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ТЕХНІКА ТА МЕТОДИ ЕКСПЕРИМЕНТУ
ENGINEERING AND METHODS OF EXPERIMENT

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RMS-R3 – THE SYSTEM FOR MONITORING THE REGION OF INTERACTIONS AND BACKGROUND AT THE LHCb EXPERIMENT (CERN)[1]

The upgraded Large Hadron Collider beauty (LHCb) detector will provide data taken in Run3 at the instantaneous luminosity of proton-proton collisions increased to $2\cdot10^{33}$ cm^{-2}s^{-1} at energies of up to 14 TeV. To ensure the safe operation of the experiment a new beam and background Radiation Monitoring System (RMS-R3) was built. RMS-R3 is based on metal-foil detector technology developed at the Institute for Nuclear Research, National Academy of Sciences of Ukraine (Kyiv, Ukraine). The system comprises four detector modules with two sensors in each. Their frequency response is proportional to the flux of incident charged particles. The modules are located around the beam pipe at a distance of 2.2 m from the interaction point. The results measured during the Run3 in 2022 testify to the reliable operation of the system. Applying the asymmetry method, high-accuracy data were obtained on the localization of the interactions region and the beam and background contribution.

Keywords: LHCb experiment, beam and background radiation monitoring system, metal foil detectors, asymmetry method.

1. Introduction

The Large Hadron Collider beauty (LHCb) detector (Fig. 1) is a general-purpose forward spectrometer at the Large Hadron Collider (LHC). The main goal of the experiment is to study the physics of heavy quarks flavors. During Run1 and Run2 data taking, the unique ability to accumulate physical data simultaneously in the collider mode and the fixed (gas) target mode (SMOG) has been demonstrated. During the 2019 - 2021 LHC long shutdown the experiment has been upgraded [1] enabling studies of nuclear-nuclear collisions at a wide range of energies from ~ 0.1 TeV in the fixed target mode [2] up to 14 TeV in the collider mode at five times increased instantaneous luminosity of ~ $2\cdot10^{33}$ cm^{-2}s^{-1}. In fact, the upgraded LHCb is a totally new detector aiming in Run3 to get data with the integrated luminosity of ~ 50 fb^{-1}. Expected integral luminosity for heavy ions measurements lasting one month are estimated in work [2] with the following indicators: Pb-Pb → ~ 0.5 nb^{-1}; p-Pb → ~ 150 nb^{-1} [3].

In particular, a new gas injection system (SMOG2, [4]) has been installed. The design of the SMOG2 system allows for an increase in the surface density of the gas by several orders of magnitude and significantly expands the number of injected gases (Helium, Neon, Argon, Krypton, Xenon, H_2, D_2, N_2, O_2). The energy of collisions varies from 0.07 to 0.115 TeV (nucleon-nucleon c.m.s.).

The new RMS-R3 follows the principle of its predecessor, the RMS-R2 [5 - 10]. Their operation is based on the technology of metal foil detectors (MFD, [11]).

2. Technical features of the RMS-R3

RMS-R3 is produced following the concept of MFD developed at the Institute for Nuclear Research of the National Academy of Sciences of Ukraine [11]. The operation principle of MFD is based on the phenomenon of Secondary Electron Emission (SEE, [12]) originated by the incident charged particles. The system has improved features (modular structure, additional protection against induced noise, etc.) and uses an autonomous reading system that includes commercially available electronics.

The RMS-R3 system comprises four detector modules located around the LHCb experiment’s beam pipe (Fig. 2).

Each module of the RMS-R3 contains two sensors. The sensors are made out of 9 × 9 cm^2 copper foil, surrounded from both sides by foils collecting SEE electrons, to which a positive voltage of 24 V is

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applied. In addition, this assembly is surrounded by two protective foils. The charge originated in a sensor under a flux of incident charged particles due to the SEE being integrated by the charge integrator. An analog value of the charge is converted proportionally to an output frequency processed by DAQ.

