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MINIMUM RESOLUTION OF **MCORD**  
AS A CONSEQUENCE OF ASTROPHYSICAL  
OBSERVATION REQUIREMENTS

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Минимальное разрешение MCORD как следствие требований астрофизических наблюдений

Для полной функциональности многоцелевой детектор (MPD) нуждается в дополнительной системе запуска для калибровки вне пучка и подавления частиц космических лучей. Прототип системы измерения космических лучей для детектора MPD находится в стадии разработки и называется MPD Cosmic Ray Detector (MCORD). Он сможет обнаруживать мюоны, идущие со всех сторон от зенита до горизонта, с информацией о векторе направления частицы. Теоретически можно будет распознать внегалактический источник космической частицы, но только в случае космических лучей сверхвысокой энергии (UHECR), подключенных к расширенному космическому ливню (ECS). Нужно использовать оптимальное разрешение положения MCORD, чтобы идентифицировать возможные источники на поверхности небесной сферы.

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Minimum Resolution of MCORD as a Consequence of Astrophysical Observation Requirements

The Multi-Purpose Detector (MPD) needs an additional trigger system for off-beam calibration and rejection of cosmic ray particles for full functionality. The prototype cosmic ray measurement system for the MPD detector is under development and is called the MPD Cosmic Ray Detector (MCORD). It can detect muons coming from all directions between zenith and horizon, with information about particle direction vector. Theoretically, it is possible to recognize the extragalactic source of a cosmic particle but only in case of Ultra-High Energy Cosmic Rays (UHE CR) connected to Extended Cosmic Showers (ECS). We need to use the optimal MCORD position resolution to identify the possible sources on the celestial sphere.

The investigation has been performed at the Veksler and Balдин Laboratory of High Energy Physics, JINR.

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## INTRODUCTION

A new accelerator complex is under construction at the Joint Institute for Nuclear Research (JINR) in Dubna. The first detector set for monitoring collisions at the new Nuclotron-based Ion Collider Facility (NICA) [1] constructed in Dubna, Russia, is called Multi-Purpose Detector (MPD) [2]. The main role of the MPD is to provide information necessary for reconstructing each event and particle tracks. The cosmic muons from the Extended Cosmic Showers (ECS) are one of the sources of additional signals. The prototype Cosmic Ray (CR) measurement system is designed for the MPD detector as an additional trigger and calibration system and works as a muons veto system. It is called the MPD Cosmic Ray Detector (MCORD) (Fig. 1, *a*) [3, 4]. In the past, similar system at CERN for the ALICE detector called ACORDE was built [5]. The main difference between those two detectors is that ALICE is located deep underground (about 60 m), whereas MPD is located on the ground level. The underground location of ALICE and other two provided experiments at the similar location with the measurement of ECS (DELPHI [6] and ALEPH [7]) give a natural barrier for filtering low energy muons ( $E < 16$  GeV) and additionally barrier for muons coming from direction close to horizontal. The MPD has a possibility to detect muons coming from all directions between zenith and horizon [8].

Detectors such as MPD are not created for astrophysical observations. Nevertheless, if they are equipped with an additional detector or one of the subdetectors is adapted to this, they can become a unique tool for observing cosmic showers. Their uniqueness lies in the fact that they are equipped with a Time Projective Chamber (TPC) detector (Fig. 1, *b*).

It was as a result of ECS observations in these three experiments at CERN that a surplus of phenomena coming from the primary Ultra-High Energy Cosmic Rays (UHE CR), inconsistent with theoretical calculations, was noticed and called Multi-Muon Events. However, each of these experiments within a few years observed only a few such cases, which is not enough to draw broader conclusions. However, such events raise reasonable doubts about our knowledge of the interaction between hadrons at extremely high energies. We encounter a similar difficulty when we touch the Greisen-Zatsepin-Kuzmin (GZK) cut-off problem [9]. According to this theory, it is impossible to observe primary particles with energy greater than  $4 \cdot 10^{19}$  eV originating from sources with a distance greater than 50 Mpc, due to, *inter alia*, interaction with background microwave radiation. One fact is that in many observatories, the presence of such particles was recorded. For this reason, attempts to identify the location of their sources are crucial.

