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LHCb TDR 4 Addendum 1
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LHCb

Addendum to the
Muon System Technical Design Report

LHCb Collaboration

CERN
Geneva, 2003

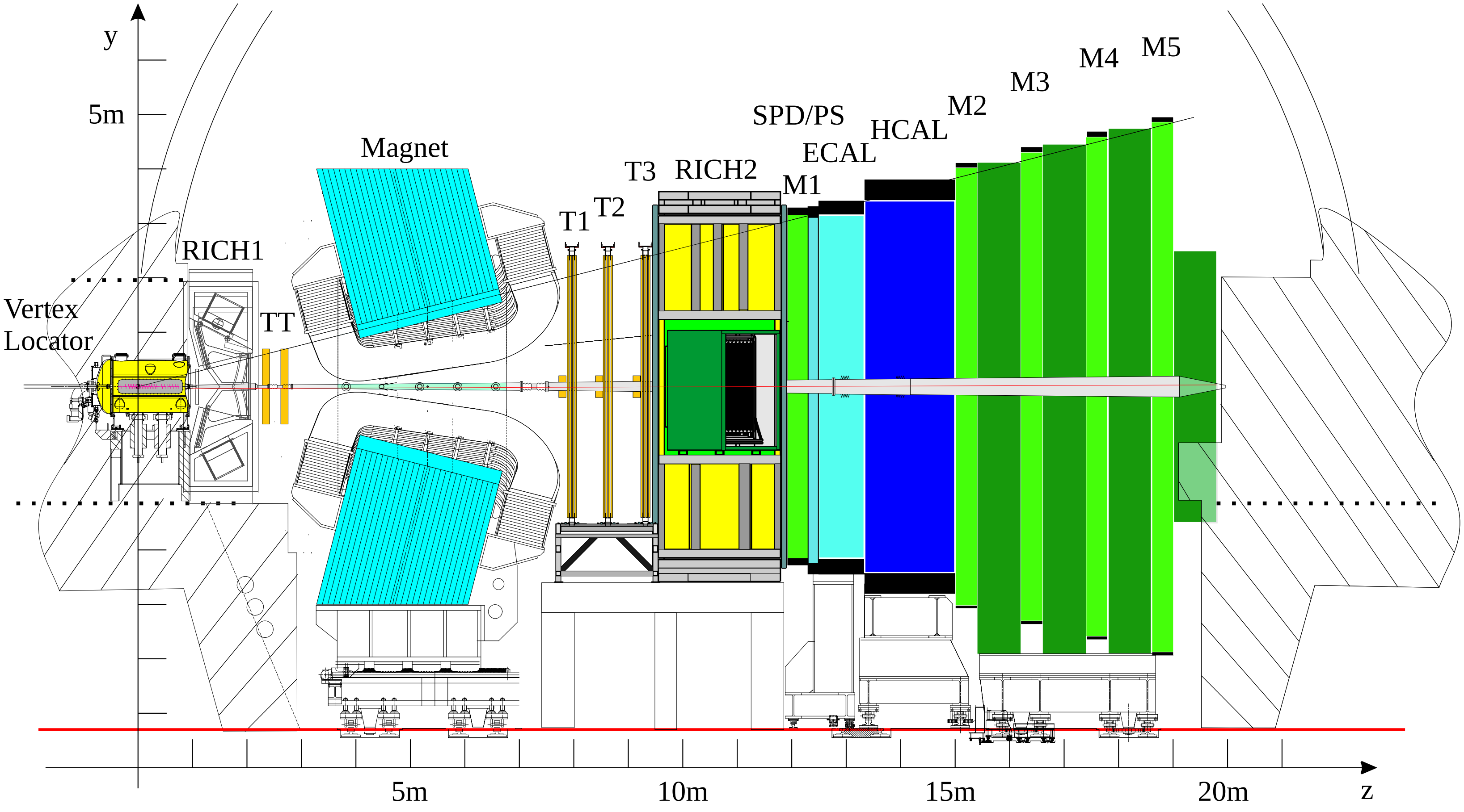

Figure 1 Side view of the LHCb spectrometer. M1 – M5 are the five Muon Stations.

1 Introduction

This Addendum to the Muon System Technical Design Report TDR (TDR) [1] is intended to be a concise description of the modifications required in the Muon System of LHCb to replace the Resistive Plate Chamber (RPC) detectors. Fig. 1 shows schematically the LHCb experiment, with the five stations (M1–M5) constituting the Muon System.

The reason for this change is basically an aging effect of the RPC, which rapidly reduces its capability to handle high rates. This is briefly explained in Section 2. The RPCs will be replaced by MWPC detectors, identical to those used in stations M2 and M3, regions R3 and R4, of the Muon System, except for the dimensions. A short update of the MWPC detector is given in Section 3.