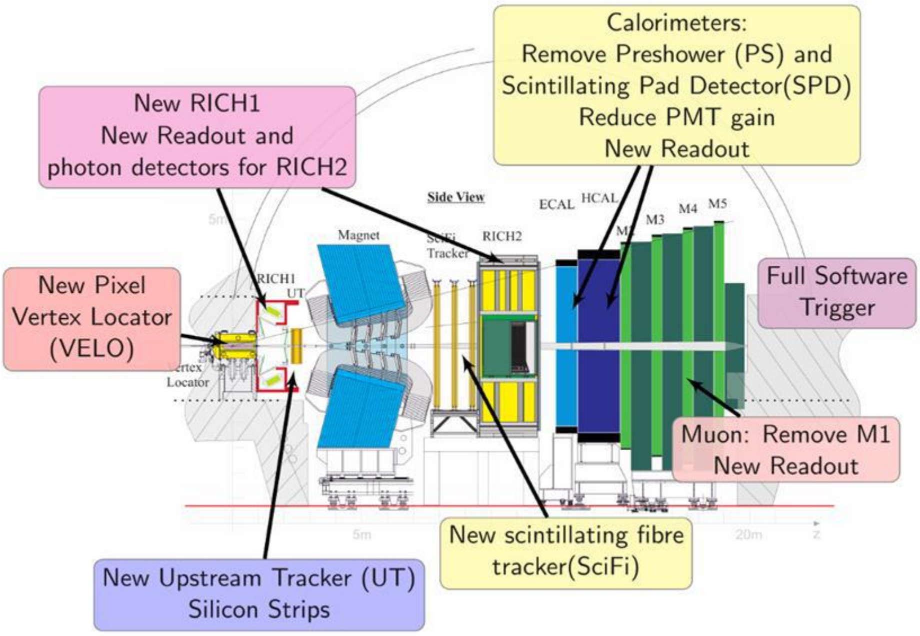


Fig. 1. Schematic view of the LHCb detector upgraded for Run3 [1].
(See color Figure on the journal website.)

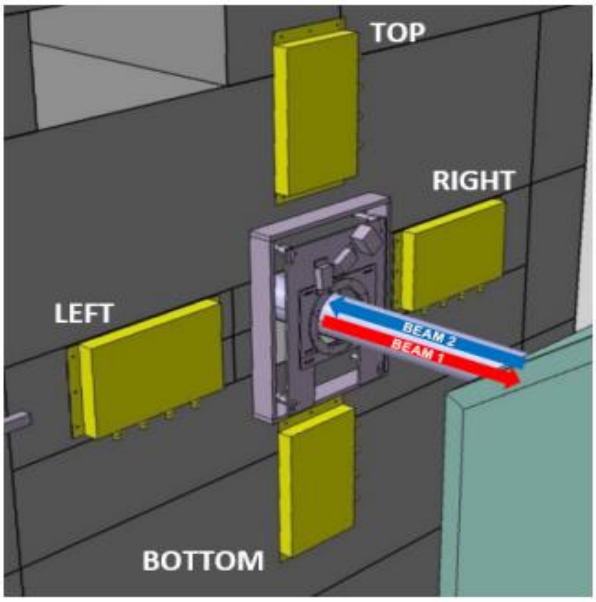


Fig. 2. Schematic representation of the location of the RMS-R3 modules relative to the beam pipe at the LHCb experiment. (See color Figure on the journal website.)

The RMS-R3 system features extremely high radiation tolerance (stable SEE emission at the fluence up to 10^{20} MIPs/cm^2), low operating voltage (tens of volts), digital output signal, linear response by charge integrators in a maximum available configuration of up to 4 MHz, charged particles flux detection capability within a range of 10^3 - 10^9 MIP/sensor/s, a relatively simple construction of a very low mass modules, low manufacturing cost.

