RMS-R3 – Radiation Hard System for Beam, Background and Luminosity Monitoring at the Upgraded LHCb Experiment

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IBIC '20 International Beam Instrumentation Conference
12-18 September 2020, Brazil (Remote)

THPP02

INTRODUCTION

Permanent monitoring and measurement of the beam&background running conditions are of paramount importance for the success of the LHCb experiment upgraded to take data in Run 3 at extremely high interaction rates of colliding nuclei at the LHC (CERN).

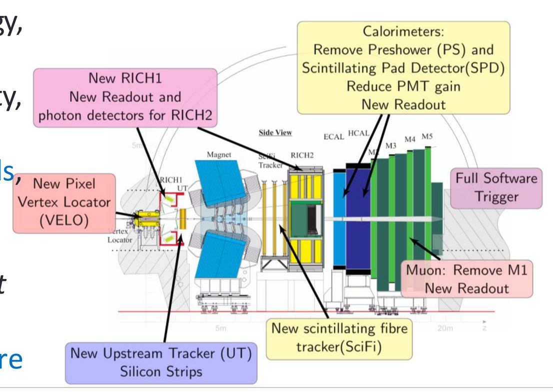
Presented here Radiation Monitoring System RMS-R3 is designed for those purposes.

LHCb EXPERIMENT. UPGRADE I (2019-2021)

- Run 3 conditions [1]:
  - Novel centre-of-mass energy, $\sqrt{s}$ = 14 TeV for p-p collisions
  - Instantaneous luminosity, $5\times L_{inst} = 2\times10^{33}\ cm^{-2}s^{-1}$
  - Step-up of radiation levels, etc.

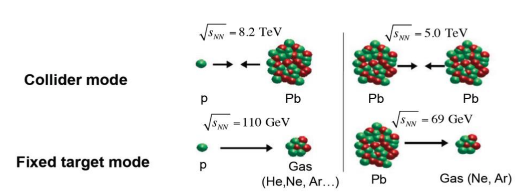
Aim to collect totally a data sample of 50 fb^{-1} over the next 10 years.

- Major hard- & software novelties [1]:
  - Triggerless readout system
  - Full software trigger with GPUs @30 MHz and CPUs@1MHz



The Upgraded LHCb detector, in fact, a brand-new detector!

- LHCb studies in Run 3 [1]:
  - flavour physics, particularly c- and b-quark physics (e.g., CP violation measurements in B and D decays)
  - flavour violating decays in the lepton sector
  - physics beyond flavour sector (e.g., electroweak, exotic physics and QCD etc.)
  - non-SM processes



LHCb heavy-ion collision programme significantly extended with the LHCb fixed-target system, called SMOG, since 2015

LHCb IT RMS IN RUN 1-2

- Main function [2, 3]:
  - Monitoring and measurement of radiation load on the silicon microstrip sensors of the Inner Tracker (IT)
- Directly measured quantity:
  - Flux/Fluence of charged particles
  - Fluence distribution over IT-2 silicon sensors for integrated luminosity of 2.5 fb^{-1} (2018) was in the range of $(0.8-4.5)\times10^{12}$ $MIPs/cm^2$
- Observables/Extracted values:
  - Absorbed dose and leakage current in IT-2 Si-sensors corresponding 2.5 fb^{-1} (2018):
  - 0.2 - 1 kGy resulting in the increase of leakage currents in the IT-2 Si-sensors in the range of 50 - 380 μA – in a good agreement with expectations (Hamburg Model) as well as with direct measurement in some sensors
- Principle of the Metal-Foil Detector (MFD) operation:
  - Positive charge originating in a thin metal foil due to the Secondary Electron Emission (SEE) under the impinging charged particles is integrated by the Charge Integrator proportionally converting its value into output frequency
- Evolution of the LHCb Integrated luminosity measured (calibrated) by the RMS in comparison with on-line official values