The conversion to an all-MWPC system poses obvious questions for the project organization. 480 RPC chambers, covering about 48% of the total detector area, will have to be replaced with wire chambers. This represents a considerable increase (more than 30%) in the number of MWPC to build. The issues of project organization, including the schedule and cost, are discussed in detail in Section 4.

2 RPC Aging

Resistive Plate Chambers were proposed in the Muon TDR [1] for installation in the outer regions (R3 and R4) of stations M4 and M5 (a total of 480 double-gap chambers). Initial tests made by us on these detectors showed that they could stand the maximum flux density foreseen in those locations ($750\,\mathrm{Hz/cm^2}$).

An extended aging test at the CERN GIF was started in January 2001 on two identical detectors. Preliminary results have been reported in [2, 3]. One detector (RPC A) was exposed to high radiation flux, the other (RPC B) was used as a reference and shielded from the radiation. HV and gas were exactly the same for the two detectors. After integrating a charge of $0.4\,\mathrm{C/cm^2}$ equivalent to 10 LHCb-years in region R4, the rate capability of RPC A was somewhat reduced, but still adequate to meet the TDR specifications. During the test the current through RPC A decreased steadily and dropped in total by a factor of about 6, as can be seen from Fig. 2. We proved that this was due to an increase of the bakelite resistivity. The increase continued even when in the second part of 2001 the irradiation ceased, while the gas was kept flushing through the detector.

The test was restarted in May 2002, this time with both detectors irradiated by the GIF source. The resistivity referred to as ρ_{20} (the value normalized at 20 $^{\mathrm{o}}$C) was measured online with a novel method described in [4]. The results (see Fig. 3) show a continuous increase of ρ_{20} for the two detectors, which reached by the end of December 2002 similar values around $2 \cdot 10^{12}$ Ωcm, although RPC B had a lower resistivity at the beginning of the test. The final value of ρ_{20} is about 100 times higher than the value at the time of detector construction in 1999. This is most likely due to the drying out of the bakelite when flushed with dry gas. The irradiation plays a secondary role: probably the current flow through the bakelite merely speeds up the drying process.

Separate measurements of the rate capability, using the charged particle beam of GIF, confirmed that the detectors could not stand more than $400\,\mathrm{Hz/cm^2}$. However, this value was obtained in July at an average temperature of 26 $^{\mathrm{o}}$C, and must be reduced by about a factor of two for operation at 20 $^{\mathrm{o}}$C (the nominal temperature in the experimental area), and by another factor of two to take into account the increased bakelite resistivity observed at the end of 2002 (Fig. 3). Thus the rate capability will be at most $100\,\mathrm{Hz/cm^2}$, a value completely inadequate for LHCb.

The trend of Fig. 3 could suggest a possible saturation of the resistivity, however this would still be too high for the Muon System. It has been proposed that a possible reversal of the effect could occur by adding water to the gas mixture. However, this could be dangerous in our high-radiation conditions, where water could give rise to HF acid formation, and was not considered as an option.

Our conclusion was that RPC detectors could be built to meet the TDR specifications, but that their performances would quickly degrade because of the resistivity increase. This fact, and a series of problems recently encountered in the RPC industrial manufacturing by other experiments led us to the decision of replacing them with MWPC detectors. Aging of MWPCs is of no concern even at rates a factor 50 above the expected rates in regions R3 and R4 of stations M4 and M5 [5].

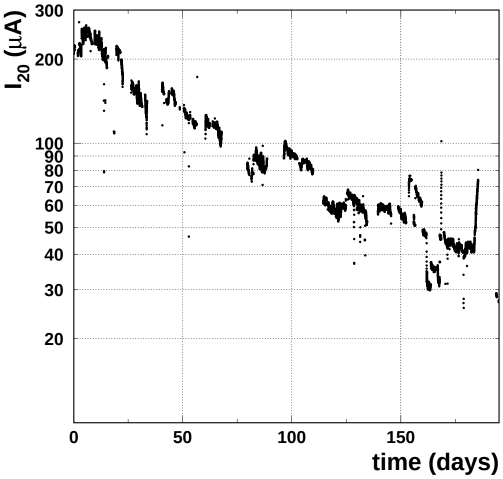

Figure 2 Current for RPC A corrected for temperature plotted versus time during the 2001 aging test. Deviations from the exponential decrease are due to changes in the HV and gas mixture, and to insertion or removal of other detectors in front of the source.