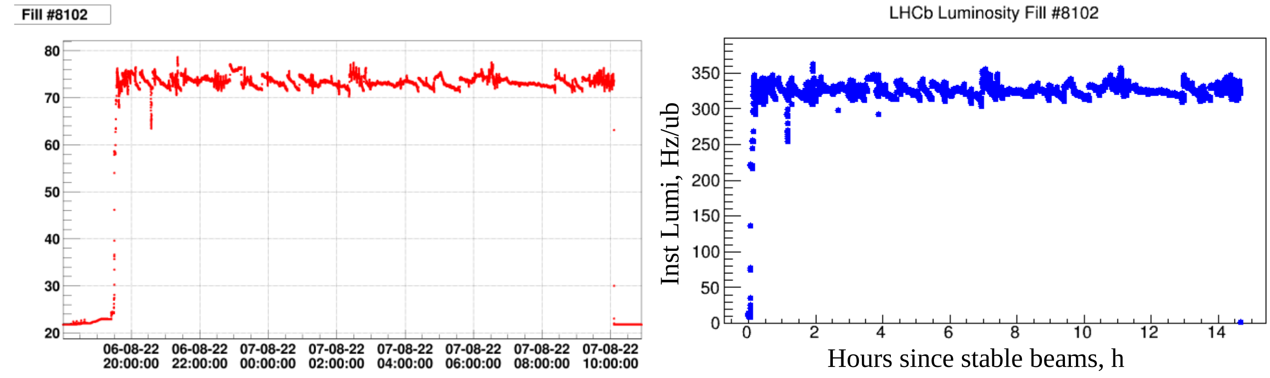
3. The RMS-R3 performance in Run 3 (year 2022) at the LHCb experiment

3.1. Linearity and stability of the RMS-R3 operation

The main experimental and physical challenge is to obtain representative, high-accuracy data. The data needs to be measured under as stable, homogeneous conditions as possible during the whole campaign of Run3. It is the main task of the RMS-R3 system to provide online information on the acceptable beam and background conditions, related to the LHC beam-beam or beam-gas interactions in the interactions region of the LHCb experiment. The RMS-R3 data have to assure that those conditions are well reproducible by the LHC beams from fill to fill. The reliability of RMS-R3 data is determined by its high linearity and temporal stability of the response, independent of the accumulated fluence of radiation load.

Fig. 3 shows the evolution of the RMS-R3 rates (top figure) and PLUME [13] luminosity measuring system data (bottom figure) measured during the fill 8102 (proton-proton collisions at a beam energy of 6.8 TeV). One may conclude on a perfect correspondence of both measurements.

PLUME is brand new detector [13] for measuring the luminosity and beam conditions at the interaction point at LHCb experiment. PLUME is based on the registration of Cherenkov radiation produced in quartz material by particles from the interaction region.



a *b*

Fig. 3. The RMS-R3 response (*a*) compared with an absolute luminosity measured by the PLUME system (*b*) during the fill 8102 (14.2 h, proton-proton collisions at a beam energy of 6.8 TeV). (See color Figure on the journal website.)

The background contribution may be originated by the beam and beam halo scattering at the edges of collimators, VELO RF foil and entrance parts of the SMOG2 system. It is important to distinguish “poor” background conditions from the optimal ones during online operation as well as at the stage of data analysis (offline process). In the next subsection of this article, an effective technique of evaluation and imaging of asymmetries (conditions of experiment) is described in details.

Such stable conditions of data taking provide efficient usage of the high-cost LHC operation. The corresponding integrated luminosity is obtained by integrating the instantaneous luminosity as a function of time over a given time interval. The higher accuracy of the measured luminosity results in a more accurate measurement of the cross-section of the process, or the value that can be derived from it.

An important part of the calibration of detectors at the LHCb experiment is the μ-scan method. By definition, the μ is the average number of visible p-p interactions per bunch-crossing [14]. The instantaneous luminosity is directly proportional to μ. The essence of the method is the calculation of calibration constant. The constant is obtained from an approximation of the detector response to the luminosity. Because μ is directly proportional to the luminosity of the experiment, we have the dependence of the detector rates on μ. The dependence is linear and allows to evaluate the reliability of the detector.

