Study of application of the Multi-Wire Proportional Chambers of the LHCb MUON detector at very high rates

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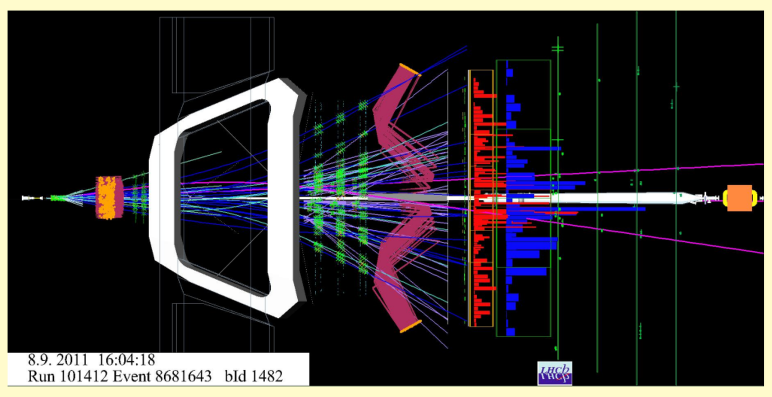
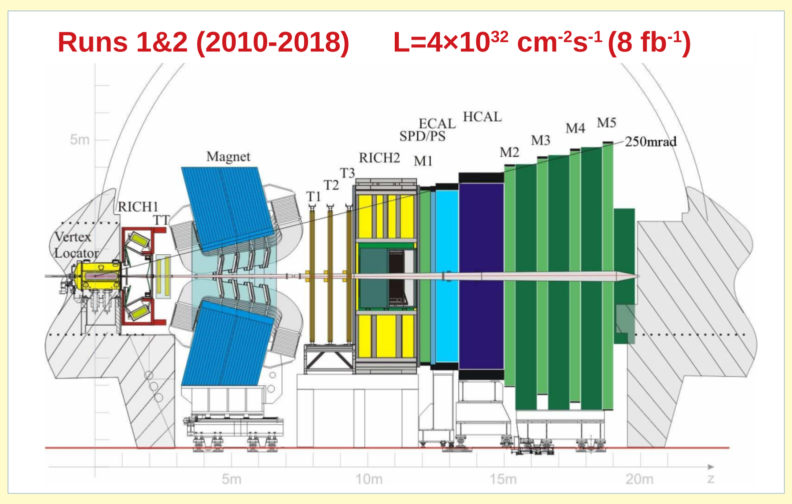
LHCb detector is forward arm-spectrometer and aimed for studies of heavy-flavour physics at the LHC. Its core program is focused on the study of exclusive final states from the decays of b- and c-hadrons.



Sub-detectors:
- Vertex Locator — VELO
- Hadron ID — Cherenkov detectors (RICH1, RICH2)
- Tracking system — silicon microstrip detector (IT) and straw drift tubes (OT)
- Calorimeters — ECAL, HCAL
- Particles ID and tracking — Muon stations M1-M5 with iron absorbers between stations

Evolution of the LHCb detector

Runs 1&2 (2010-2018) L=4x10^{32} cm^{-2}s^{-1} (8 fb^{-1})

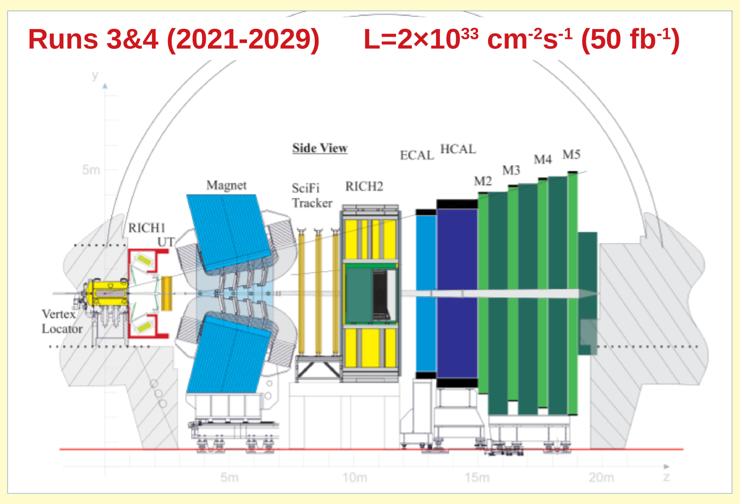


Current LHCb detector [1]