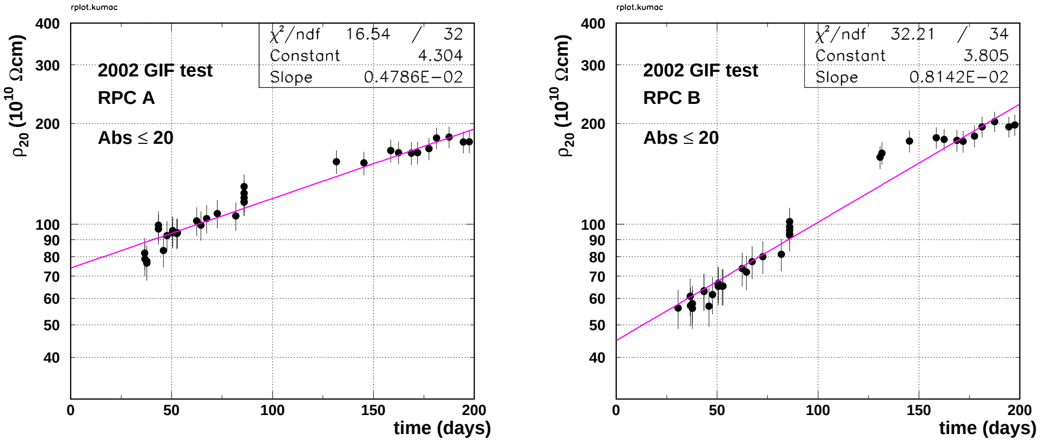

Figure 3 Bakelite resistivity (normalized at 20 ^{o}C) vs. time for two similar RPC exposed to photons from the GIF during the 2002 aging test. The time origin is the beginning of the test (1 May 2002).

3 MWPC Detectors

The MWPC detector has retained its basic structure, described in the Muon TDR [1] and in the references therein, except for some design modifications dictated by the results of the various R&D studies. The most important are the increase of wire pitch from 1.5 to 2 mm and the use of two gaps, instead of four, in station M1. These modifications are described below. The detailed design of the detectors will be discussed in the EDR/PRR scheduled for April 2003.

3.1 Wire Pitch

The basic geometry of the MWPC as described in the TDR [1] leads to an electric field of 8 kV/cm on the cathodes at the operating point. As a consequence, the tolerances for detector construction are very tight, and the large electric field on the cathode might cause additional problems in the long term operation.

It is well known that the cathode field can be reduced by increasing the wire pitch, which leads on the other hand to a reduced time resolution and in turn to a reduced efficiency within a 20 ns time window. Simulation studies showed that the time resolution has an intrinsic limit and cannot be improved in reducing the wire pitch below 1.5 mm. This value has therefore been assumed optimal and used for the prototype studies at the time of the TDR, accepting the drawbacks caused by the large cathode field.

In a recent beam test a detailed performance comparison of double-gap chambers with 1.5 mm and 2 mm wire pitch has been carried out [7]. An important result has been that a time resolution of about 4 ns at the operating point can also be obtained with 2 mm wire spacing, leading to 99% double-gap efficiency within a 20 ns time window, fully satisfying our requirements. Fig. 4 compares the results for both wire and cathode readout obtained with the two different wire pitches. It was therefore decided to adopt the larger wire pitch for all chambers. In addition 100 kCHF in wire cost can be saved.

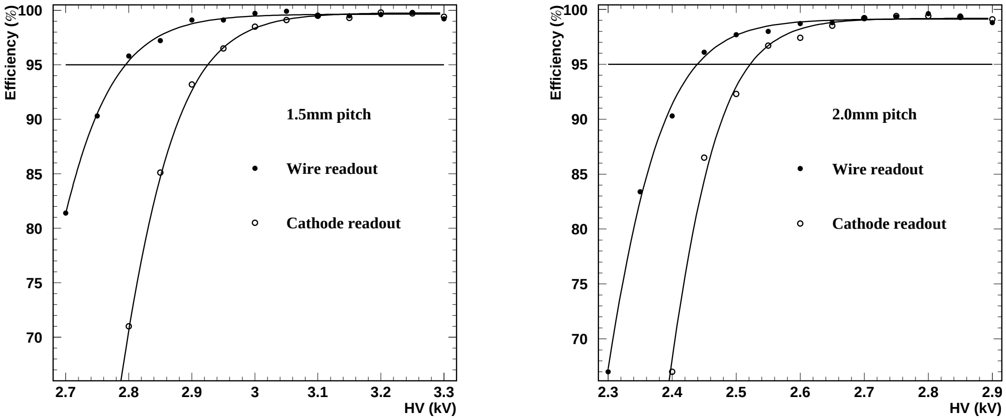

Figure 4 Double-gap MWPC efficiency for wire and cathode readout in a 20 ns window. 1.5 mm pitch (left) and 2.0 mm pitch (right).