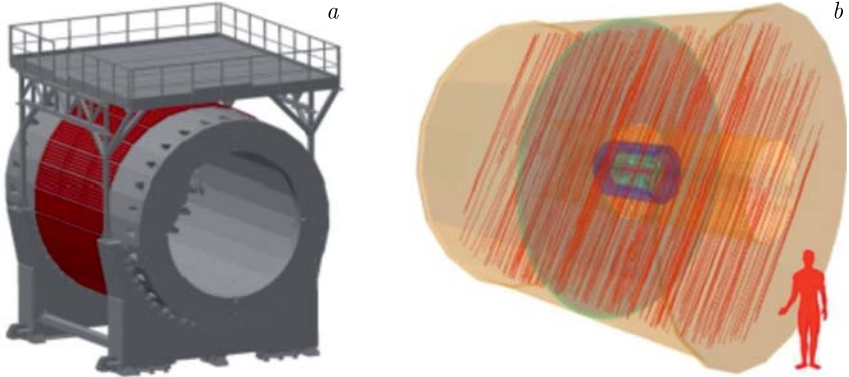


Fig. 1. *a*) The MCORD detector (red color) on the MPD body; *b*) the ALICE TPC detector with the multi-muon event tracks [5]

Generally, cosmic ray particles have an isotropic distribution due to their interaction with the magnetic field from stars and galaxies. Anyway, it is theoretically possible that in the case of UHE CR, the impact of these fields on the particle path will be so small that it will be possible to identify their source. Based on data from the ACORDE project, one team was able to determine the location of such a potential source [10]. The high level of uncertainty for this measurement, mainly from very small case statistics, gives us the argument that it is necessary to collect better statistics. Both the MPD and MCORD detectors can become the appropriate tools. The following study shows how to determine the minimum necessary resolution of the MCORD detector system to estimate the location of event sources on the celestial sphere with sufficient accuracy.

## CALCULATION OF THE MCORD ANGULAR RESOLUTION

The expected accuracy of the MCORD resolution is based on the following assumptions:

- The accuracy of determining spherical celestial coordinates depends on that of the scintillator passage position, related to the particular cosmic ray event.
- Assumed accuracy of the scintillator position determination is about 5–7.5 cm along the  $X$ -axis and 7.5 cm along the  $Y$ -axis (on the  $X$ -axis it depends on detector time resolution, and on the  $Y$ -axis — on scintillator width).
- The two layers of scintillators registering a single event are separated up to  $D = 6.5$  m (the MCORD layer surrounding the MPD).
- We assume that the maximum accumulation of measurement errors occurs when the scintillators are located on the opposite directions (Fig. 2). In other cases, the angles of maximum variation are smaller.

- Taking into account the above conditions, we can estimate the maximum errors in the angles measured along the  $X$ – $Y$  axes (Fig. 2).

With the critical configuration of detecting scintillators (Fig. 2), when the CR event has the direction perpendicular to the detector's axis of symmetry, we can assume that the maximum errors in the angles meet the equations

$$\operatorname{tg}(\Delta\alpha_X) = \frac{\Delta X}{D/2} \quad \text{and} \quad \operatorname{tg}(\Delta\alpha_Y) = \frac{\Delta Y}{D/2}. \quad (1)$$

Therefore, the final maximum errors are

$$\Delta\alpha_X = \operatorname{arctg}\left(\frac{2\Delta X}{D}\right) \quad \text{and} \quad \Delta\alpha_Y = \operatorname{arctg}\left(\frac{2\Delta Y}{D}\right). \quad (2)$$

If we assume the critical case that the errors accumulate, i.e.,  $\Delta\alpha_X \simeq \Delta\alpha_Y$ , the possible total error in determining the angle on the celestial sphere will be

$$\Delta\alpha_{\max} \simeq \sqrt{2} \Delta\alpha_X. \quad (3)$$

In other individual cases, we can determine the total error from the formula

$$\Delta\alpha = \sqrt{(\Delta\alpha_X)^2 + (\Delta\alpha_Y)^2}. \quad (4)$$

Finally, we can receive the total maximum errors in the measured angles ( $\alpha$ ). By applying a typical error range of position measurement in  $X$  and  $Y$  on scintillator (up to 5–7.5 cm), the final errors in angles on the