RICH1, RICH2 - Ring Imaging Cherenkov detectors
Trigger Tracker (TT) - silicon microstrip detector
T1, T2, T3 = Tracking stations 1..3
SPD/PS = Scintillating Pad Detector/Preshower
ECAL = Electromagnetic Calorimeter
HCAL = Hadron Calorimeter
M1..M5 = Muon stations

U1

Runs 3&4 (2021-2029) L=2x10^{33} cm^{-2}s^{-1} (50 fb^{-1})

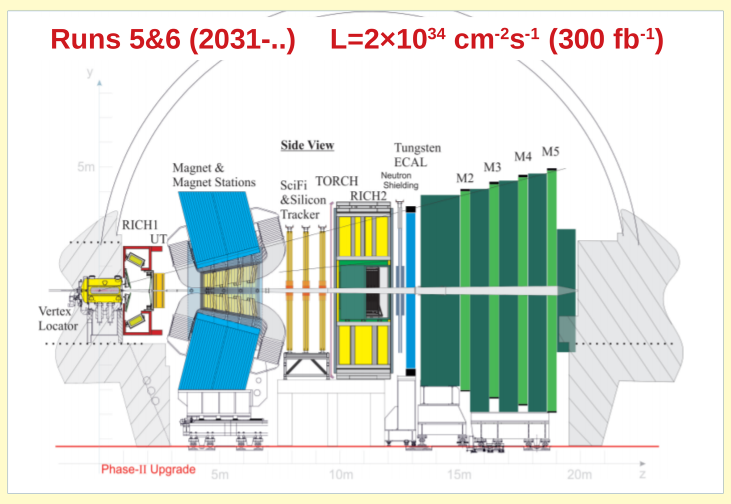


LHCb detector after Upgrade 1 [2]

UT = Upstream Tracker
OT/IT → SciFi Tracker = Scintillating Fibre Tracker
New Software trigger (40MHz) instead of L0 HW trigger (1MHz)
M1 station is removed (was used for L0 HW trigger)
Background shielding:
Beam plug attenuator for Muon detector (before Run3)
HCAL will be replaced by Fe-Wall shield (before Run4)

U2

Runs 5&6 (2031-..) L=2x10^{34} cm^{-2}s^{-1} (300 fb^{-1})



LHCb detector after Upgrade 2 [3]

Magnet stations (low-momentum tracker)
High granularity silicon tracker (for IT)
Fast timing detector (TORCH) for RICH
Tungsten ECAL
Neutron shielding
Deep upgrade of Muon detector

Present Muon Detector (MD)

MD provides the LHCb experiment with a trigger for b-hadron decay channels containing muons in the final state.

The detector consists of 5 stations M1..M5 are interleaved with iron absorbers to select penetrating muons.

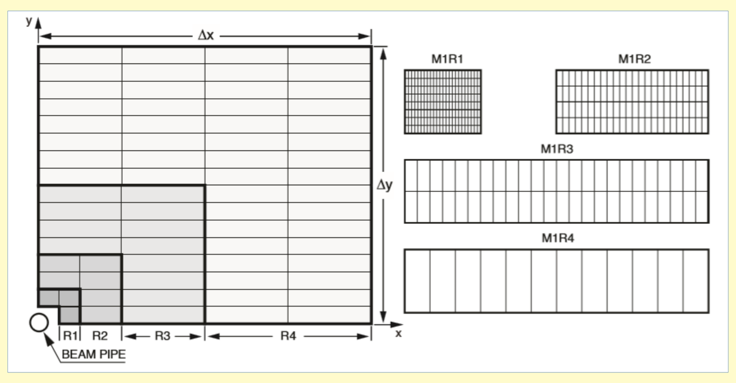
Each station is divided into four regions R1..R4 with the ratios of areas 1:4:16:64, while the irradiation per unit area decreases.