3.2 Layout of M1 chambers

The chamber design is unchanged in stations M2 – M5, with four gaps, read independently in two pairs. In order to minimize the material in front of the electromagnetic calorimeter and preshower, M1 chambers will have only two gaps instead of four. The two gaps will be read out by independent preamplifiers in order to retain adequate redundancy. Simulations have shown that the trigger efficiency is practically unaffected, even for single-gap efficiencies as low as 80% [6], leading to a chamber efficiency of 96%.

In station M1 the panel core will be Nomex honeycomb [1], in contrast to polyurethane foam (Esadur 120) foreseen as core material for the panels in the other stations. Esadur panels can be built industrially for a rather low price (Fig. 5). On the other hand, Nomex honeycomb has the advantage of a radiation length considerably larger than Esadur.

With this design the average thickness of M1 decreases from $0.33\,X_0$ to $0.15\,X_0$. We have a wide experience with Nomex honeycomb, since it was used in most of the prototypes already built.

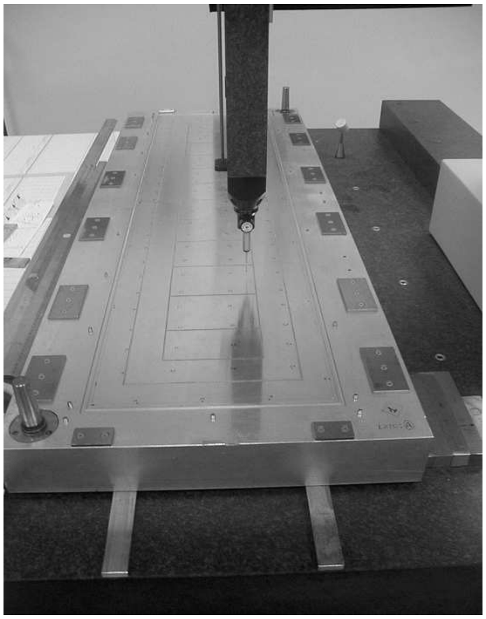

Figure 5 Precision mold for industrial production of the panels by injection of polyurethane foam. The foam is injected betweeen two copper-clad FR4 laminates.

3.3 MWPC production

In the original planning four centers to produce 864 MWPCs were forseen: one in St. Petersburg's Nuclear Physics Institute (PNPI), two in Italy (Ferrara and Laboratori Nazionali di Frascati, LNF), and one at CERN.

These centers will be equipped with similar tooling, which is automated to a large extent to speed up the construction, and allows to obtain the required precision and tolerances. The main equipment consists of:

1. a table for gluing the wire frames to the panels (Fig. 6)
2. a wiring machine (Fig. 6)
3. an automated station for laser soldering of the wires (Fig. 7)
4. an automated station to check the wire tension and pitch (Fig. 7)

The implementation of this tooling minimizes human intervention, in particular for the wiring and soldering of the planes.

The construction time for a chamber is now dominated by the various gluing processes. Most of the epoxy-based glues used need about 8 hours before sufficient polymerization is reached. The construction capacity in the various centers is furthermore limited by the number of chamber components which

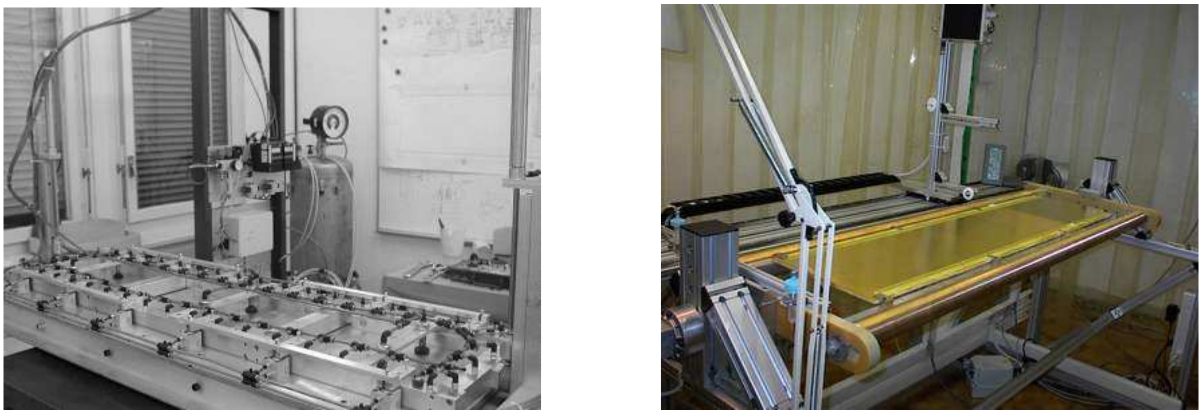

Figure 6 Gluing table for preparation of the panels (left); automated wiring machine (right). This machine can also be used for wire gluing.