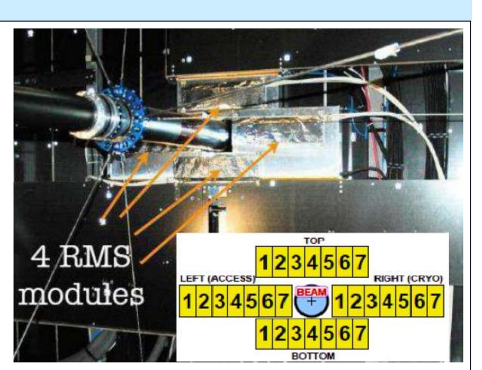
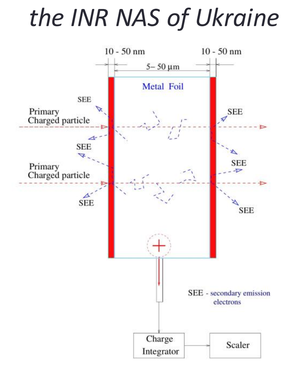
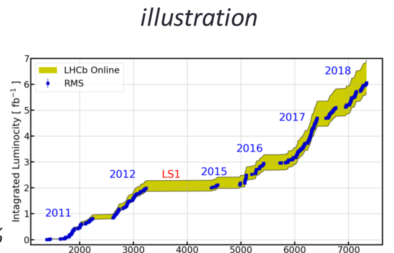


Photo. The RMS (Run 1, 2) fixed at IT-2 station: four detector modules each containing 7 MFD sensors (built under technology developed at the INR NAS of Ukraine



MFD operational principle illustration



Comparison of the integrated luminosity measured by the RMS (blue markers) and the LHCb measured one during 2011-2018. The green band corresponds to 10% of uncertainty

RMS-R3 DESCRIPTION

Objective of the RMS-R3 implementation

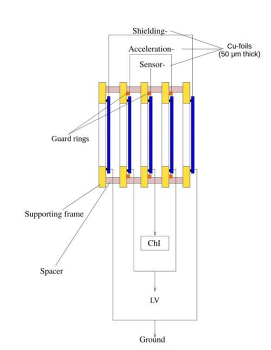
- The RMS-R3 is functionally projected for online monitoring running conditions near the interaction point of the LHCb experiment (IP8) during the various stages of the program at the nominal levelled instantaneous luminosity of $2\times10^{33}\ cm^{-2}s^{-1}$, measuring, in particular:
  - beams interaction rate (relative luminosity);
  - position of the IP8 (via calculation of the asymmetries in detector modules);
  - background from collimators;
  - radiation loads (charged particles fluxes distribution).
- To this end, four RMS-R3 detector modules with two sensors each are cross symmetrically located around the beam pipe approximately at 2 m from the IP8 region in the backward hemisphere of the LHCb detector.
- Specifications for all complementary monitoring systems given in [4].

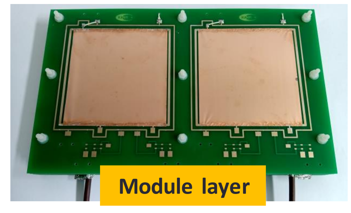
Key features of the RMS-R3

- Well understood and reliable principle of operation (SEE in MFD)
- Low operational voltage (24 V), digital output
- High radiation tolerance (up to fluence of 10^{20} $MIPs/cm^2$ or a GGy level)
- Relatively low price of fabrication, commercially available readout (RE) electronics
- Large dynamic range (10^3-10^9 MIPs/sensor/s, output linear response up to 4 MHz)

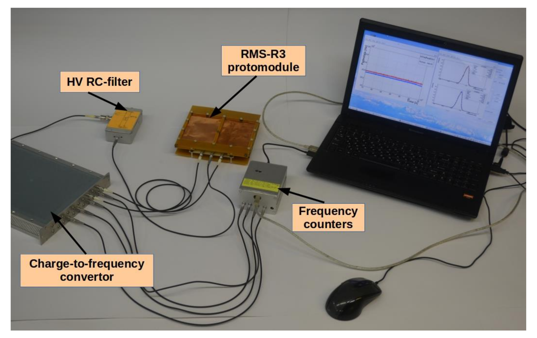
Detector design improvements

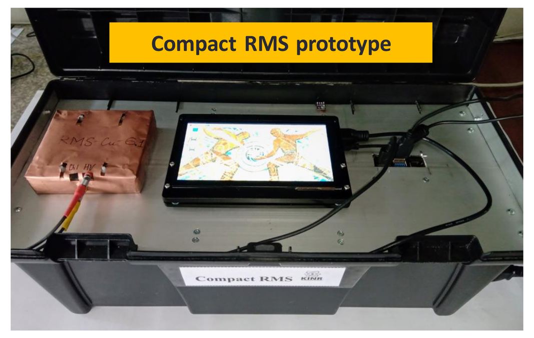
- Module comprises 2 sensors 9×9 cm^2
- 5-layer structure made out of modular PBC frames
- Sensor layers: 50 μm cooper foils
- Special guard rings added for sensor and LV-layers
- RC-filters (τ = 1 s) on LV-layers
- Detector enclosure made of fiber glass material covered with Al-shielding