The whole detector comprises 1380 chambers (1368 MWPCs and 12 GEMs — only M1R1 chambers) for a total area of 435 m^2 and ~ 122k physical channels.

Since the requirements on spatial resolution and rate capability strongly vary in different stations and regions, different chamber segmentations and different readout techniques were employed (see Table).

In the outer regions (R4) there are large wire pads while in the inner regions(R1..R3) there are small cathode pads(R3) or smaller logical pads(R1, R2) obtained by crossing cathode pads with narrow wire strips.

For muon ID and triggering efficiency > 95% the efficiency of each muon station must exceed 99% within a time window 25ns (40MHz) to unambiguously identify the LHC bunch crossing.



Left: Quadrant of a muon station. Each rectangle is one chamber. There are 276 pcs for each station. Right: division into logical pads of 4 chambers of 4 regions (the same for all stations).

	M1	M2	M3	M4	M5
z	1210	1527	1647	1767	1887
Δx	384	480	518	556	594
Δy	320	400	432	464	495
R1	[24 × 8] 1 × 2.5	[48 × 8] 0.63 × 3.1 (0.5 × 2.5)	[48 × 8] 0.67 × 3.4 (0.5 × 2.5)	[12 × 8] 2.9 × 3.6 (2 × 2.5)	[12 × 8] 3.1 × 3.9 (2 × 2.5)
R2	[24 × 4] 2 × 5	[48 × 4] 1.25 × 6.3 (1 × 5)	[48 × 4] 1.35 × 6.8 (1 × 5)	[12 × 4] 5.8 × 7.3 (4 × 5)	[12 × 4] 6.2 × 7.7 (4 × 5)
R3	[24 × 2] 4 × 10	[48 × 2] 2.5 × 12.5 (2 × 10)	[48 × 2] 2.7 × 13.5 (2 × 10)	[12 × 2] 11.6 × 14.5 (8 × 10)	[12 × 2] 12.4 × 15.5 (8 × 10)
R4	[12 × 1] 8 × 20	[24 × 1] 5 × 25 (4 × 20)	[24 × 1] 5.4 × 27 (4 × 20)	[6 × 1] 23.1 × 29 (16 × 20)	[6 × 1] 24.8 × 30.9 (16 × 20)

Basic info about stations M1-M5 and regions R1-R4. Dimensions (cm): z — distance to the IP; Δx, Δy — dimension of quadrant. Rows R1-R4 show granularity (X*Y): 1 - number of logical pads, 2 - logical pad size, 3 - size of the logical pads projected onto station M1.

Muon detector performance

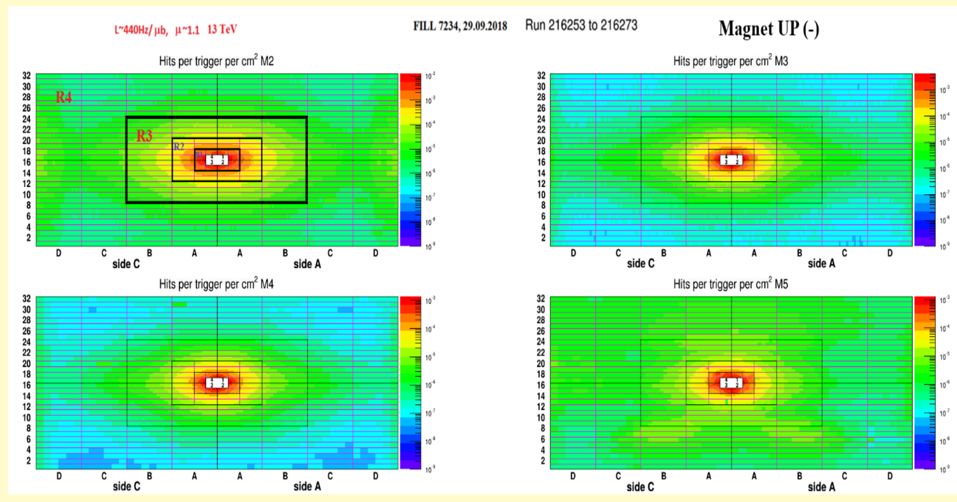
In Runs 1&2 the Muon detector was operated at luminosity L=4x10^{32} cm^{-2}s^{-1} (2 times higher of planned). Nonetheless, most regions meet the 99% efficiency requirement [4].