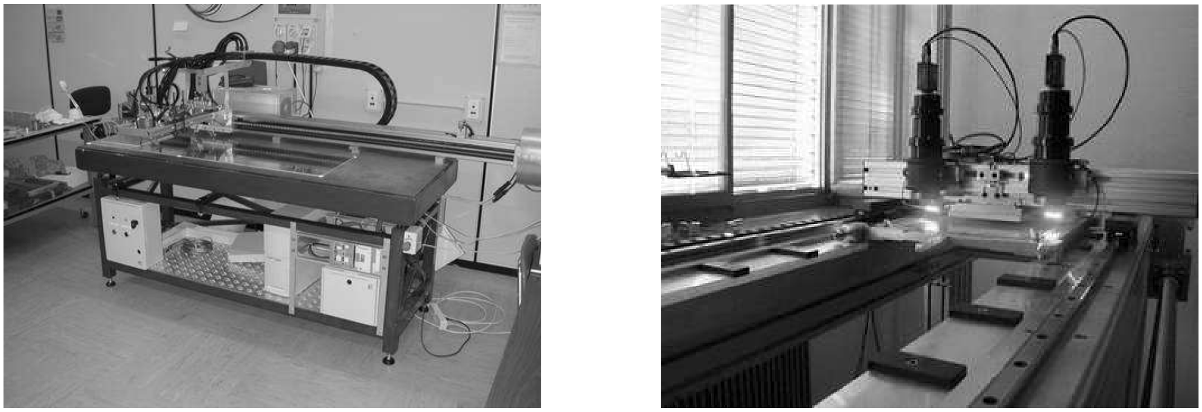

Figure 7 Laser soldering station (left); station for wire pitch and tension check (right).

can be prepared in parallel and the available space. Other time consuming phases are the final assembly and testing, which require significant human intervention.

3.4 Chambers for the inner part of M1

The two inner regions (R1, R2) of station M1 are exposed to particle rates above $100\,\mathrm{kHz/cm^2}$, and require good aging properties for the detectors [1]. We have tested different technologies for this region: one is triple-GEM, the others are modifications of our standard MWPC design.

A full-size triple-GEM prototype for R1 ($20 \times 24\ \mathrm{cm^2}$) has been tested succesfully on beam [8], using standard GEM foils. This technology seems particularly promising because of its aging properties. Our X-ray tests have shown that triple-GEM performances do not suffer after more than 10-year of LHCb operation.

The idea behind the MWPC modification is to reduce the accumulated charge by halving the gas gain, without any change to the average signal charge on the cathodes. In one design the cathode pads on both sides of the wire plane are read out, in the other the wires are placed asymmetrically in the gap at 1.25 mm from the cathode pads read out, which allows also to reduce somewhat the cluster size. A full size prototype for region R1 with both configurations was successfully tested on the beam [9]. The accumulated charge on the wires for the modified MWPCs would be about $1.4\,\mathrm{C/cm}$ in 10 years of LHC operation in region R1, and $0.6\,\mathrm{C/cm}$ in region R2.

A decision on the technology will be taken in Summer 2003, after an extensive aging test has been performed at the ENEA-Casaccia facility near Rome [10] with a ^{60}Co source. A test run has already taken place.

4 Project Organisation

The decision to abandon the RPC technology poses a number of organization issues to the Muon Group and to the Collaboration. Excluding the two innermost regions of M1, the number of MWPC detectors passes from 864 to 1344, and in terms of surface area this represents almost a 100% increase. Unlike RPCs, MWPC detectors cannot be produced industrially and therefore demand more manpower for the construction. On the other hand, recent problems in the industrial construction of RPC detectors have required a substantial increase of institute personnel for quality control and tests, making the overall effort rather similar for both detectors. Some synergies are also possible for an all-MWPC solution. In this section we will address these problems and present our construction plan and schedule. We also update, whenever applicable, the information given in the TDR.

4.1 Production centers

According to the original plan with four production centers, PNPI had the responsibility of the 384 chambers of R4 in stations M2,M3 (stations with wire readout only). CERN was assigned the 72 chambers with combined cathode-pad and wire readout of stations M2–M3, R1–R2. The remaining 408 chambers (cathode-pad readout) were assigned to Ferrara and LNF.