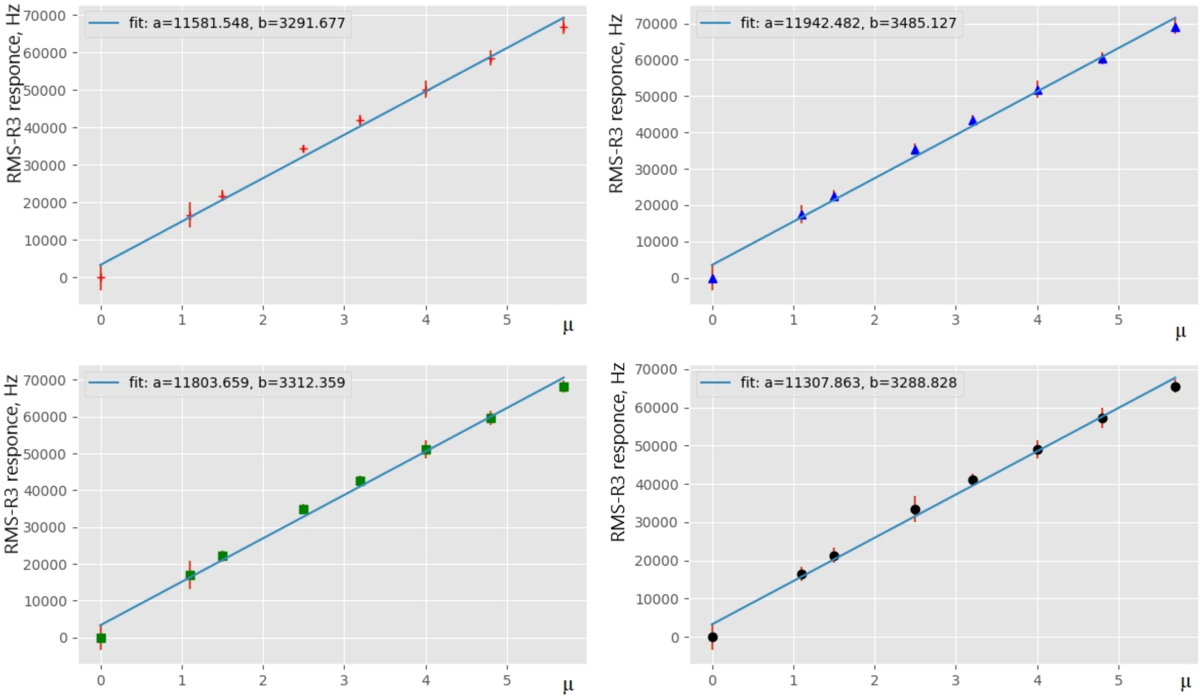


Fig. 4. Dependence of detector module rates on μ (for 5σ error). Modules: *top* (upper left figure); *bottom* (upper right figure), *left* (down left figure) and *right* (down right figure). (See color Figure on the journal website.)

Fig. 4 shows the response rate of each of the RMS-R3 detector modules (the average value of the sum of the response of the two sensors inside of each module) as a function of the μ. The LHCb nominal instantaneous luminosity of $2 \cdot 10^{33}$ cm^{-2}s^{-1} is reached at μ = 4. Taking into account the fact that at μ = 0, the response of RMS-R3 should also be equal to 0, we are able to estimate the linearity of the response of RMS-R3 with minimal impact of the background on the RMS-R3 response. The RMS-R3 data demonstrate its perfect linear response (for an error of 5σ) to increasing luminosity. Moreover, its dynamic range allows for reliable data taking at the luminosity increase by an order of magnitude, which is important from the point of view of the emergency case of a sudden increase of the luminosity and post-mortem evaluation of the caused radiation load onto the LHCb detector.

3.2. RMS-R3 monitoring interactions region by asymmetry method

The geometrical layout of the RMS-R3 detector modules was designed in a way to apply the well-known method of data analysis calculating the "left - right" and "top - bottom" asymmetries of the detector rates. The asymmetry is calculated according to Eq. (1):

$$A_{ij} = \frac{R_i - R_j}{R_i + R_j}, \qquad (1)$$

where R_i and R_j are the rates of sensors i and j, respectively, corresponding either to "top - bottom" or "left - right" pairs of detector modules (see Fig. 2).