The main factor of the inefficiency of MWPCs is the dead-time of Frontend electronics (FE): ~70..100 ns [5].

The most irradiated MWPCs (Stations M1-M2, Region 1) having the rates ~1 MHz per FE-channel. It leads to 10% of losses and near ~98% level of efficiency for M1R1 and M2R1 chambers [4].

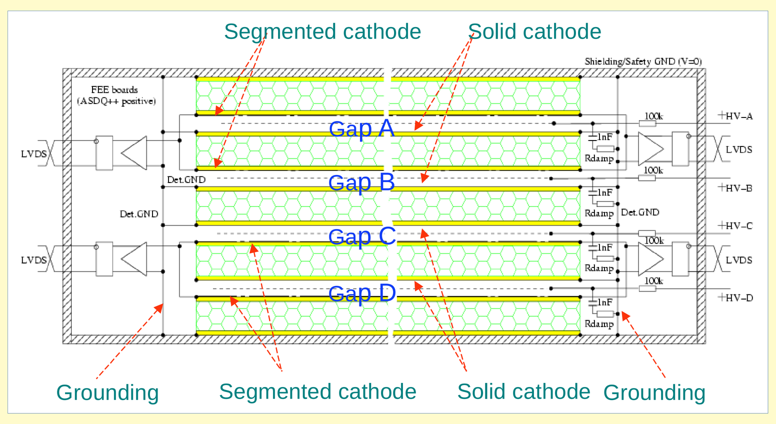
Over 9 years of operation, the most irradiated MWPCs collected charge ~0.6 C/cm of wire and there is no sign of aging (reduction of gain/efficiency/time resolution)! [6]

MUON occupancy M2..M5: Hits per trigger per cm²



With new Software trigger after U1 we will have flexible granularity of the physical channels on the level of muon chambers. It means flexible segmentation of stations by regions. We can follow the occupancy at working conditions.

Cross-section of present 4-Gaps chambers of M2-M4 stations



Gas mixture	40% Ar + 55% CO2 + 5% CF4
Anode-cath gap	2.5mm
Anode wire diameter	30 um
Anode wire step	2mm
Operating voltage	2.5-2.8 kV (2.65 kV - working voltage)
MWPC readout type	- Wire pads (R4) - Anode & cathode pads (R1-R2 in M2-M3) - Cathode pads (everywhere else)
Hit efficiency	99% (in 25ns time window)
Time resolution	2.5-4 ns

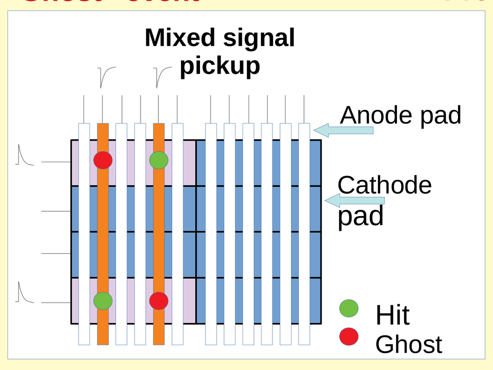
The main challenges at high rates

In Run3&4 planned luminosity is 5 times higher of Run1&2 and the dead time of FE-electronics becomes one of the main factors of expected inefficiency of chambers especially in central regions (R1, R2).