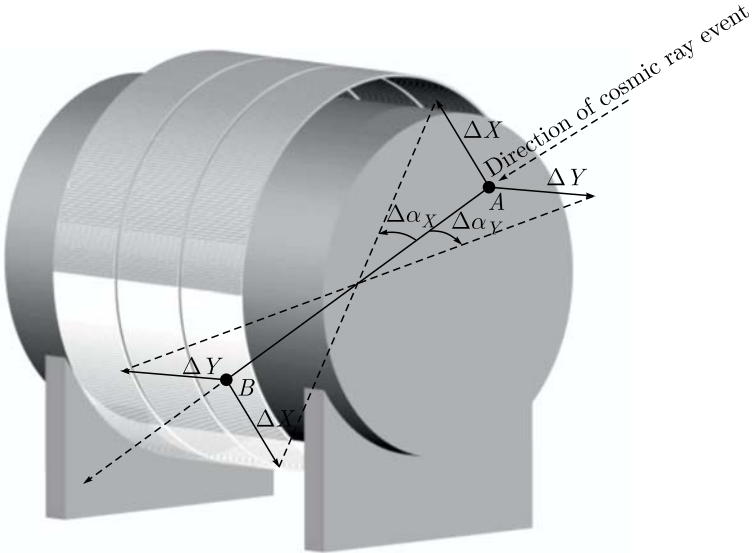


Fig. 2. The example of the geometric configuration, where errors of positional angles on the celestial sphere accumulate (maximize). The error values in  $X, Y$  are visually magnified to make the differences more visible

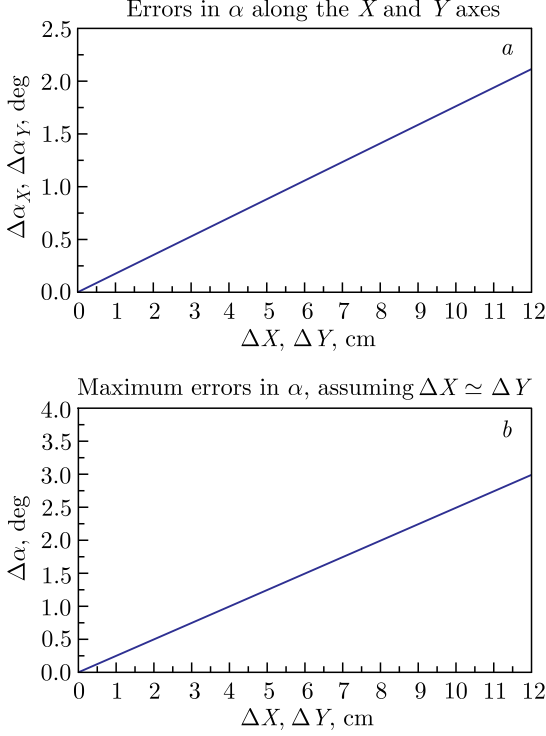


Fig. 3. *a*) Errors in positional angles along the  $X$  and  $Y$  axes; *b*) maximum error in the positional angle

celestial sphere can be calculated, as shown in Fig. 3. One can see that for scintillator errors of approximately 5 cm, the accuracy of the position in the sky within 1-deg limit is always fulfilled. For 7.5-cm errors, the accuracy can be considered as conditionally acceptable. In consequence, we can define MCORD requirements for astrophysical observations. We are able to obtain the estimated position of UHE CR. Typically, we can achieve an accuracy of 1 deg, but with a maximum error on scintillators up to 7.5 cm in  $X$  and  $Y$ , slightly degraded but still acceptable. Such a level of accuracy should be sufficient to detect the single source because they are generally well separated. The most UHE CR, e.g., blazars, are generally sufficiently isolated. In order to make progress compared to previous results, we should keep errors within 1 deg or better. In our previous studies [10], total errors reached a few degrees. Therefore, the critical accuracy of the scintillator should preferably be limited to 5 cm. In case of a very rich bundle of high-energy muons, the statistics improve the accuracy of the limits slightly. However, as results from other detectors have shown, the dispersion of such a bundle can reach a few degrees. There are other essential measurement factors; one of them is

a very rigorous time service. It is preferable to maintain coordinated universal time (UTC) rather than local time.

## CONCLUSIONS

We can see that MCORD, along with the entire MPD detector, can contribute to a significant increase in the observational material regarding the identification of ECS created by primary particles from UHE CR sources. Therefore, attempts to identify these sources so far have either failed or the results have very high uncertainty. The calculations show that the MCORD detector can meet the requirements for such measurements and allow for the possible identification of such sources. Thanks to the calculations described above, we can estimate the accuracy limit of our system.

In addition, a unique advantage is a fact that the MCORD detector will work in a set with several other MPD detectors like TPC, which will be able to improve the accuracy of the identified position and additionally enable the identification of some particles and their charge.

The proposed observations are extremely important from the point of view of solving the GZK cut-off problem or improving our knowledge of hadron interactions at extremely high energies. Previous observations carried out with the help of similar detectors in the past at CERN gave us more questions and doubts than answers, the main reason for which was the very limited statistics of the collected data.

The planned MCORD detector along with the MPD time projection chamber show the unique opportunity of the very precise measurement of atmospheric muon multiplicity distributions as a function of the zenith angle of primary cosmic particle, up to nearly horizontal showers. Until now, such measurements have not been achievable.

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