The detector rates are dependent on the luminosity and background, polar and azimuthal angles, and solid angle of the detectors. The remarkable feature of the asymmetry value A_{ij} is that it is not dependent either on the luminosity or the solid angle of the detectors as far as they are present in the numerator and denominator in Eq. (1). It is evident that any change in the position of the interaction region or background contribution will change the value of A_{ij}. Two-dimensional distributions of A_{ij} ("left - right" vs "top - bottom") provide more distinctive and representative information. Below we present some examples illustrating the power of the method. Fig. 5 shows zoomed view of asymmetries distribution observed during a stable fill with p-p collisions at 6.8 TeV.

Here, the horizontal and vertical axes are in units of "left - right" ($\alpha_{\mathrm{horizontal}}$) and "top - bottom" ($\alpha_{\mathrm{vertical}}$) asymmetries, correspondingly. Let us notice that accordingly to the Eq. (1) physical event might populate a 2D plane of asymmetries ranging from –1 to 1 in horizontal and vertical directions. As one can see, there is the well-pronounced concentration of events (locus) with a center of gravity (c.o.g.) value for asymmetries at $\alpha_{\mathrm{vertical}} = -25.90 \cdot 10^{-3}$ and $\alpha_{\mathrm{horizontal}} = -9.85 \cdot 10^{-3}$. These values are very small (on a plane asymmetry with values from –1 to 1) and are measurable due to the extremely stable operation of the RMS-R3 system.

An example demonstrating the sensitivity of asymmetries distribution to a change in the experimental conditions is presented in Fig. 6, where two well-separated events localizations are observed.

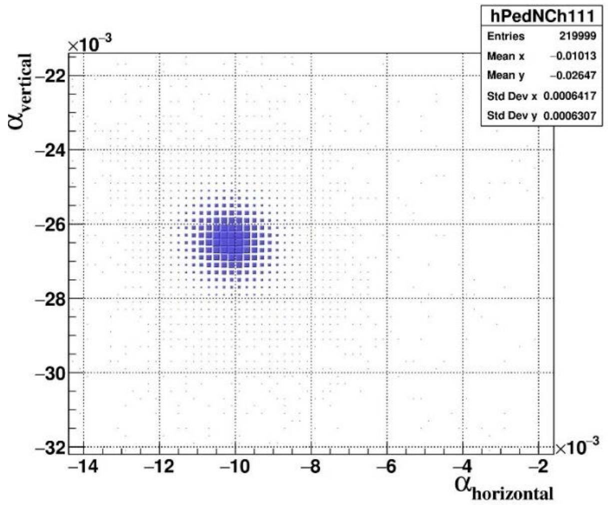


Fig. 5. Zoomed view of two-dimensional distribution of asymmetries: "top - bottom" ($\alpha_{\mathrm{vertical}}$) vs "left - right" ($\alpha_{\mathrm{horizontal}}$) observed during a stable fill with p-p collisions at 6.8 TeV. (See color Figure on the journal website.)

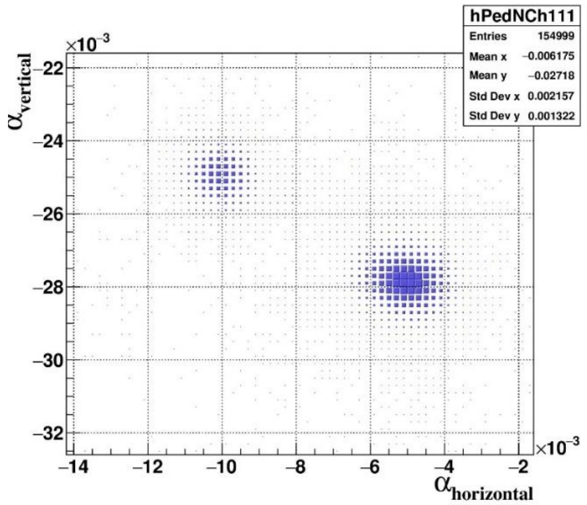


Fig. 6. Zoomed view of two-dimensional distribution of asymmetries: "top - bottom" ($\alpha_{\mathrm{vertical}}$) vs "left - right" ($\alpha_{\mathrm{horizontal}}$) observed during a stable fill with p-p collisions at 6.8 TeV. Two loci correspond to the cases with VELO OPEN: $\alpha_{\mathrm{vertical}} = (-27.75 \pm 0.05) \cdot 10^{-3}$ and $\alpha_{\mathrm{horizontal}} = (-4.95 \pm 0.05) \cdot 10^{-3}$; VELO CLOSED: $\alpha_{\mathrm{vertical}} = (-24.95 \pm 0.05) \cdot 10^{-3}$ and $\alpha_{\mathrm{horizontal}} = (-9.85 \pm 0.05) \cdot 10^{-3}$. (See color Figure on the journal website.)