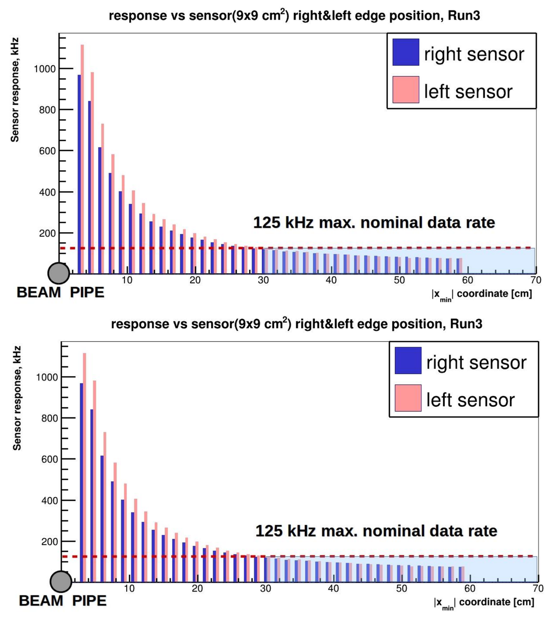
Experimental setups for detector testing and characterization





MC SIMULATION

- MC parameters:
  - 10^4 pp collisions at 13 TeV
  - $L_{inst} = 2\times10^{33}\ cm^{-2}s^{-1}$
  - $\sigma_{pp,\,total}$ = 102.5 mb
- Hit-to-response conversion:
  - Conversion factor:
  - K = 550 MIPs/sensor
  - Sensor size: 9×9 cm^2



Response distributions for various positions of RMS-R3 modules with respect to the beam pipe along X (top) and Y (bottom) axis

RMS-R3 READOUT ELECTRONICS

Charge sensitive integrators

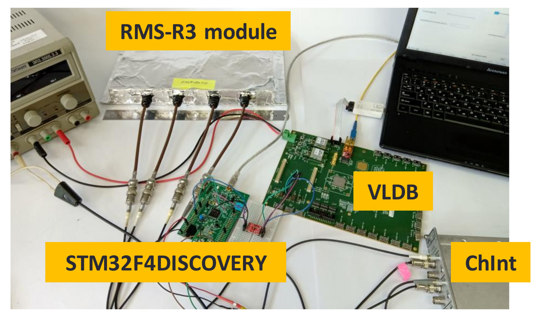
- Universal ADC FE, KINR developed
- Charge-to-frequency conversion: input current is converted into a sequence of output pulses with a frequency proportional to it
- Sensitivity: 10 fA – 1 Hz
- Input current range: 1 fA – 20 nA
- Excellent linearity: ±0.02% @2 MHz
- Radiation hardness ~3 kRad

