plane. The projectivity of the chambers to the interaction point has been indicated

In regions R1 and R2 the chambers have either the cathode-pad readout or the combined readout of the wire and cathode pads to provide the required higher granularity in these regions. The chamber arrangement in the Muon System is illustrated in Figs. 4–6. The same height of the chambers in one station allows to use the "ladder" structure and to avoid complications in the boundary areas between different regions. Figs. 4–6 show how the overlapping in x and y is arranged eliminating any dead zones in the whole station. Also seen is the projectivity of the chamber sizes in x and y direction. The total detector area is 435 m^2. Altogether, the Muon

System will contain 1360 four-layer chambers with $4.5 \cdot 10^6$ wires and about 120,000 front-end channels.

The muon trigger algorithm, illustrated by Fig. 2, requires hits in all five stations M1–M5, the muon direction is determined finally by the hits in stations M2 and M1. Thus determined algorithm can provide about 40% trigger efficiency for muons from the $b \to \mu X$ reaction by setting P_T cut = 1.5 GeV/c, while suppressing the minimum bias background by a factor of 100. The trigger efficiency becomes 60% with P_T cut = 0.8 GeV/c, however, with only factor of 30 minimum bias suppression.

It is also possible to determine the muon direction by using hits in M2 and M3 without information from M1. The advantage to operate without station M1 is evident, as this station should work in the most severe background conditions. However, the quality of the trigger becomes worse in this case. Still this option could be used if the minimum bias suppression on a level of 30 could be allowed by the acquisition system. In this case the muon trigger efficiency will be by $\sim$ 20% lower than in the option with station M1. Both these options were first considered in the PNPI analysis [2].

3.6.2. Study of muon chamber prototypes

During the period 1998–2001, a series of muon chamber prototypes (10 prototypes in total) have been constructed at PNPI and tested in a pion beam at CERN. These R&D studies allowed to optimize the chamber geometry parameters, the gas mixture, and the front-end electronics parameters. Finally, a full-size prototype (M2R4-01) of the muon chamber for region R4 in station M2 has been constructed.

Fig. 7 shows the construction of the M2R4-01 prototype, and Fig. 8 displays a sample of the signal at the analog output of the front-end (FE) electronics with which the M2R4-01 prototype was equipped.

The M2R4-01 prototype contains four layers of wire chambers with the sensitive area of 25×120 cm^2. The cathode panels are made by gluing 1.5 mm thick Cu-clad FR4 plates to