The production of 480 extra chambers of large size will require either a substantial boosting of the capacity in the existing four centers or the addition of new ones. Boosting the capacity cannot be solved simply by adding extra manpower, since also extra tooling and space is required. Moreover, it would be complicated and expensive to move technicians and physicists from one institute (e.g. one of those originally involved in the RPC production) to another. It was therefore considered more efficient to add another center in Italy (INFN 3) and a second center in PNPI (PNPI 2). For INFN 3 Firenze is the candidate [1], since they could easily enlarge the clean room already planned for CMS. PNPI 2 will be the center presently used to assemble the CSC chambers for the Endcap-Muon-System (EMU) of CMS, which will end its activity at the end of 2003. PNPI 2 will take in charge 192 chambers (M4R4) but could increase this number in case of need. The remaining chambers will be shared among the Italian centers, which will in total be responsible for 696 chambers. No changes for the CERN center are foreseen. The total production capacity has enough margin to accomodate unforeseen delays.

Table 1 summarizes some basic parameters related to the production. It is worth recalling that the number of chambers is not a direct measure of the construction effort. The nominal production rates try to take into account these factors and are also corrected for the holiday periods.

In order to estimate the production curve, we have assumed that the nominal rates will be reached after some training period. Its duration was estimated to be between four and seven months for the different centers, during which the production rate will progress up to the nominal value. The longer learning periods apply to centers where extensive training of personnel is needed. Centers starting later have a steeper learning curve, since they could somewhat profit from the experience of those which began their production earlier.

Fig. 8 shows graphically the production of chambers. The production will will be completed by beginning 2006. Even considering the possibility of redistributing part of the chamber production among centers in case of unexpected difficulties, the safe assumption is that the construction will end in March 2006. The overall work program and schedule are summarized in Fig. 9.

4.2 Installation and commissioning

Installation and commissioning are shown in Fig. 9. The first part of the muon system to be installed are the muon filters. This work will be carried out during the year 2004.

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[1] The matter is subject to approval from INFN. Discussions are in an advanced phase.

Table 1 Nominal capacity of the production centers and approximate dates for start of production (see text).

Center	PNPI 1	PNPI 2	LNF	Ferrara	INFN 3	CERN
No. Ch.	576		696			72
Rate (est.)	20/mo.	16/mo.	10/mo.	10/mo.	10/mo.	4/mo.
Start date	Jul 2003	Jun 2004	Jul 2003	Oct 2003	Jan 2004	Jul 2003

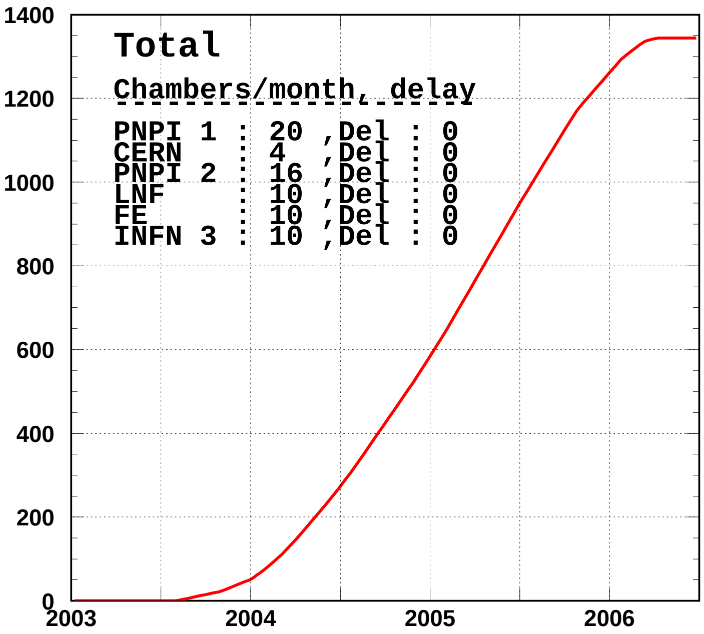

Figure 8 Planned total chamber production in all centers. For the input data see Table 1.

The muon chambers will undergo installation and commissioning starting in the second half of 2005, after the installation of the support structures together with the required infrastructure (gas pipes, electronics racks etc.) has been terminated. All chambers should be installed by the end of July 2006, with a short interruption for the LHC injection test, scheduled in April.

Commissioning with other LHCb sub-detectors, using common DAQ will begin in October 2006. Six months of operation in this mode are foreseen to ensure the muon detectors will be ready to take data at nominal LHCb luminosity in April 2007.

4.3 Milestones

The major milestones for the Muon System are summarized in Table 2. A more detailed schedule, showing the details for the various production centers, will be presented in the EDR.