The locus with a c.o.g. value for asymmetries at $\alpha_{\mathrm{vertical}} = -27.75 \pm 0.05$ and $\alpha_{\mathrm{horizontal}} = -4.95 \pm 0.05$ corresponds to the case of data taking during a period of time when vertex detector parts were retracted from the proton beam line (VELO OPEN). Another locus with a c.o.g. value for asymmetries at $\alpha_{\text{vertical}} = -24.95 \pm 0.05$ and $\alpha_{\text{horizontal}} = -9.85 \pm 0.05$ corresponds to the case when vertex detector parts were positioned at their nominal distance from a beamline (VELO CLOSED).

Fig. 7 illustrates the procedure of determination of the c.o.g. values of loci observed on a two-dimensional distribution of the detector's rate asymmetries. As an example, the data from Fig. 6 are used which were obtained during a stable fill with p-p collisions at 6.8 TeV, while vertex detector parts were sequentially kept at two positions: VELO OPEN and VELO CLOSED (corresponding loci are described in the caption to Fig. 6).

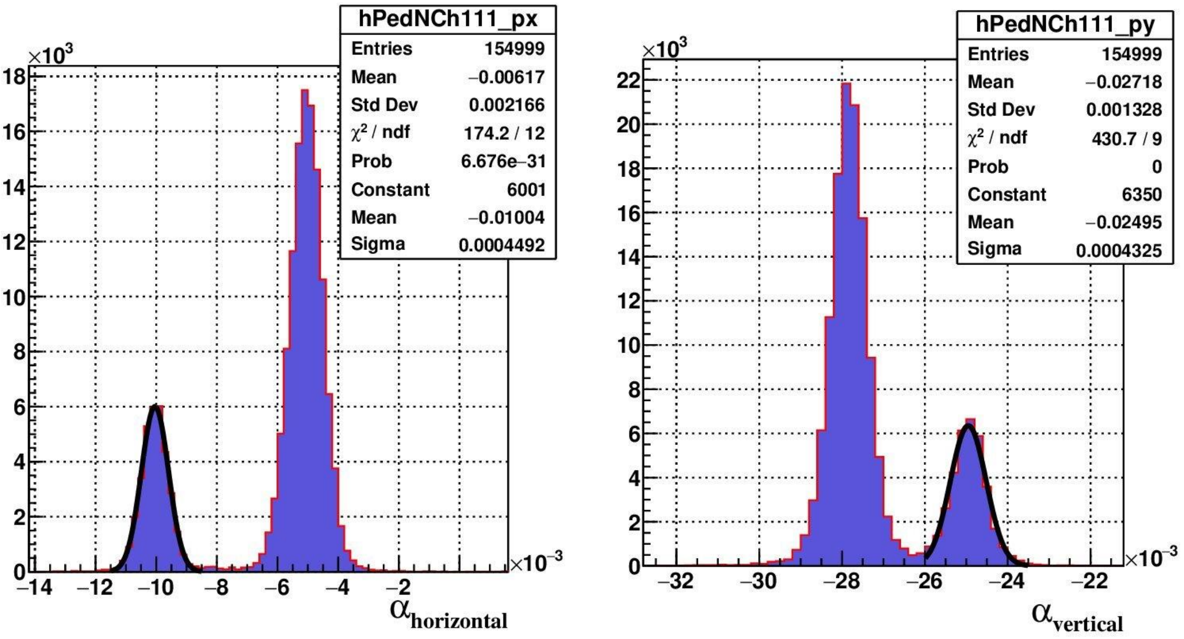


Fig. 7. Projections of two-dimensional distribution of asymmetries observed during a stable fill with p-p collisions at 6.8 TeV (see Fig. 6) onto horizontal (*left panel*) and vertical (*right panel*) axes. (See color Figure on the journal website.)