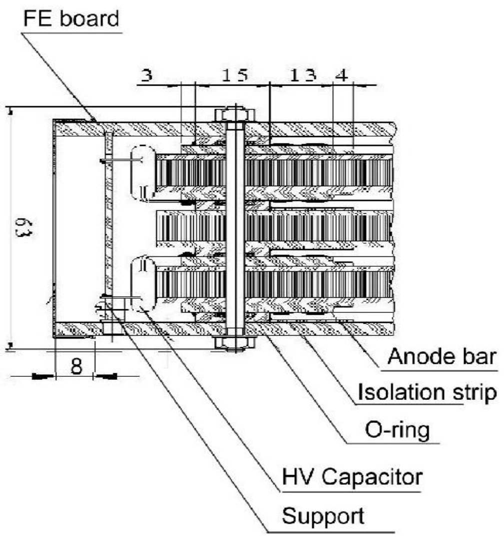

Fig. 7. View of a wire fixation side of the M2R4-01 prototype

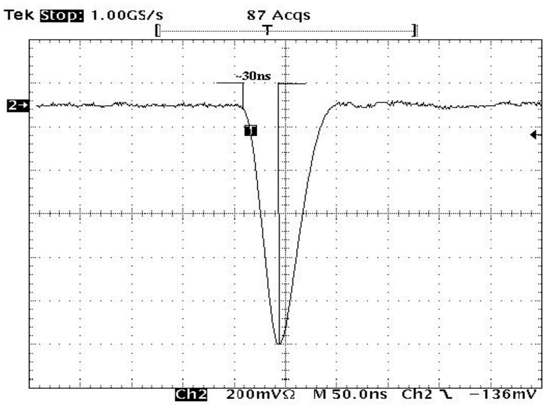

Fig. 8. Signal from a beam particle at the analog output of the SONY++ chip

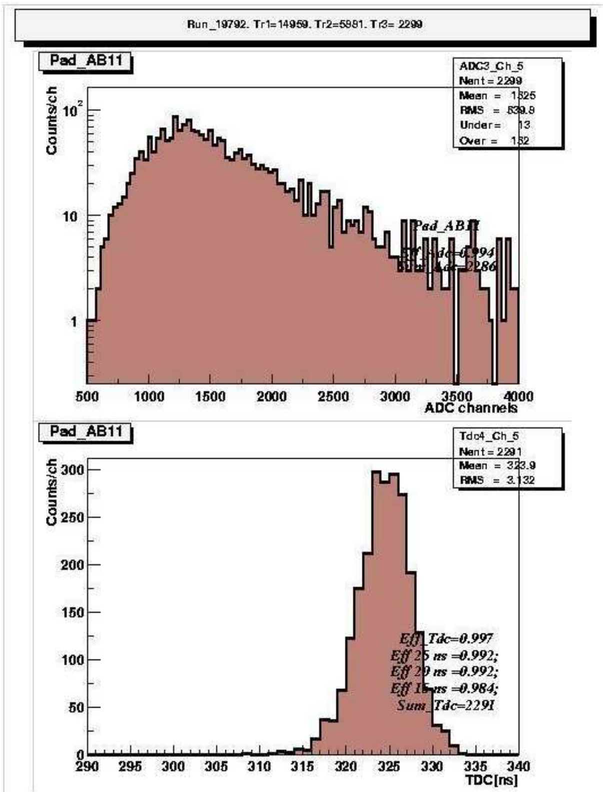

Fig. 9. An example of ADC and TDC distributions of signals in a double-gap mode. Thresh = 30 mV. Beam on pad 11. HV = 3.1 kV. Ar(40%) + CO2(40%) + CF4(20%). ADC pedestal = 260 ch. TDCeff(20 ns) = 99.2%; TDC-rms = = 3.13 ns

6 mm thick honeycomb panels. The flatness of thus prepared panels proved to be within ± 50 μm. The wire fixation bars (anode bars) as well as the cathode bars were glued to the cathode panels with a controllable layer (50 μm) of the epoxy glue. The thickness of the bars was 2.45 ± 0.01 mm. The anode wires of 30 μm in diameter were wound around the cathode panels containing the wire fixation bars. The wire spacing was 1.5 mm, and the wire tension was 50 g. In addition, two 100 μm guard wires were put at each side of the wire plane. The wires were first glued and then soldered to the anode bars. After that they were cut behind the soldering places thus making the four anode planes electrically independent. The whole stack of the panels was bolted together with the help of 20 studs. The gas tightening was provided by the O-rings around the studs and by the RTV layers around the external surface of the bars. Such construction allowed reassembling (if needed) of the chamber.

The anode wires in each wire plane were grouped together forming 4.95×25 cm^2 wire pads. There were 24 wire pads in each plane. Two opposite wire pads from the neighbour planes were connected through decoupling capacitors to one common preamplifier, so the chamber operated in the "two double-gap" mode with 48 readout channels in total. The high voltage was applied to the anode planes, while all the cathodes were grounded.

The front-end electronics used in the first PNPI prototypes was based on the discrete elements. It was specially optimized for conditions of the LHCb experiment. The M2R4-01 prototype was equipped with FE electronics based on the 4-channel SONY integrated chips developed for the ATLAS project. However, an active adapter was added in front of the SONY chip which reduced the input impedance to 25 Ω (from 80 Ω), reduced the width of the signal to 60 ns (from 200 ns), increased the gain by a factor of 3 and introduced tail cancellation. Thus modified chip (SONY++) showed very good performance comparable to that achieved with the previously used PNPI electronics.

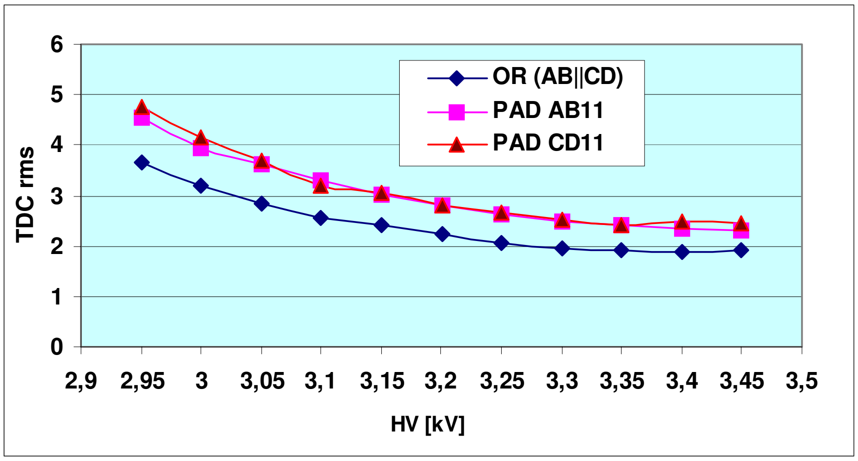

Fig. 10. Time resolution of M2R4-01 prototype for double-gap and four-gap modes

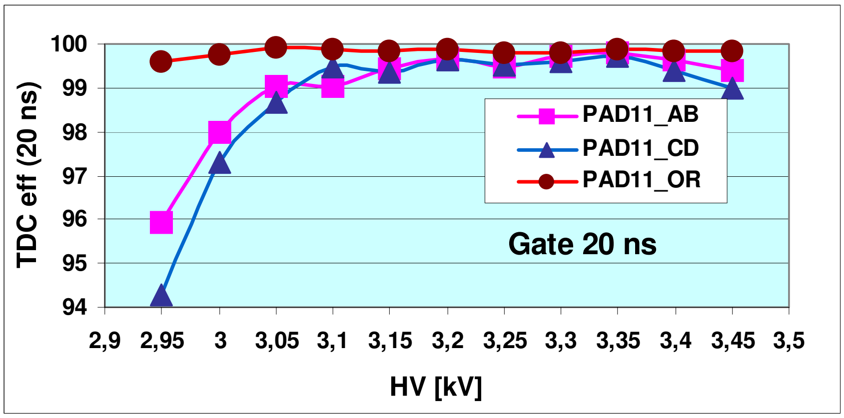

Fig. 11. Efficiency of M2R4-01 prototype for double-gap and four-gap modes

The beam test of the M2R4-01 prototype performed at CERN in November 2001 showed that it satisfies all LHCb requirements with solid redundancy. Fig. 9 demonstrates the amplitude and time distributions of the signals from a wire pad in a double-gap chamber at the nominal HV-value.