Table 2 Muon Project Milestones

Milestone	Date
MWPC	
Engineering design completed	04.2003
Begin chamber production	07.2003
10% chamber production	03.2004
50% chamber production	02.2005
Chamber production and test completed	03.2006
Chambers for the inner part of M1	
Technology choice	06.2003
Chamber construction completed	12.2005
Electronics	
Full chain electronics test completed	06.2003
Integrated Circuits	
CARIOCA review and decision on FE chip	09.2003
DIALOG design and test completed	09.2003
SYNC design and test completed	09.2003
IC Engineering Run (CARIOCA,DIALOG,SYNC)	12.2003
FE Boards	
Begin board production	04.2004
10% board production	08.2004
50% board production	03.2005
Board production and test completed	10.2005
IB,ODE,SB Boards	
Begin board production	04.2004
10% board production	12.2004
50% board production	06.2005
Board production and test completed	12.2005
Muon filter and support structures	
Iron filter installation completed	12.2004
Chamber support structures installed	06.2005
Commissioning	
Muon System commissioning completed	09.2006
Muon System ready for beam	04.2007

4.4 Costs

The total cost for the Muon System has been carefully revised. Quite precise cost estimates are now available for most items, including the electronics, where all the components have been designed and final prototypes are in preparation. With respect to the TDR we have an increase of the detector costs and a reduction in the electronics cost. Part of the cost increase for the detectors is due to the replacement of the RPCs.

Table 3 shows the cost estimate split according to the system components. For the chambers and electronics about 10% for spares and contingency have been included.

The cost now includes the M1 inner part, under the assumption of a mixed GEM-MWPC solution, with triple-GEM equipping region R1. The extra expenses due to the modifications of the gas system have been taken into account. The overall cost of the system (subtracting 4000 kCHF of the iron filter, which was already made available from the CERN reserve) is slightly higher with respect to the 6830 kCHF of the TDR. Note that the cost of about 200 kCHF for the engineering run of the three ASICs (CARIOCA, DIALOG and SYNC) is not included, as it is considered part of the development phase.

The costs for the assembly in the PNPI production centers, the shipping and part of the tooling are reported in Table 3 under the “Miscellaneous” entry.

The CARIOCA chip is the baseline option for the front-end; the cost would increase by about 700 kCHF in case the adapted ASDQ chip should be required.

4.5 Division of responsibilities

Institutes currently working on the LHCb Muon project are: Centro Brasileiro de Pesquisas Fisicas CBPF, Rio de Janeiro (Brazil), Universities and INFN of Cagliari, Ferrara, Firenze, Roma “La Sapienza” (Roma I), Potenza, Roma “Tor Vergata” (Roma II), Laboratori Nazionali di Frascati LNF (Italy), Petersburg Nuclear Physics Institute PNPI, Gatchina (Russia) and CERN. Work on the Level 0 Muon trigger is carried out by CPPM Marseille in close collaboration with the Muon group.

The sharing of responsibilities for the main Muon Project tasks is listed in Table 4. It is not exhaustive, nor exclusive. Details of the responsibilities for the various system components will be finalized by the time of the engineering design reviews.