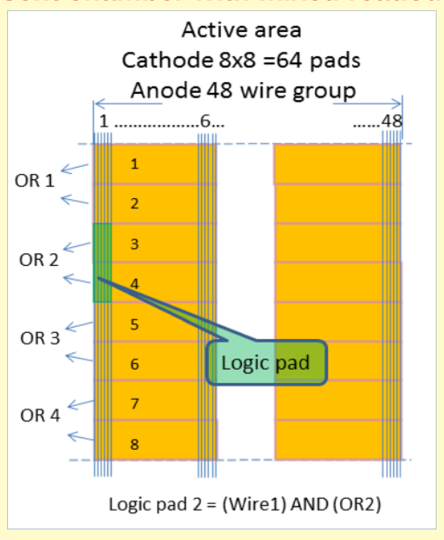
To keep the required efficiency of muon chambers ~99% with a max dead time of FE ~100ns the maximum acceptable rate must not exceed ~0.5MHz per physical channel.

The counting rate could be reduced by increasing the granularity of the pad MWPCs.

«Ghost» event



Present chamber with mixed readout



«Ghosts» - multiple hits overlapped in 25 ns time window in single logical matrix and cause loss of hits. The probability of «ghosts» grows as ~L^2.
Ghosts can appear in the mixed-readout MWPCs (in M2M3/R1R2) and could be vanished by ***replacement mixed-readout MWPCs with high granularity pad chambers.***

Estimated performance of chambers in Run3 (L=2E33 cm^{-2}s^{-1})

Chamber design	Pad size(a=anode, c=cathode), cm²	*Max counting rate per FE-channel, MHz	«Ghosts» probability and FE-electronics dead-time losses, %	Total Efficiency (2 bi-gaps in «OR»), %
Present M2R1	3.75x3.15(c); 0.63x25.2(a)	2.15	15.7; 17.3	88.6
M2R1 HG	1.25x3.15(c)	0.59	-; 5.16	99.0
Present M2R2	7.5x3.15(c); 1.25x25.2(a)	1.7	9.5; 11.5	94.3
M2R2 HG	2.5x3.15(c)	0.43	-; 3.8	99.3

* With beam plug shielding (Attn. Factor 0.5 for M2R1 and 0.75 for M2R2)

Background

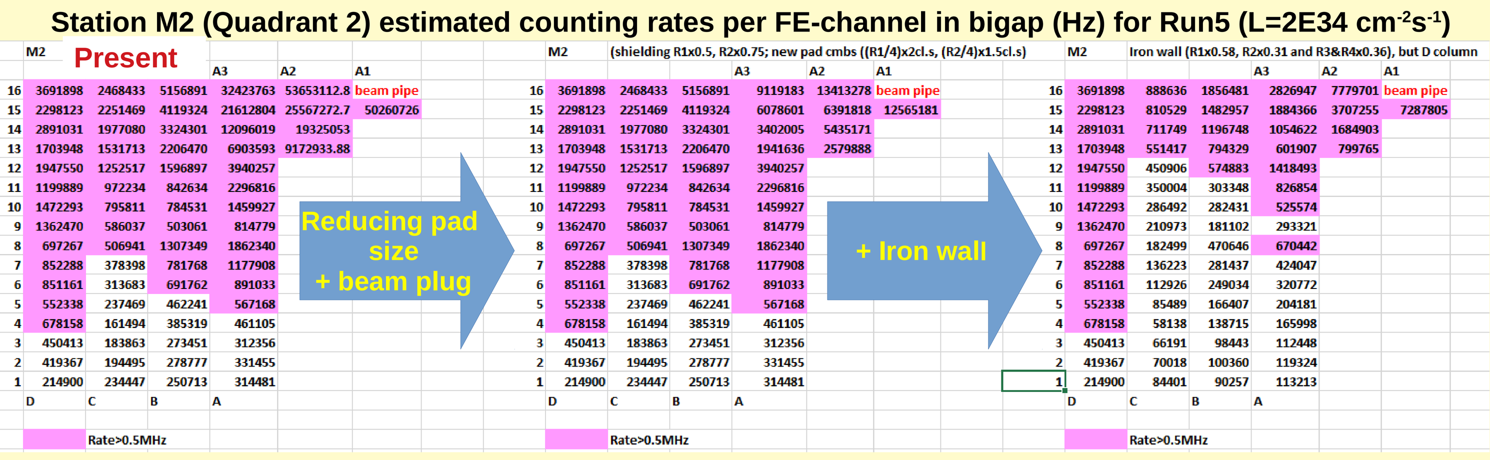
The first part of the background caused by **particle interaction with beam pipe will be reduced by the additional shielding and beam plug** (will be mounted before Run3).