Fig. 10 presents the time resolution (rms) and Fig. 11 – the efficiency (Eff(20ns)) measured at various HV-values in the double-gap and four-gap options. One can see that the required Eff(20ns) $\geq$ 99% is obtained already with one double-gap chamber. The other double-gap chamber serves for redundancy and for extension of the operational plateau to lower HV-values. In the four-gap option the plateau riches 500 V. The other characteristics of the prototype performance were found as follows:

– The gas gain proved to be uniform over the whole area of the chamber and for different gaps within $\pm 20\%$.
– The noise level was below 50 Hz per channel.
– The total cross-talk probability in the operational region up to HV = $HV_{nominal}$ + 150 V was less than 10%, and it was dominated by the cross-talk between the neighbour channels.
– The chamber could operate with high beam intensities up to 10^5 particles/sec$\cdot$channel without visible degradation of the time resolution and efficiency.

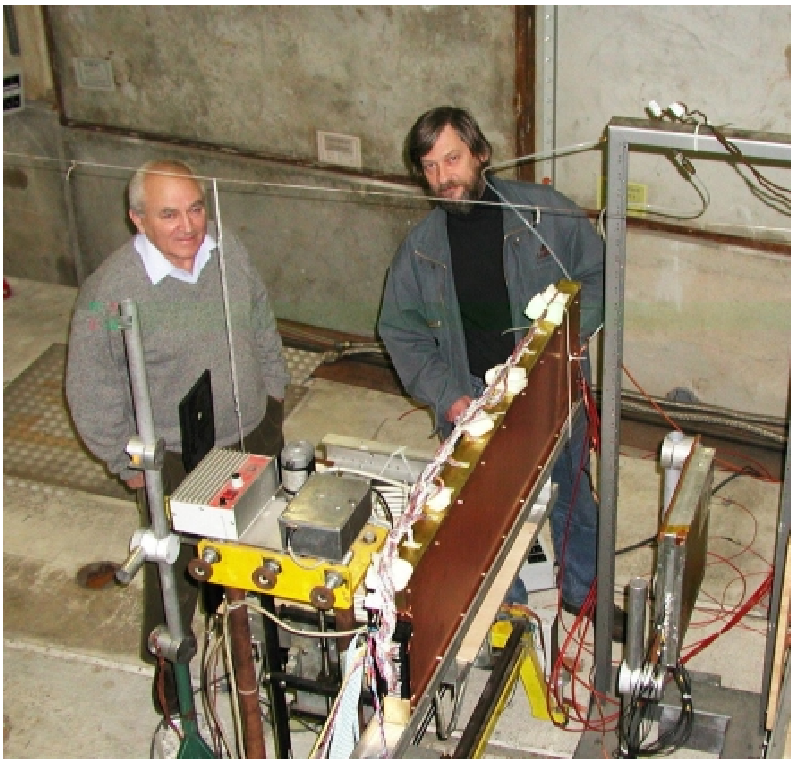

Fig. 12. M2R4-01 in the T11 beam area at CERN

3.6.3. Preparations for mass production of the muon chambers

The test results of the MWPC prototypes were considered in the LHCb collaboration as satisfactory, and the decision has been taken to start preparations for mass production of the muon chambers. In total more than 1000 4-layer chambers should be constructed. 400 of them should be assembled at PNPI. These will be the chambers with wire pad read out for region R4 in stations M2, M3. To perform this task, a special assembly facility (400 m^2) was prepared at PNPI. This facility will be equipped with special tooling: a wiring machine, bar-gluing equipment, an automated wire-soldering machine, a wire-spacing and wire-tension control machine, various test equipment. The mass production should be started in the mid of 2003 and finished by the end of 2005. All chambers should be equipped with front-end electronics, tested at PNPI and delivered to CERN for installation in the LHCb detector. In the future, the PNPI team will share responsibility for operation of the whole Muon System.

References

[1] LHCb Technical Proposal, CERN/LHCC 98-4.

[2] M.Borkovsky *et al.*, LHCb 1997-007 Muon.

[3] N.Saguidova *et al.*, LHCb 1998-059 Expt.

[4] B.Bochin *et al.*, LHCb 2000-003 Muon.

[5] B.Bochin *et al.*, LHCb 2000-102 Muon; LHCb 2000-114 Muon; LHCb 2001-025 Muon.

[6] LHCb Muon System Technical Design Report, CERN/LHCC 2001-010.