A shift of the asymmetry locus at VELO CLOSE condition could indicate contribution of the beam halo scattering at the RF shielding of the VELO system. This is a topic for further research.

Two peaks in Fig. 7 correspond to the projection of the data from two loci present in Fig. 6. The solid lines represent their gaussian fit, which is used to extract values for the c.o.g. of loci as well as related errors. Some additional results of the asymmetry measurements for p-p collisions and collisions of the proton beam with nuclei of the gas target (fixed target regime) are shown in the Table.

The c.o.g. coordinates of the asymmetries locus for p-p collisions and proton beam interactions with a fixed (gas) target nuclei. For beam-gas collisions the vertex detector is always closed (VELO CLOSED)

Collisions	c.o.g. coordinates of the asymmetry loci: $\alpha_{\text{horizontal}}$; α_{vertical} (both, times 10^{-3})
p-p (VELO CLOSED)	(–9.85 ± 0.05); (–24.95 ± 0.05)
p-p (VELO OPEN)	(–4.95 ± 0.05); (–27.75 ± 0.05)
p-Ar (gas target)	(–3.45 ± 0.05); (–26.65 ± 0.05)
p-He (gas target)	(–9.75 ± 0.05); (–24.55 ± 0.05)
p-H_2 (gas target)	(–9.55 ± 0.05); (–25.45 ± 0.05)

The data in Table show that mean values of asymmetries measured by the RMS-R3 are very close to zero, as should be expected from the point of view of its symmetrical geometrical layout and precision mounting of the detectors with respect to the beam line. On the other hand, data shown in Figs. 5 and 6 (as well as similar ones for many other LHC beams fills) demonstrate unambiguous confidence in the possibility of distinctive observation of locus movements under variation of either position of the interaction region or conditions of the experiment. This is possible due to the high stability of RMS-R3 performance, allowing measurement detector rates difference with an accuracy of a few hertz at the frequency range of 100 kHz.

4. Summary and outlook

RMS-R3 was successfully built and commissioned at the LHCb experiment for the Run3 data-taking campaign. The performance results obtained in the year 2022 prove that the system is stable and has a perfectly linear response to instantaneous luminosity with a safety factor of 10. It is a reliable integral part of the LHCb detector, which provides online monitoring of the beam and background conditions. Its data allow monitoring of the evolution of the luminosity as well as the region of its localization. Using the asymmetry method, it was demonstrated that RMS-R3 is a sensitive tool to distinguish interaction regions for p-p collisions and proton beam interactions with nuclei of various gases in a fixed target regime.

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RMS-R3 - СИСТЕМА МОНІТОРИНГУ ОБЛАСТІ СВІТНОСТІ ТА ФОНУ В ЕКСПЕРИМЕНТІ LHCb (CERN)

Оновлений детектор Великий адронний колайдер (LHCb) забезпечить накопичення даних у серії вимірювань Run3 при миттєвій світимості протон-протонних зіткнень до $2 \cdot 10^{33}$ см$^{-2}$с$^{-1}$ при енергіях до 14 ТеВ. Для забезпечення ефективного режиму роботи експерименту було розроблено та введено в експлуатацію нову систему радіаційного моніторингу пучка та фону (RMS-R3). RMS-R3 базується на технології металево-фольгових детекторів, що є розробкою Інституту ядерних досліджень НАН України (Київ, Україна). Система складається з чотирьох модулів по два сенсори в кожному, з частотним відгуком, пропорційним потоку налітаючих заряджених частинок. Модулі RMS-R3 розташовано навколо іонопроводу на відстані 2,2 м від точки взаємодії. Результати, що були отримані при вимірюваннях протягом Run3 у 2022 р., свідчать про надійну роботу системи. Застосовуючи метод асиметрії, отримано високоточні дані щодо локалізації області світності та впливу пучка і фону.

Ключові слова: експеримент LHCb, система радіаційного моніторингу умов пучка та фону, металеві фольгові детектори, метод асиметрій.

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