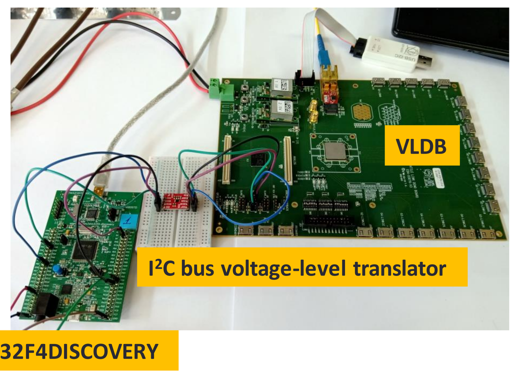
Frequency counters

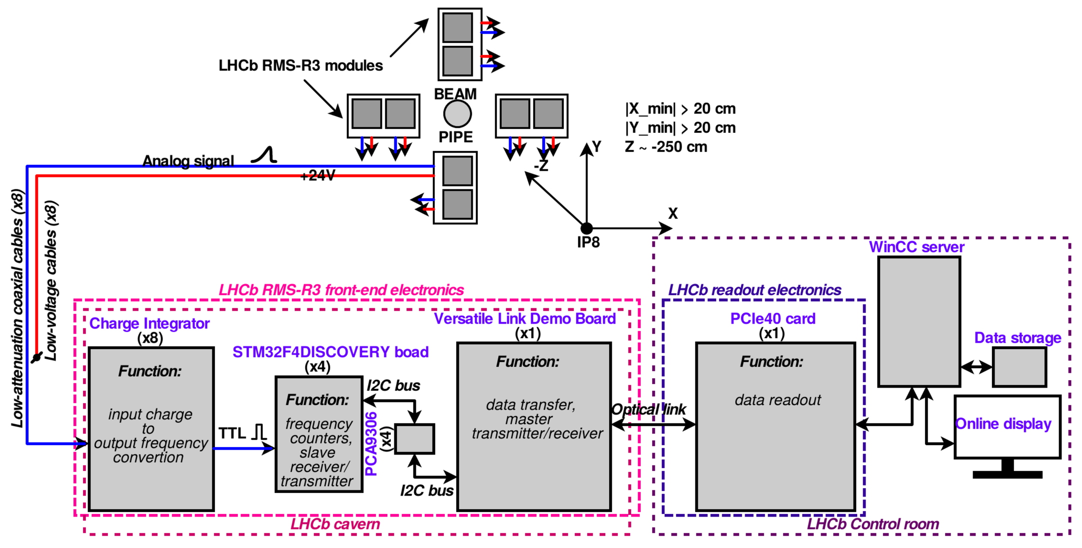
- Based on the STM32F4DISCOVERY board
- STMicroelectronics developed
- 2 32-bit programable timers (counters)
- I2C interface to communicate with the VLDB board

Versatile Link Demonstrator Board (VLDB) [5]

- CERN ESE group developed
- Evaluation board for rad-hard Optical Link ecosystem
- 4.8 Gpbs data transfer link between FE and BE
- Radiation hardness: of up to 400 MRad





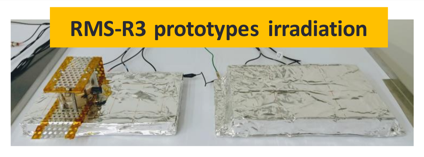


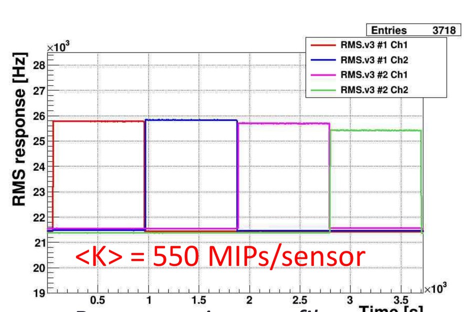
Block diagram of the readout chain of the Upgraded RMS-R3. The front-end electronics connected to 4 2-sensor modules that are placed around the beam pipe in front of the VELO comprise the Charge Integrators, frequency counters implemented on the STM32F4DISCOVERY board with a microcontroller and the VLDB board. Measured data are transferred to the global LHCb readout system

RMS-R3 PERFORMANCE STUDIES

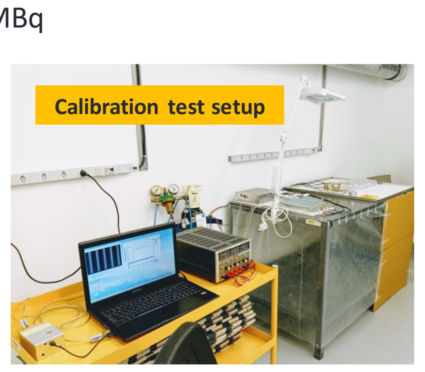
Reference calibration

- Flux φ, conversion factor K, response R
- φ [MIPs/sensor/s] = K [MIPs/sensor] × R [Hz]
- MIPs: beta, E_{max} = 2.28 MeV, RS Sr-90/Y-90, 30 MBq