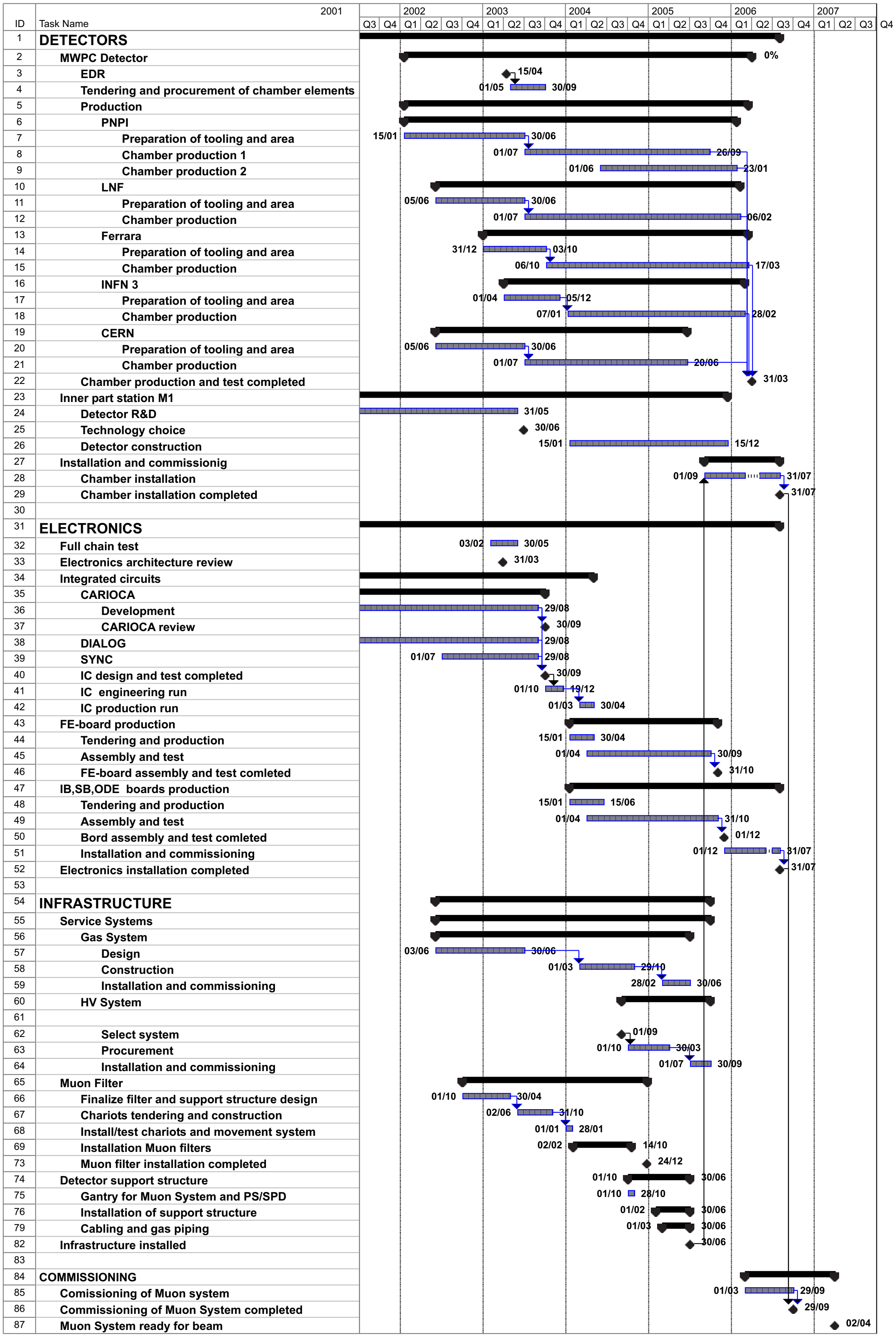

Figure 9 Schedule of the LHCb Muon System, showing production and installation of the detectors, electronics, and the infrastructure.

Table 3 Muon project cost in 2000 prices (kCHF)

Item	Unit	Number of units	sub-total (kCHF)
MWPC detector:			2200
Panels	piece	7000	
Special cathodes	piece	2000	
Wire	km	2750	
Wire fixation bars	m	6500	
Frames	piece	21500	
HV boards	board	5000	
Various connectors	piece	30000	
Spacers	piece	40000	
Miscellaneous:			680
Tooling			
Assembling	chamber	576	
Shipping	chamber	576	
Inner part station M1:			100
Detectors	chamber	36	
Electronics:			3000
CARIOCA chip	piece	16000	
DIALOG chip	piece	8000	
FE boards	board	8000	
Spark Protection boards	board	8000	
LVDS links	link	8000	
IM boards	board	165	
SYNC chip	piece	4000	
Off-Detector-Elec. boards	board	160	
Service boards (ECS)	board	160	
L1 boards	board	12	
Optical links to L0 trigger	link	1250	
Crates	crate	42	
LV power supplies/cables	system		
Services:			1000
MWPC Gas System	system	1	
MWPC HV System	system	1	
Support Structures	module	10	
Muon filter:			4000
Muon System TOTAL			**10980**

Table 4 Muon project: sharing of responsibilities. For the MWPC construction the sharing is still preliminary.

Task	Institutes
MWPC	
Construction	
Station M1, R3 – R4	Ferrara, LNF
Station M2 – M4, R4	PNPI
Station M5, R4	INFN 3
Stations M2 – M3, R1 – R2	CERN
Station M2 – M5, R3	LNF, Ferrara
Station M4 – M5, R1 – R2	LNF, Ferrara
Testing	
All stations	CERN, LNF, PNPI, Roma I, Roma II
Inner part of station M1:	
Construction and testing	To be decided
Readout electronics:	
CARIOCA chip design, production and testing	CERN
DIALOG chip design, production and testing	Cagliari
SYNC chip design, production and testing	Cagliari
FE-boards (production and testing)	CBPF, Roma I, Potenza
IB boards, design, production and testing	LNF
SB boards, design, production and testing	Roma I
ODE boards, design, production and testing	Cagliari, LNF
Services:	
Gas systems design and construction	CERN, INFN
Monitoring, Control (ECS)	CBPF, Roma I
Experimental area infrastructure:	
Chamber support structures	CERN, LNF
Muon filter support structures	CERN
Muon filter installation	CERN

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