Background hits not correlated with muons (in time / tracks) put a great fraction (up to 92%) of the counting rate of FE-electronics in inner regions.

The main fraction of background is associated with hadronic cascades in the calorimeters, the muon shield, accelerator parts that produce **low-energy electrons** by (n,γ) reaction and subsequent Compton-scattering or by photoelectric effect in the detector materials [7].

But! Generated electrons cause signal in only one detector gap (not like penetration tracks of muons!) and could be rejected by «AND»-logics of signals in bi-gaps.

Station M2 (Quadrant 2) estimated counting rates per FE-channel in bigap (Hz) for Run5 (L=2E34 cm^{-2}s^{-1})



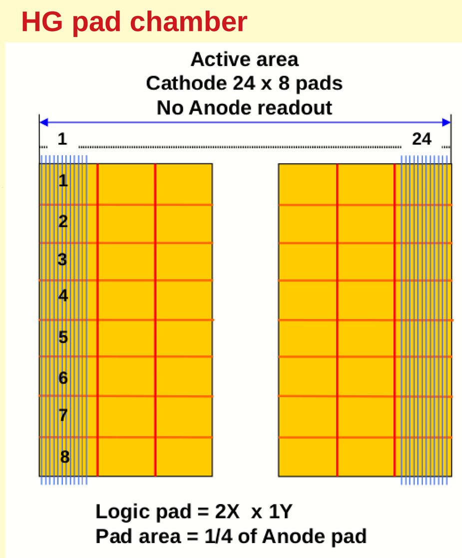
Cluster size for new pad chambers (rate reduced by factor 4) included as 2 for R1 and 1.5 for R2 => rate reduction by factor 3/8 (R2) and 2 (R1)

Data of special Run normalized to 2808 colliding bunches and extrapolated to L=2x10^{34}

New high granularity detector

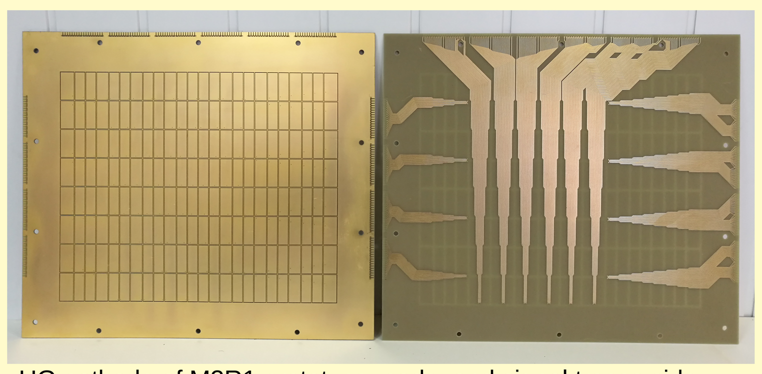
For Run3 the most irradiated chambers (M2R1, M2R2, M3R1) will be replaced with high granularity (HG) pad chambers. Cathodes is divided to 24x8 array of pads which are read by separate FE-channels. The area of pad ~1/4 of area of anode pad in current chambers.