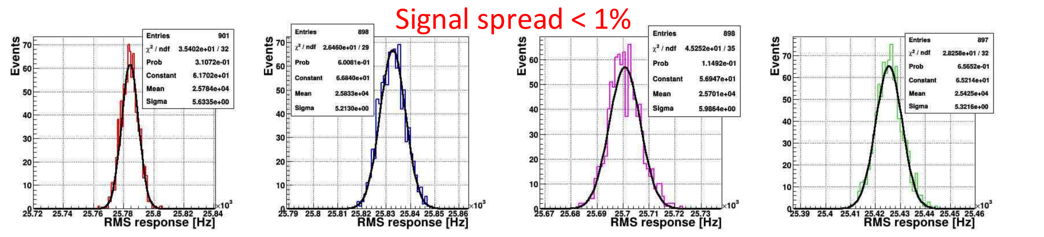




Response time profiles



Signal spread < 1%

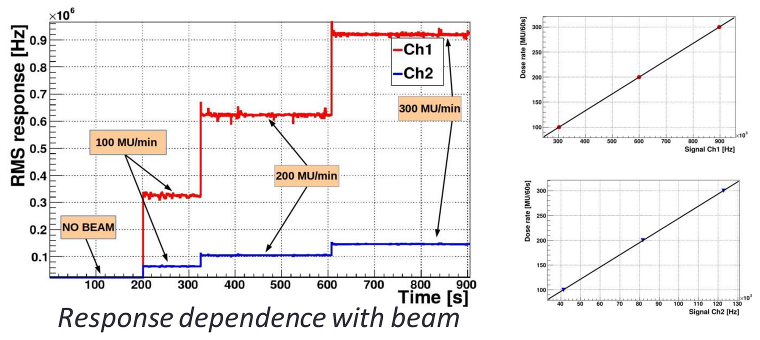


Response projections

Response linearity estimation

- Test at X-rays source (CLINAC)
- Beam energy: up to 6 MeV

Good linear response in the dynamic range

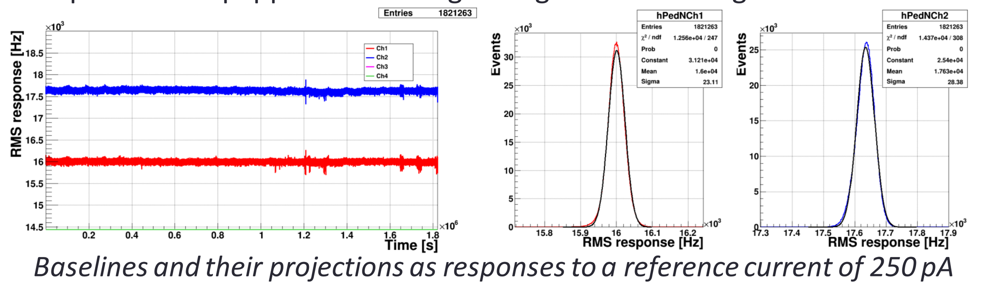


Response dependence with beam intensity increased

Long-term time stability and noise

- Baselines measurement for about 21 days
- Readout: Compact RMS equipped with Charge Integrators featuring the conversion of 1 fA – 1 Hz

Readout channels noises < 1%



Baselines and their projections as responses to a reference current of 250 pA

CONCLUSIONS

- The final version of the LHCb RMS-R3 modules have been produced applying new technological and technical improvements to a concept of MFD and successfully tested at INR NAS of Ukraine.
- The obtained results have demonstrated expected stability of operation (~1% reproducibility of a sensor's response as well as baseline fluctuations within few Hz at the level of 20 kHz) that is good enough for monitoring of relative luminosity and background at IP8 online.
- Readout electronics have been upgraded with 32-bit frequency counters implemented on the STM32F4DISCOVERY board with a microcontroller which will provide second-by-second monitoring and enable RMS-R3 operation in a standalone regime of data acquisition as well as its integration into the central LHCb monitoring system.

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ACKNOWLEDGEMENTS

- We acknowledge LHCb members G. Corti, E. Thomas, M. Karacson, R. Lindner, N. Tuning and Ph. Bertreix, V. Tromel from HSE-RP Group for their expertise and assistance in organizing and performing RMS-R3 prototypes tests at CERN.
- We thank KINR colleagues V. Kyva, O. Kshyvanskyi, V. Militsiia, D. Storozhyk for their contribution into the LHCb RMS upgrade.
- This work has been performed in frames of the LIA IDEATE activity with partial financial support within the STCU Project P9903 and the NAS of Ukraine Targeted Research Programme-1230 "Fundamental research on high-energy physics and nuclear physics (International Cooperation)".