HG pad chamber



New MWPC with high granularity design:
+ ~4 times higher rate capacity
+ only cathode readout — no «ghosts»
+ using of existing frontend electronics

Requires additional readout channels: for chambers M2R1/M2R2 — 24pcs x 16ch FEBs per chamber (14 FEBs per chamber in present), LV- and control lines



HG-cathode of M2R1 prototype: pads- and signal traces side

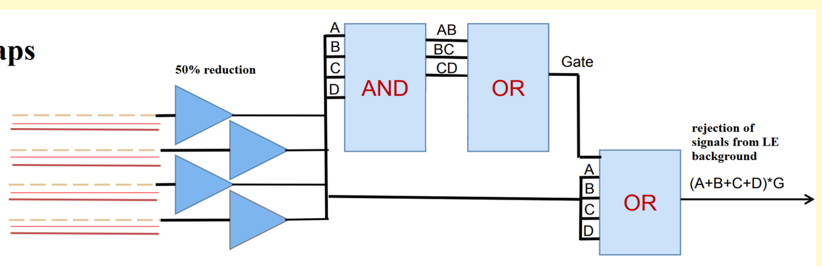
HG M2R2 prototype is ready and successfully tested at PNPI and GIF++.

HG M2R1 prototype is under construction at PNPI.

New FE-electronics for future upgrade

Since 2031 (Run5) with HL-LHC the expected luminosity is L=2x10^{34} cm^{-2}s^{-1} (50 times higher of present). There is expected rates up to ~1 Mhz/cm2. To keep required efficiency of MD 2 it is proposed:

1. ***Read each gap separately*** => reducing incoming rate in 2 times per physical channel



Proposed FE-logic for each logic channel

Fraction of penetrating particles (FPP):

$$FPP = \frac{Rate(\mathrm{AND})}{Rate(\mathrm{OR})},$$

Rate (AND) – signals of bi-gaps in "AND"
Rate (OR) – signals of bi-gaps in "OR"

fraction of correlated hits (%)

	M2	M3	M4	M5
R1	7	5	10	8
R2	9	8	12	10
R3	15	22	30	20
R4	32	45	45	12

G.Graziani, Report for Muon group.

2. Combine neighbor gaps by «AND» into 3 bi-gaps (AB, BC, CD) and form by «OR» **the 3-layered logical channel** (AB+BC+CD). Background event gives a hit only in one of the consecutive gaps and it will be rejected "on-fly".
3. Adding a gate opening an «OR» of all four gaps which is formed as requirement of at least one «AND» in neighbor gaps: (A+B+C+D)*G.

Finally, the suppression of uncorrelated hits by FE-logic can give a reduction of output rate up to 10 times in the external readout electronics and can make it significantly cheaper.

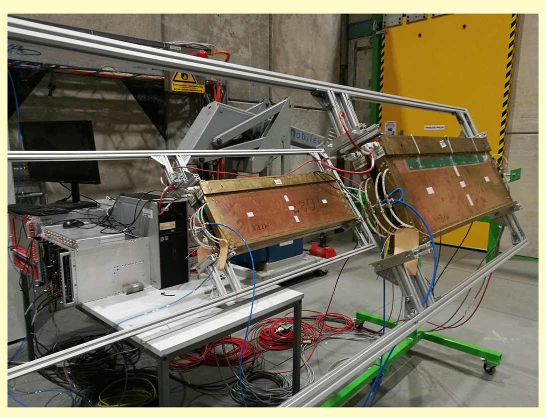
The solution to these tasks is the main direction of work for the coming years!

GIF++ facility for MWPC tests

Gamma Irradiation Facility (GIF++) [8] in combination with muon beam allows to test and study of signal/background sensitivities of new detectors and electronics, the study of the aging of detectors.

Properties of GIF++

- Gamma source: 16.65 TBq Cs-137 with photons energy of 0.66 MeV
- Flux of Gamma photons ~ 1.5 MHz/cm2 at distance 1.5m
- System of movable Pb and Al attenuators can reduce the intensity with factor 1..46000
- Muon beam from SPS H4 with muon's energy 100 GeV. Beam diameter 10cm and intensity 1E4 muons per spill (~1E6 muons/hour). Muon beam is available 6-8 weeks a year only.



New muon trigger stand for testing of new detectors and electronics

The new test setup is constructed for GIF++ facility at CERN and consists of two 4-gap muon chambers that work in coincidence mode.

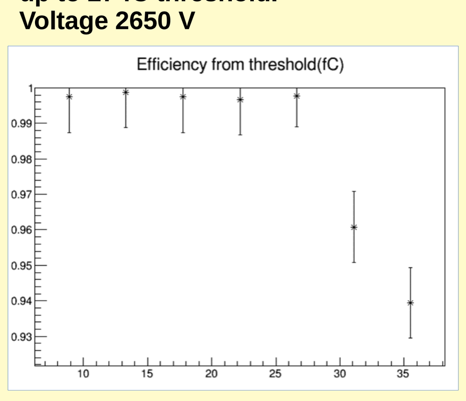
Each chamber has a very low sensitivity to gamma-background. So, rare cosmic muons can be observed in the presence of heavy gamma-background of the GIF++.

Main studies of prototypes at GIF++:

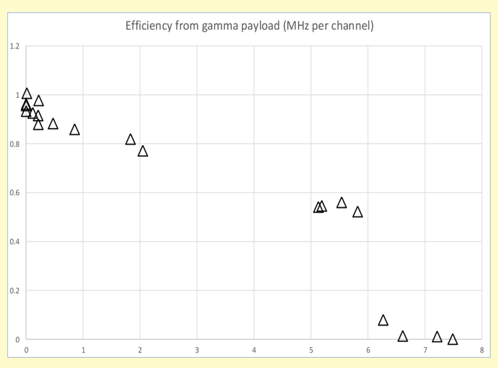
- Validating characteristics of prototypes
- Investigating the dependence of the muon registration efficiency from a high payload of uncorrelated gamma hits
- Advanced studies of undesirable electronics effects such as after-pulsing, crosstalk
- Studies chamber's parameters stability on very high intensity, with currents up to 300 uA per gap

The prototype M2R2 efficiency measurements

The M2R2 prototype efficiency more than 98% (on single bi-gap) up to 27 fC threshold. Voltage 2650 V



Muon efficiency via Gamma radiation payload is nonlinear after a rate of 6MHz per FE-channel in bi-gap. Measured dead time ~88 ns.



Conclusion

1. The muon detector of LHCb is one of the largest instrument of this kind worldwide, and one of the most irradiated. Nonetheless, the detector provides required efficiency and we see no sign of aging in MWPCs after ~9 years of operation even where the collected charge was ~0.6C/cm of wire.

2. The main factor of the inefficiency of detector is dead time of FE-electronics. To keep detector efficient enough in Run3 (L is 5 times higher of present) the HG MWPCs will be used for "hot" regions with existing FE-electronics. New chambers will also allow getting rid of «ghost» events that will appear in mixed-readout chambers.

3. Background shielding and its suppression is one of the important tasks for future upgrades as the fraction of associated hits is up to 92-93% in inner regions. After Upgrade1 it's expected significant reduction of background hits with beam plug (50% for M2R1) and Fe-Wall (~40% for M2R1).

4. For future Run5 with L 50 times higher of the present value, the most of the area of the detector could be covered with HG MWPC with granularity of the physical pads suits to the FE rate capacity. Application of MWPCs in "hot" regions associated with the proposed concept of new FE-electronics which suppress uncorrelated background hits and reduce output rate in external readout electronics and make it cheaper.

5. The performance of new detectors and electronics at a heavy gamma-irradiation environment can be studied and tested with the muon trigger is constructed and already in use at GIF++ facility.

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INTERNATIONAL CONFERENCE ON INSTRUMENTATION FOR COLLIDING BEAM PHYSICS (INSTR-2020), 24-28 February 2020, Budker Institute of Nuclear Physics, Novosibirsk, Russia